

# Wave Height Climatology Assessment from Multi-mission Satellite Altimeter for Renewable Energy



**Marith Banati Barata, Ami Hassan Md Din  
and Abdullah Hisham Omar**

**Abstract** The fact that we will lose the source of fossil fuel in the future is undeniable. Hence, it is crucial to find the replacement of this resource. In present day, wave energy is found to be one of the sources of renewable energy. This chapter is proposing to assess the wave height climatology over the Malaysian seas in order to support renewable energy. The key step in the assessment of wave height climatology over Malaysian seas, South China Sea, Malacca Straits, Sulu Sea and Celebes Sea, is by acquiring an accurate and reliable wave height data. The Radar Altimeter Database System (RADS) was used to extract the 24 years of significant wave height data from January 1993 to December 2016. Altimetry-derived wave height data were validated with ground truth observation from wave buoy and Acoustic Doppler Current Profiler (ADCP). The wave height magnitude and pattern were then analysed particularly to see its characteristic during monsoon season. The monthly average of altimetry significant wave height from January 1993 to December 2016 was mapped in this study. The findings clearly show that the Northeast monsoon has the most significant effect of wave height variation over Malaysian seas, while the Southwest monsoon has minimal effect. The reliability of satellite altimetry also proved based on the RMSE and correlation results, which are 0.2515 m and 0.9396, respectively. This study offers useful wave height information especially related to renewable energy in the Malaysian seas for future studies.

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M. B. Barata · A. H. M. Din (✉) · A. H. Omar  
Geomatic Innovation Research Group (GIG), Faculty of Geoinformation  
and Real Estate, Geoscience and Digital Earth Centre (INSTEG),  
Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia  
e-mail: amihassan@utm.my

M. B. Barata  
e-mail: marithbanati@yahoo.com

A. H. Omar  
e-mail: abduallahhisham@utm.my

A. H. M. Din  
Institute of Oceanography and Environment (INOS), Universiti Malaysia  
Terengganu, Kuala Terengganu, Terengganu, Malaysia

**Keywords** Wave height · Climatology data · Renewable energy  
Monsoon season · Radar altimeter database system

## 1 Introduction

Fossil energy is being attributed as one of the main sources of global warming event. This further supports the need for replacement of this source. Various wave, tidal and current energy converters have been invented to explore the big potential of marine power, especially wave energy. Other than the only well-known water grounded source is hydroelectric dams, waves from the ocean also have the same potential to be a widely utilisable. Wave energy has a number of significant benefits including predictable source, profusion, massive load aspect and low eco-friendly effect and accessibility compared to other renewable energy sources [1].

Assessments have been done in verifying the potential of wave height as a source of renewable energy in various regions [2]. Previously, a study regarding wave energy and wave height in Malaysian Seas was conducted by Aziz [3]. The difference of wave heights within the monsoon seasons enables this environmental phenomenon to make an impact on the wave energy produced. The ocean wave rose up by gaining energy transformed from sun and wind. The wind that created by solar energy blows in the middle of the sea, which then transferred the energy to the ocean surface in order to convert winds energy to wave energy [4]. After the energy is transformed, it can mobilise thousand miles with low energy loss. Basically, the wave energy produced by the waves relies on the wind energy received.

The aim of this study is to produce the map of wave height climatology over the Malaysian seas in order to support renewable energy. Therefore, wave data plays the most important role in wave energy assessment. Acquiring the reliable and accurate wave height climatology is one of the essential phases in the evaluation of wave height. The wave height data from satellite altimeter needs to be verified by in situ measurements using offshore buoy in order to evaluate the quality of altimetry-derived wave height. There are limitations in the verification process since the measurements from a buoy are point-based while the satellite data produces measurements in a form of sets of gridded data with interpolation. A research was done by Shanas et al. [5] as resulted that the altimeter measurements represent a good data source to enhance our understanding of the variability even near the coast [5]. Satellite altimeter also has a wide coverage of data which makes the data more reliable for the climatology purposes. In this study, the satellite altimetry data are verified using two in situ measuring instruments which are offshore buoy and Acoustic Doppler Current Profiler (ADCP).

