Significant wave height assessment using multi mission satellite altimeter over Malaysian seas

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Abstract. Satellite altimeter is one of the useful technique to study the variation of ocean parameters with a good temporal and spatial measurements. In situ measurements such as buoy has own disadvantages in terms of spatial observations. Thus, with the combination of satellite altimeter and buoy can improve the significant wave height measurements for both spatial and temporal over the seas. Generally, the measurement of significant wave height from altimeter using the Ku-band signal, while SARAL is borne with Ka-band altimeter (AltiKa). The aim of this research is to study the reliability of wave height data from the satellite altimeter to support marine renewable energy development. This Significant wave height (Hs) is retrieved from multi mission satellite altimeter by Radar Altimeter Database System (RADS) and evaluated using in-situ measurement over the Malaysian seas (0ºN - 14ºN and 95ºE - 126ºE). A validation with selected buoys located at Sabah Sea (5.83 N, 114.39 E) and Sarawak Sea (5.15 N, 111.82 E) is performed by statistical approach and presenting good correlation of 0.92 and 0.18 for RMSE. A climatology assessment is performed by analyzing the condition of significant wave height during monsoons. This paper highlighted, collocation between altimeter and buoy are well-correlated and reliable to use for a marine analysis for renewable energy development.

1. Introduction

Satellite altimeter has known as one of the important techniques for marine oceanography studies. For over twenty years, altimeter has provided large scale of ocean information including wind speed, ocean current, sea surface height, tides, ocean depth and significant wave height [1]. Altimeter has brought a new way in marine study especially for ocean renewable energy assessment. Ocean wave can be categorize as part of the marine energy to provide huge energy for electric generation [2]. A conventional method as moored buoy give direct and continuous measurements, but this method is very sparse due to less mooring of buoy in vast areas and facing with missing data in the data measurements [3]. According to [4], buoy and observing ships facing limitation in providing a good spatial coverage and temporal resolution. Unlike with altimeter, the observations are accurate, reliable and provide temporal and spatial coverage [5].
Numerous study has evaluated the accuracy and reliability of satellite altimeter in providing good measurements by comparing them with ground-truth buoy. Previous study on the application of altimeter products is by [6], evaluated the comparison of wave height observations with in situ measurement at Indian Ocean Region shows an acceptable collocation and RMSE with value of 0.96 and 0.21m, respectively. From the study by [7], the launching of HY-2 altimeter in August 2011 by China, studying a comparison with National Data Buoy Center and NASA altimeter products (j1 and j2 missions) showing good validation results of RMSE with range from 0.23 m to 0.33m and concluded the accuracy of significant wave height measurements from HY-2 is favourable to the measurements from Jason-1 and Jason-2. While, the research by [8] for the collocation of Jason-1 mission observation versus the in-situ data in the Gulf of Mexico presenting correlation of 0.73 and RMS differences of 0.17-0.30 m. Altimetry data contributed more reliable measurements of significant wave height covered all seas in the world [9].

1.1. Significant Wave Height
According to NOAA’s National Weather Service (NWS), there are three basic of ocean wave characteristics including wave formation, wave dimension and significant wave height. Large numbers of merging waves that travelled from various places, directions and speeds comprised the ocean surfaces called as wave spectrum. Ocean consists with varies of wave generates from different places, height and sources called wave spectrum, and the average height of the highest 1/3 (one-third) wave spectrum defined as significant wave height (Hs). Significant wave height used in this study because it is the constant value of consecutive wave height in a wave record.

1.2. Satellite Altimeter
Theoretically, altimeter missions use nadir-pointing concepts to measure a precise time taken of emitted and returned altimetry signal. A signal from on board altimeter sensor is transmit towards the ocean surface. The interaction of signal between ocean surface will reflect back to the sensor and measure precisely. Figure 1 presents the graphical presentation of altimetry principle. As the signal returned back to the sensor, slope of the leading edge defined the significant wave height [10].