The 24 years of wave height data used in mapping the climatology of wave height over Malaysian seas from January 1993 to December 2016. The wave height data are mainly taken from satellite altimetry that has been known as a reliable data source over the years [6]. Studies from Abdullah et al. [7] and Aziz et al. [8] proved that the satellite altimetry is a reliable device to collect the wave height data and it

only has a few centimetres discrepancy in terms of accuracy. Satellite altimeter works by emitting a small pulse of microwave radiation with identified strength towards the sea surface. Then, the interaction of sea surface and the emitted pulse will be reflected back to the satellite altimeter. From the interaction, the travel time is measured precisely. In determining the wave height, several corrections like the behaviour of the radar pulse through the atmosphere, sea state bias and other geophysical signals have to be done [9].

### 1.1 Principle of Satellite Altimeter

Theoretically, satellite altimeter is a nadir-pointing instrument that measured the time travel of transmitted microwave radiation to be reflected back to the satellite. From the computed round trip radar pulse time, the wave height is obtained. 1700 pulses per second emitted in the interaction between ocean wave height and the reflected back satellite signal [10]. The range  $R$  from the satellite to ocean wave surface is predicted from the round trip travel time of

$$R = R^{\wedge} - \sum \Delta R_J \quad (1)$$

$R^{\wedge} = ct/2$  is the range calculated by ignoring the refraction based on speed of light  $c$  and  $\Delta R_J$ ,  $J = 1, \dots, N$  is the correction for the numerous biases between mean reference wave height and mean electromagnetic scattering surface. It also applies the correction for the numerous components of the atmosphere. The predicted range of orbit height and the wave height which are relative to the centre of the Earth varies along the satellites orbit from along-track dissimilarity. The height  $h$  of the targeted ocean wave which is relative to reference ellipsoid (Earth fit earth centre) is the result of the range measurements as follows:

$$R = H - R^{\wedge} = H - R^{\wedge} + \sum \Delta R_J \quad (2)$$

The radar target to the wave height is given by (2) that relative to the reference ellipsoid is affected by the uneven surface of the geoid, variation of wave height (types of tides) and atmospheric pressure loading response by the sea surface. The pulses are transmitted as footprints that were described as beam-limited footprint. It will specify the target surface area of wave height within the transmitted footprint. The design of the beam-limited altimeter limitation can be overcome by transmitting a very short pulse with duration of a few nanoseconds using a small antenna [11]. Figure 1 illustrates the schematic diagram of satellite altimeter system and its principle.

Practically, the situation is far more complicated. Several factors have to be taken into consideration in order to reduce the errors in getting the travel time such as the orbital error and hardware problem like electronic time delay, clock drift,

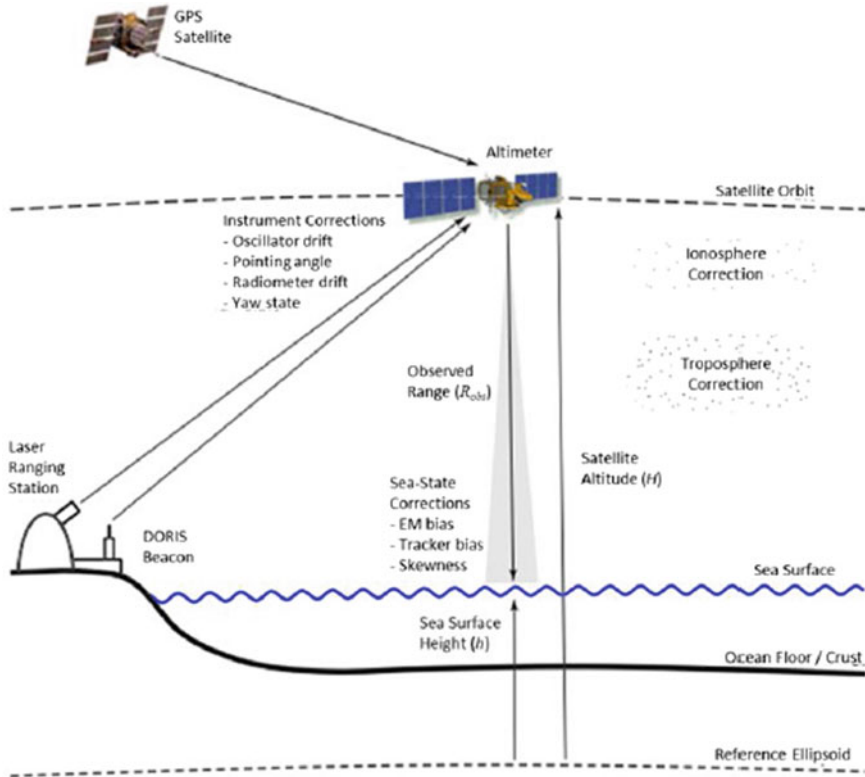


Fig. 1 Schematic view of satellite altimeter measurement [12]

offset antenna phase centre, centre of gravity, time lagging of observations, doppler shift error and more [8].

## 2 Research Approach

### 2.1 Area of Study

This study covers the Malaysian seas which includes South China Sea, Malacca straits, Sulu Sea and Celebes Sea (see Fig. 2). The South China Sea indicates the great possibility of producing high wave energy. This is because the location exposes to the Northeast monsoon from November until February for each year. The monsoon season will let winds to transfer the high energy to the ocean wave. Consequently, the wave height will increase rapidly.



Fig. 2 Study area of wave height distribution in Malaysian seas

## 2.2 Altimetry Data

Nowadays, altimetry data are distributed through many agencies like NOAA, AVISO, EUMETSAT and PODAAC. Besides, the Delft Institute for Earth-Oriented Space Research (DEOS) for Satellite Altimetry and the NOAA laboratory cooperate in the development of Radar Altimeter Database System (RADS). The RADS is well-known as a harmonised, certified and cross-calibrated sea-level database from all satellite altimeter missions [8]. In RADS, the latest corrected range and geophysical state of the ocean wave are able to access by the users [1]. They can also produce their own altimetry products based on their particular interests [9]. The altimetry data (RADS) products were verified and validated by DEOS. Besides, RADS database also consistently updates and makes corrections to their system, verify accuracy format and reference system parameters. This system also provides the need of scientists and operational users to have ready value-added sea-level data [1]. Presently, RADS allows users to extract the data from some present and past satellite altimeter missions. In this study, the satellite altimetry data used are data from January 1993 to December 2016. This study employs the gridded data from nine satellite altimeters, which are TOPEX, ENVISAT, ERS-1, ERS-2, JASON-1, JASON-2, JASON-3, SARAL and CRYOSAT. The monthly average wave height data set was used in the mapping process.

## 2.3 In Situ Data

Buoy and ADCP were used in this study for the validation process of satellite altimetry data. Acoustic Doppler technology is flexible in the measurement of sea

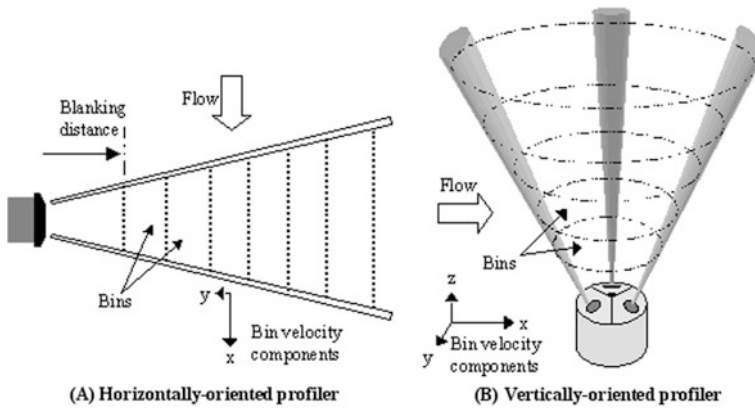


Fig. 3 The ADCP physical profile orientation [14]

conditions. However, this technology can be limited and it is less effective at measuring the small-scale kinematic fluctuations caused by waves and turbulence. The ADCP is equipped with acoustic transducers which ping at a minimal frequency rate of 2 Hz [13] (see Fig. 3). It is noted that the ADCP measures wave height through sounds energy of which may be absorbed by the water each time it pings. Therefore, the data collected may not be very accurate. The acoustic transducer will be tilted  $20^\circ$  away from its vertical in order to measure the wave height pattern. The Doppler Shift in the returned signal estimated in order to compute the velocity of the beams. From the calculated returned signal, the wave height estimation is attained.