![Figure 1. Altimetry principle](image)

where, $R$ referred to slant range measured from angle, $\theta$ or called as antenna pointing angle. $\theta^\prime$ is the incidence angle and $A_f$ is the antenna footprint area [12]. Furthermore, several factors have been considered to diminish error for time travel calculation such as orbital error, hardware error (antenna phase center, time delay, clock drift, Doppler shift error), ionospheric error, tropospheric error and more [13].

1.3. Buoy
Buoy is an instrument utilized by the oceanographer to supply information for ocean study and weather forecast. Thus, most of the country has deployed a buoy network for meteorological and scientific study. For example, USA docked vast of buoy network covered the coast, Hawaii Islands and Gulf of Mexico [14]. Now, buoy is supported with multi-sensor that applicable to measure various of ocean parameter such as wave height, wind speed, ocean current, ocean temperature, meteorological
parameters, and salinity [15]. This revolution has improved the purpose of buoy for marine studies especially a real-time measurement. According to [3] explained the pros of the wave buoy including real-time observation, easy deployment and maintenance, and cost effective. But, it is defenceless to vessel like ships and debris and inaccurate in intense condition such as storm. Other than that, buoy also attached with Global Positioning System (GPS) for positioning purpose.

2. Methodology

2.1. Multi-mission Data

A 24 years data retrieved from multi mission altimeters starting from 1993 until 2016 with 0.25° x 0.25° resolution. Radar Altimeter Database System (RADS) is a database develop from the cooperation of Delft Institute for Earth-Oriented Space Research (DEOS) for Satellite Altimetry and the NOAA laboratory. RADS data always update and often used for ocean parameters assessment including generate their own altimetry products based on the user’s interest [13]. Auto processing were conduct to retrieve 24 years of 3 phases data namely daily, monthly and climatology. Table 1 shows the altimetry characteristics for selected missions used in data processing.

| Missions | Phase | Cycle numbers | Cycle (days) | Spacing at Equator (km) |
|----------|-------|---------------|--------------|------------------------|
| TOPEX    | A     | 112-364       | 10           | 315                    |
|          | B     | 369-481       |              |                        |
| POSEIDON | A     | 113-361       | 10           | 315                    |
| ERS-2    | A     | 004-169       | 35           | 80                     |
| JASON-1  | A     | 001-260       | 10           | 315                    |
|          | B     | 262-371       |              |                        |
| JASON-2  | A     | 000-131       | 10           | 315                    |
| CRYOSAT2 | A     | 001-4-025     | 30           | 250                    |
| ENVISAT1 | B     | 006-094       | 35           | 80                     |
|          | C     | 095-111       |              |                        |

2.2. Buoy Data

Two selected buoys provided by oil and gas company are used to measure the significant wave height. Significant wave height data from buoy used frequency domain with a full spectrum and hourly recorded. These significant wave height data from buoy will be act as a benchmark, the accuracy of the data source from the buoys are important and always been used to assess the significant wave measurements from other techniques [16]. Table 2 present the specifications of the buoy stations.

| Buoy        | Depths (m) | Latitude | Longitude | Data period          |
|-------------|------------|----------|-----------|----------------------|
| Sabah Buoy  | 1050       | 5.83 N   | 114.39 E  | November 2004-December 2007 |
| Sarawak buoy | 120        | 5.15 N   | 111.82 E  | January 2009-January 2012 |

2.3. Analysis

The collocation of in situ measurement such as buoy with satellite altimeter is the essential aspect for altimeter validation as these techniques provide different spatial and temporal resolution [1]. Inter comparison of both measurements is crucial to identify the relationship of observations from both methods [17]. This validation appointing in situ measurement as a benchmark, in which altimetry significant wave height are collocate with the buoys [18]. A monthly analysis of significant wave height data from both techniques were perform by generating time-series graph. Distribution of significant wave height data is analysed to assess the correlation and biased from the measurements.

According to [7] buoy technique supply point-based temporal observations for the ocean wave height while, satellite altimeter measurements are the spatial variation in a simultaneous time.
combination is important as a key performance for significant wave height assessment, at once proved the reliability of altimetry significant wave height. Based on the result, analysis of the measurements from the altimetry missions with respect to the moored-buoy, supplied an indicator variable for future analysis and the accuracy enhancement for the altimeter observations.