The ADCP data was provided by the Institute of Oceanography and Environment (INOS), Universiti Malaysia Terengganu, which includes monthly data from 2012 to 2016, but there were gaps in the data for several months.

The buoy is equipped with accelerometers to measure vertical heaves, or up and down movements to measure wave heights and swell period. The accelerometer will then calculate the data and interpret it in the form of wave height at the point where it is obtained. Figure 4 shows the schematic buoy mooring set up at 37 m depth of water level.

The buoy data were provided by oil and gas company who positioned the buoys at Sabah and Sarawak. The 24 years worth of wave height data from Malaysian seas that was retrieved from RADS is compared with offshore buoy and ADCP for the validation purposes. This is to evaluate the satellite data with the in situ measurement.

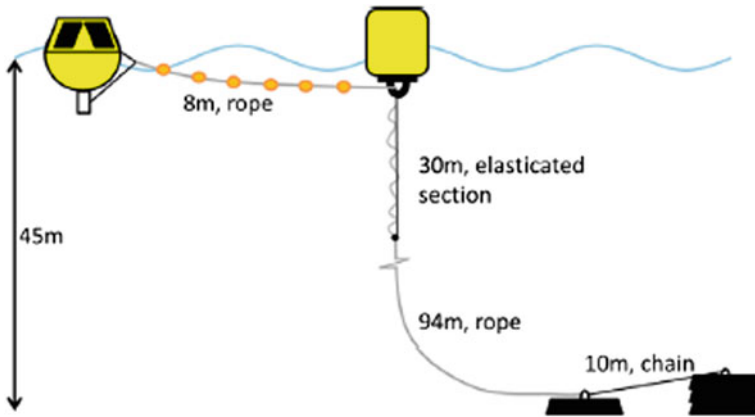


Fig. 4 A schematic of the buoy tie up setup during the installation in 37 m water depth, not to scale [15]

### 3 Result and Discussion

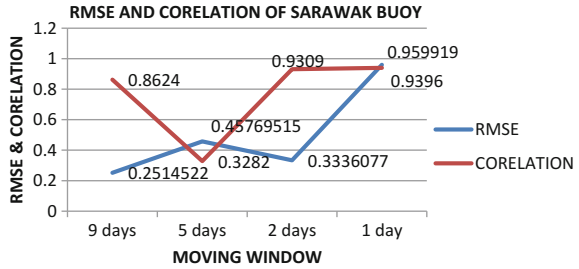
#### 3.1 Data Verification: Altimetry-Derived Wave Height Versus Ground Truth-Derived Wave Height

There are two points of offshore buoy which consist of wave height data set located in Sabah and Sarawak. The other point of ground truth observation is ADCP in Terengganu. All these points were used as a benchmark in validating the satellite altimetry data. The points are located in Sabah waters at 5.83 latitude and 114.39 longitude and in Sarawak waters at 5.15 latitude and 111.82 longitude. The ADCP is located at 05.44 latitude and 103.16 E longitude (Refer Fig. 1).

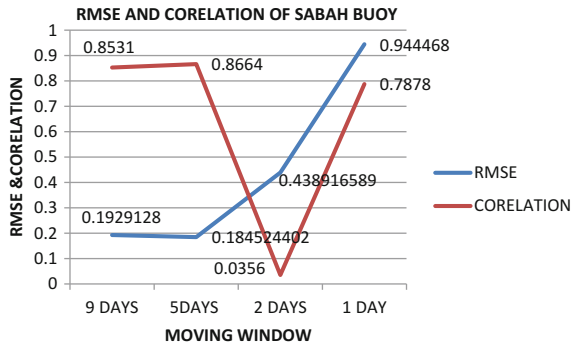
In this validation process, it was evaluated with four types of moving windows which are 9, 5, 2 and 1 days. The altimeter data was gridded in  $0.25^\circ \times 0.25^\circ$  for spatial resolution. The verification process used the monthly data from January 1993 until December 2016. The root mean square error (RMSE) and correlation of the ground truth and altimetry observations are evaluated.

Based on the results, the RMSE and the correlation coefficients for all three verification points can be calculated. All three verification points show the different results for the best moving windows average. The Sarawak buoy data that were used in this verification was from October 1995 until January 2012. Based on Fig. 5, the smallest of RMSE for Sarawak buoy is by applying 9 days moving windows with 0.25145 m. However, it shows the opposite results for the best correlation coefficient analysis with 1 day moving windows giving the best results with 0.95992. In Sabah area, 5 days moving windows showed the best results for RMSE and correlation with 0.1845 m and 0.8664, respectively (see Fig. 6). The duration of buoy data in Sabah was from November 2004 until December 2007.

**Fig. 5** The RMSE (m) and correlation results for Sarawak buoy



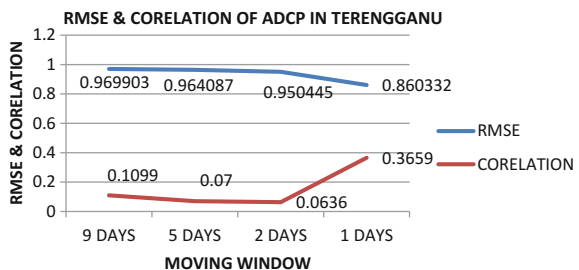
**Fig. 6** The RMSE (m) and correlation results for Sabah buoy



Next, Fig. 7 showed the result of reliability of ADCP in Terengganu with the 1 day moving windows as the best result for RMSE and 5 days for correlation. The RMSE value is 0.860332 m and the correlation is 0.3659. The ADCP data duration is from June 2012 until June 2016. This shows that ADCP has the latest result compared to the buoys but ADCP only provides data for several months in each year.

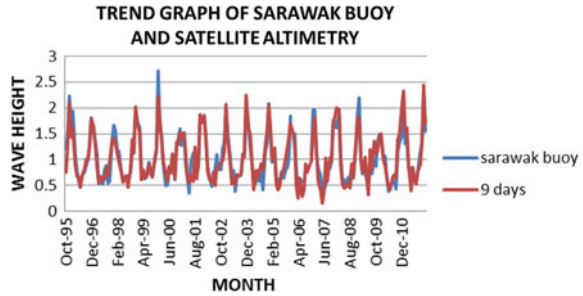
In producing climatology maps, the best moving window has to be chosen. Therefore, the readings from the Sarawak offshore, 9 days moving window was chosen to produce the wave height climatology maps. This is because the in situ data is the longest among the three points which is more reliable in this validation process. The agreement of the in situ measurement can be seen through the trends graph. The altimeter data was obtained from  $0.25^\circ \times 0.25^\circ$  grids.

**Fig. 7** The RMSE (m) and correlation results for ADCP in Terengganu





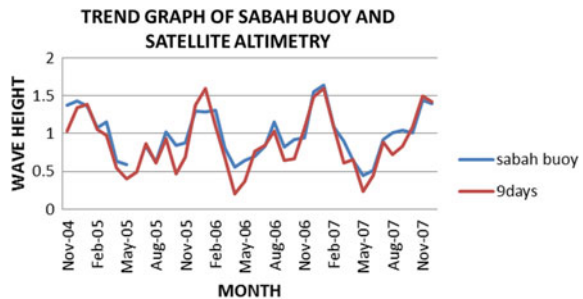
**Fig. 8** The trend graph of Sarawak buoys and satellite altimeter based on 9 days moving windows

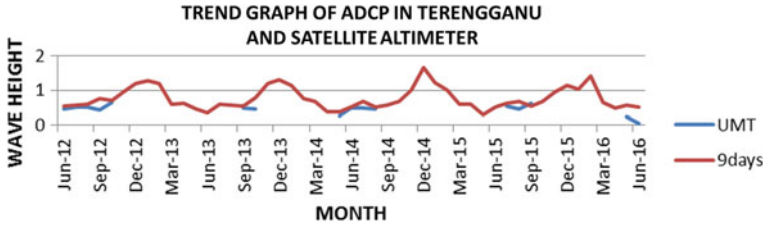


Based on Fig. 8, the wave height data from altimetry and buoy showed a similar trend and pattern. This result gave a good indicator of the reliability and validity of altimetry-derived wave height data. The differences of wave height between these two instruments were around less than 0.5 m. However, there are a few months in 1997, 2001, 2003, 2004 and 2010 showing the agreement of satellite altimeter and buoy quite loose, where the buoy data did not follow the pattern of satellite data. The satellite data in that particular year were taken from Topex, ERS-2 and Envisat. As informed, these satellites have already been improved in its accuracy like the Topex is a dual frequency satellite that is used to remove the path delay being caused by the ionospheric-free electron and also equipped with experimental sensor. Envisat also equipped with multiple sensors and developed an environmental satellite for the mapping of earth change. So, the accuracy of satellite was not doubted. The disagreement on these several months can be related to the hardware problem of the buoy. It can be seen that the unfollow pattern of buoy happened in the low wave height where we can justify that the buoy did not cope with low depth measurement.