As a marine-tropical country, Malaysia has facing with monsoons throughout the years and there are categorised as Northeast monsoon (Nov-Feb), 1st-inter monsoon (Mar-Apr), Southwest monsoon (May-Aug) and second-inter (2nd) monsoon (Sep-Oct). The importance of monsoons assessment is to study the condition and effects of monsoon towards the significant wave height. This assessment will be explaining the long-term condition of significant wave height during each monsoon and different region including Malacca Straits, South China Sea, Sulu Sea and Celebes Sea.

3. Results and Discussion

3.1. Validation with buoy

A time series graph is produced to illustrate the collocation between the in-situ and altimetry mission. Mean bias is performed to analyse the estimation of altimetry significant wave height over the true value of buoy. Thus, this mean bias calculation is explained the measurements of observed value (satellite altimeter) whether under- or overestimate the true value (buoy).

\[
\text{Mean Bias} = \frac{1}{n} \sum_i (Hs(A) - Hs(B))
\]

where \( n \) is the number, \( Hs(B) \) is the buoy significant wave height; meanwhile, \( Hs(A) \) is the altimetry significant wave height. A monthly time series graph of buoy-satellite altimeter is produced for both locations. Figure 2 and Figure 3 showing the trend line of significant wave height measurements from both methods.

![Figure 2](image)

*Figure 2. Trend graph of buoy-altimetry for buoy station located at Sabah Sea.*

From Figure 2 the trend line of monthly measurements from buoy and altimeter shows a simultaneous trend at most of the time. But there is a data gap occur in June 2005 from the buoy measurements because of the systematic error from the buoy itself. In Oct 2005, Apr 2006, Sept-Oct 2006, May 2007 and Aug 2007, the figure shows the measurements of significant wave height from the altimetry missions are lower compare with the in-situ. But, the altimetry significant wave height presenting a same trend line as well as the measurements from the buoy with small value of mean bias -0.096 m.
Figure 3. Trend graph buoy-altimetry for buoy stations located at Sarawak Sea

Time series graph of buoy-satellite altimeter for point located as Sarawak Sea is showing in Figure 3. Data gaps from the buoy measurements that were occur in Aug 2001, Jan 2006 and Jul-Oct 2006. The same reason is applied for this situation where there is an instrumentation error happen in buoy located at Sarawak Sea for the respective months. For the mean bias calculation is 0.006 m. From the results, showing mean bias for the Sarawak buoy is smaller compare with the Sabah buoy. Bias is occurring may be due to error in measuring device resulting in systematically error. But previous study showing that the collocation of data between satellite altimeter and ground-truth buoy has a good relationship. Further analysis of correlation and RMSE calculation is performed and presented in a scatter plot graph.

\[
RMSE = \sqrt{\frac{1}{n} \sum (Hs(A) - Hs(B))^2}
\]

(2)

Figure 4(a) and (b) presented the correlation graph including the RMSE value, correlation coefficient and linear regression equation between the buoy and multi-mission satellite altimeter for buoy at Sabah and Sarawak Sea. According to the both graphs in Figure 4(a) and (b), a positive linear regression has appeared for both measurements of satellite altimeter and buoys. The value of correlation for both measurements showing a positive value where both techniques has strong relationship of significance wave height. The equation of linear regression is \( y = mx+c \), where the y-intercept defined as \( c \).

(a) Figure 4. Linear regression, correlation coefficient and the RMSE value for collocation of buoy vs satellite altimeter at Sabah buoy (a) and Sarawak buoy (b)
The graphs present a favourable correlation between the measurements of satellite altimeter and buoy. The RMSE value is referring the accuracy of the altimetry with 0.18 m. Previous study by [20] showing the assessment of SARAI/Altika and Jason-2 satellites with moored-buoy have RMSE value of 0.20 m and 0.24 m, respectively.