On the other hand, as shown in Fig. 9 Sabah’s buoy did not achieve the pattern like the one in Sarawak but the ascending and the descending trends show the reading is still following the pattern. The satellite track is affecting the trends since the benchmarking data from satellite is an interpolation point. It is different with buoy because the buoy is a point-based measurement which will give a better reading at its point. At some point, there are slight differences in the pattern of Sabah buoy trend. In February 2005, February 2006 and August 2007, the wave

**Fig. 9** The trend graphs of Sabah buoy and satellite altimeter based on the 9 days moving window





**Fig. 10** The trend graph of ADCP in Terengganu and satellite altimeter based on the 9 days moving window

height pattern from the buoy was slightly different from the pattern of satellite altimetry. In this duration, the satellites that provide the wave height data are from Topex and Jason-1. Jason-1 is similar to Topex that emits dual frequency to the target wave which gets the orbit determination from GPS.

Next, the trend of ADCP with altimetry at Terengganu area was as shown in Fig. 10. There is a major gap between months for each year. It can justify that the data gap affecting the reliability of RMSE and correlations result in the verification process. The ADCP physical operations usually will innate single-ping measurement uncertainty of  $0.30 \text{ ms}^{-1}$ . This reduces to about  $0.025 \text{ ms}^{-1}$  uncertainty in the 5-min ( $N > 100$ ) of the whole profile approximates. The Doppler Shift also happened since the ping travels in the water. The average of these uncertainties is further calculated during the 1000-km integration [16]. By comparing the location of ADCP and the buoys, it can clearly be seen that the ADCP is deployed in the nearshore area. This location has many disturbances like the high volume of bubble in nearshore area may cause the turbulence that will affect the accuracy of ADCP.

### 3.2 Mapping of Wave Height Climatology from 1993 to 2016 Over Malaysian Seas

The climatology of wave height over Malaysian seas from 1993 to 2016 was shown in Fig. 11. In general, the wave height climatology shows a constant result in all areas for the past 24 years over Malaysian seas. In the nearshore area, the climatology shows a stable calm wave where the height only between 0 and 1 m are shown in the blue colour. The yellow colour on the map indicates a high value of the wave height average in the middle South China seas which reached about 1.7 m. The monsoon seasons are affecting the wave heights in South China Seas since this area is quite open to the wind currents. So, the winds of the monsoon seasons are affecting the wave heights average in that particular area.

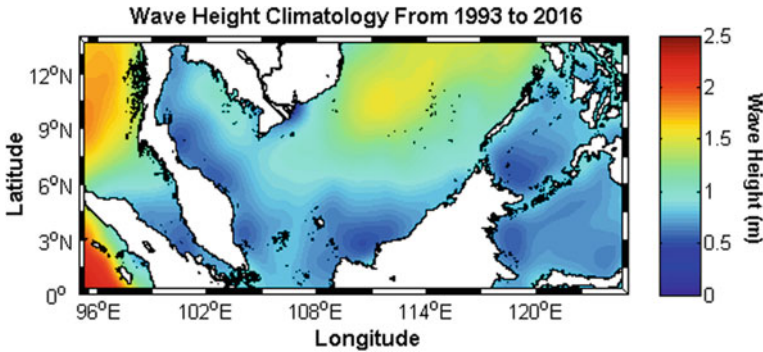


Fig. 11 The wave height climatology over Malaysian seas from 1993 to 2016

### 3.3 Time Series of Wave Height Over Malaysian Seas

Basically, these four seas are having three different tidal events, where Sulu Sea and Celebes Sea are facing mixed tides, South China Sea are having semi-diurnal tides and Malacca strait is having diurnal tides event. These events are affecting the wave height data in that particular area. As seen in the Fig. 12, in Malacca strait, there was actually a quite high wave height documented in 1996 and it became lower in the other three years but increased back in 2000. In the South China Sea, the same event also happened in 1996 but the wave height lowered after that and it has not been stable since that (see Fig. 13). The wave height has not been stable until 2002 and the same event happens again from 2009 until 2016. The variety of wave height data can also be seen in Fig. 14, where the Sulu Sea had the most drastic changes of waves compared to the other seas. Based on Fig. 2, the Sulu and Celebes seas are in a closed area, and both have had mixed tides but the pattern of wave heights time series are quite different. In Celebes Sea (see Fig. 15), the drastic changes of wave heights only happened in 2001 and 2007.