3.2. Satellite track
Multi-mission altimetry is used to assess the accuracy of the altimetry significance wave height at each buoy stations at a certain time. For altimetry tracking, single mission of satellite is used in order to evaluate the satellite tracks over the selected buoys. This further assessment is crucial in order to assess the spatial resolution by indicating the closest distance of satellite tracks with the buoy. Table 3 showing the closest distance track between the satellite altimeter at the buoys. The closest distance of satellite altimeter with the buoy station is CRYOSAT2 with 3.17 km and 0.55 km, respectively. This is because a Ku-band altimetry CRYOSAT2 has a very dense spatial sampling pattern compare with other missions with only 7.5 km across-track distance at the equator [19].

| Satellite | Phase | Distance near to Sabah buoy (km) | Distance near to Sarawak buoy (km) |
|-----------|-------|-------------------------------|-------------------------------|
| CRYOSAT2  | A     | 3.17                          | 0.55                          |
| JASON-1   | A     | 99.46                         | 101.96                        |
|           | B     | 38.78                         | 12.75                         |
| JASON-2   | A     | 99.31                         | 102.03                        |
| ENVISAT1  | B     | 15.55                         | 0.57                          |
|           | C     | 16.67                         | 26.13                         |
| POSEIDON  | A     | 99.43                         | 101.76                        |
| TOPEX     | A     | 99.9                          | 102.04                        |
|           | B     | 38.96                         | 13.06                         |

The combination of multi-mission altimetry showing a good significance for us to examine dynamics of the sea characteristics and useful to provide point measurements of significance wave height along their ground tracks and good spatial resolution. The increasing number of altimetry mission can help to improve the along track resolution over the study area with the availability of more cycle. Figure 5 presenting the satellite tracking over the Malaysian seas and buoy stations from the satellite as mention in Table 3.

![Figure 5](image_url)  
**Figure 5.** Along-track of altimetry missions from the combination of Cryosat2 (Light Grey), Topex (Green), Jason-1(Blue), Jason-2 (Pink) and Envisat (Blue)

3.3. Climatology analysis due to seasonal effect
Four different seasons were discussed to assess the condition of significant wave height over Malaysian seas during the monsoons. Henceforth, to choose a suitable location in Malaysian offshores/near offshores by locating particular areas that received large scale of wave height. Among these four monsoons, Northeast monsoon received high average of wind speed up to 5.7 m/s followed
by Southwest monsoon, 4.5 m/s [21]. A wave form caused by wind is called as a wind wave that generated by the transfer of wind energy into water and produced smooth undulation of swell waves.

3.3.1. Northeast monsoon
Northeast monsoon brought a rainy season at most of the places in Malaysia and occur from November until end of the February. Wind from South China Sea with the combination of cold air outbreaks from Siberia region has blown towards Malaysia region and produce 10 to 30 knots of winds. Figure 6 is presenting the climatology of significant wave height during the Northeast monsoon where the condition of significant wave height of east coast at the Peninsular Malaysia is 1.4 m and 0.5 m at the west coast area along the Malacca Straits. Contrast to the coastline areas of Sabah and Sarawak facing the South China Sea, the range of the significant wave height values is 1 m up to 1.5 m. During this monsoon, this figure presenting South China Sea with greater wave height compare with the other seas. South China Sea recorded 1.5 m up to 2.7 m of significant wave height and followed by Sulu Sea located at the east coast of Sabah with value of significant wave height up to 1.3 m. Among all the Malaysian seas, Malacca Straits possessed with less significant wave height with value less than 1 m; meanwhile, at Celebes Sea the condition of significant wave height can achieve up to 1 m.

![Figure 6](image)

**Figure 6.** Significant wave height climatology for Northeast monsoon from 1993 to 2016 (Nov-Feb)

3.3.2. Southwest monsoon
Southwest monsoon is happened in the early of May until end of the August. In Malaysia, Southwest monsoon brought a drier season throughout the months and facing with minimum scale of rainfall except east of Sabah. The location of Malaysia at the equatorial line possessed a stable atmospheric conditions which the winds are flown in southwest direction with minimum speed less than 15 knots slower than Northeast monsoon. Figure 7 is showing the measurements of altimetry significant wave height climatology during the Southwest monsoon.

![Figure 7](image)

**Figure 7.** Significant wave height climatology for Southwest monsoon from 1993 to 2016 (May-Aug)
According to Figure 7, Southwest monsoon has less significant wave height compared with Northeast monsoon. All Malaysian seas including Malacca Straits, Celebes Sea and Sulu Sea has an average of 0.6 m except for South China Sea with values between 0.6 m to 1.2 m. Both Northeast and Southwest monsoons, has less significant wave height in Malacca Straits region in reason the Malacca Straits region is ringed by Sumatra Island and block the movement of winds from the southwest direction [21]. From previous study [21] has concluded Malacca Straits has possessed a slow wind movement with 2.4 m/s compare with the other sea regions. It has to believe that low wind speed will affecting the dispersion of wave to form a great swell wave.

3.3.3. Transition monsoons

Transition monsoon or known as inter-monsoon has occurred twice a year during March to April called as First-inter monsoon and September to October as Second-inter monsoon. The movement of winds from both northeast and southwest regions are very slow and happened in a few months in which the wind movements were fluctuate and became slow [22]. Figure 8(a) and Figure 8(b) represents the significant wave height condition over the Malaysian seas during the transition monsoons happened.

![Figure 8. Significant wave height climatology for First-inter monsoon from 1993 to 2016 (Mar-April); (a) First-transition and (b) Second-transition.](image)

Because of the fluctuation of wind movements during this monsoon, a slow wind speed has occurred with speed less than 3.0 m/s [21] and led less significant of wave height in every region of Malaysian seas and affect most of the wave height condition. Figure 8(a) presents South China Sea experienced a moderate significant wave height with range from 1 m up to 1.5 m while Malacca Straits, Sulu Sea and Celebes Sea facing with less values range from 0.5 m to 1 m. While, in Figure 8(b) presenting the climatology map of significant wave height over the Malaysian seas during the Second-inter monsoon. Compare with the first transition, Second-inter monsoon showing the lesser significant wave height condition for all parts of Malaysian seas. The transition monsoons have experienced small scale of significant wave height compare with the Southwest monsoon and Northeast monsoon as shown in Figure 9.

![Figure 9. Monthly climatology of significant wave height for each sea regions over 24 years.](image)
A variation of significant wave height over the Malaysian seas in different spatial and time have brought a great deal in studying the condition of significant wave height. Overall, the Malaysian seas facing with high significant wave height during the Northeast monsoon with the highest at South China Sea with value up to 3 m. The location of Malaysia at the equatorial region generally known as doldrums commonly a low-pressure area with a low wind speed and a small scale of wave height compare to the ocean region in the north and south hemisphere.

4. Conclusion
As a conclusion, the altimetry significant wave height measurements over the Malaysian seas is analysed. The 24 years of data has proven the reliability of altimeter measurements to provide good wave information. Collocation of significant wave height between altimeter technique and buoy has shown good relationship by assessing through the statistical analysis. For buoy station at Sabah Sea, the correlation value is 0.9237 and the RMSE value is 0.18 m; meanwhile, for buoy station at Sarawak Sea has value of 0.9274 for correlation and 0.18 m for RMSE. A positive value of correlation from different measurements defined both data of altimeter and buoy were well-correlated. The significance of this statistical analysis is to evaluate the accuracy and precision of the altimetry significant wave height. As a result, the observations of significant wave height from the altimeter sensors were reliable to use for study and research approached.

The climatology of significant wave height over the Malaysian seas is analysed with significance to study the condition and variability of significant wave height in particular place and time. Four different parts of Malaysian sea as mentioned in section 3 are selected and examined. The results have shown South China Sea possessed more significant wave height compare to the other parts of Malaysian seas including Sulu Sea, Celebes Sea and Malacca Straits. Northeast monsoon experienced more significant wave height compare to the other monsoons and provide a maximum significant wave height to coastal areas facing the South China Sea including the east coast of Peninsular Malaysia and north coast of Sabah and Sarawak. In a meantime, this study proposed these coasts are suitable for the ocean wave renewable energy development, in recommendations a study for the marine energy resources must be conducted.

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