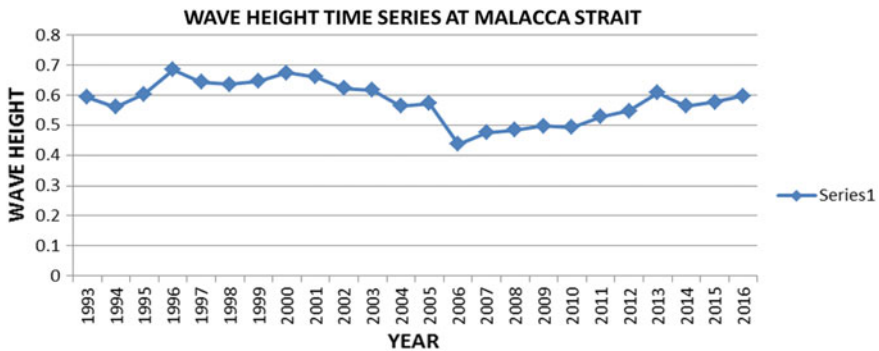


Fig. 12 Time series of monthly wave height for the Malacca Straits from 1993 to 2016

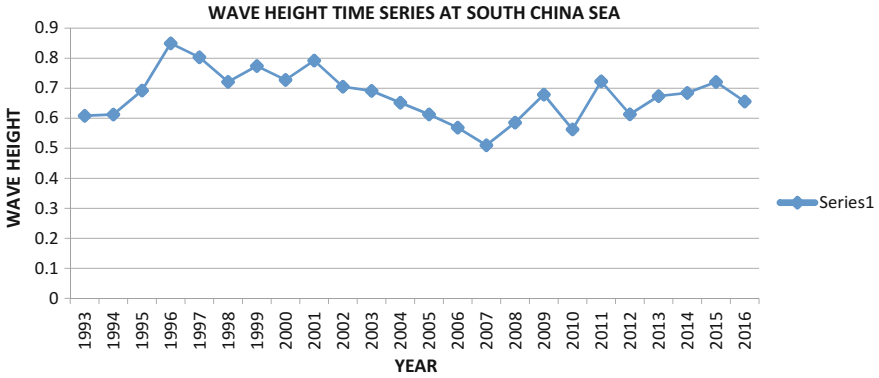


Fig. 13 Time series of monthly wave height for South China Sea from 1993 to 2016

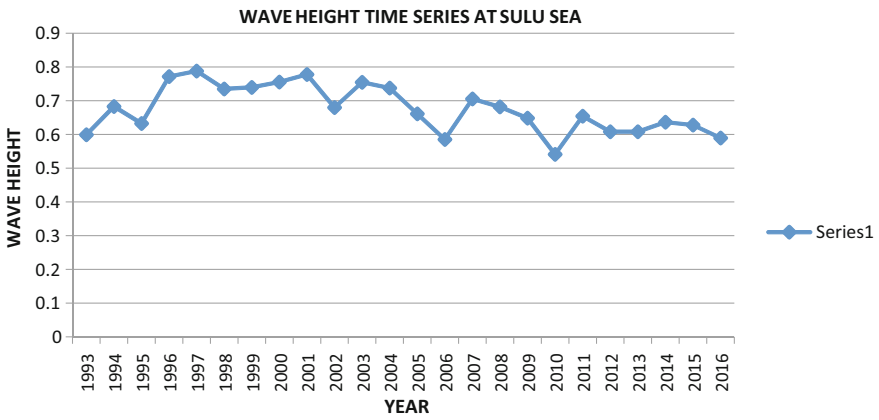


Fig. 14 Time series of monthly wave height for the Sulu Sea from 1993 to 2016

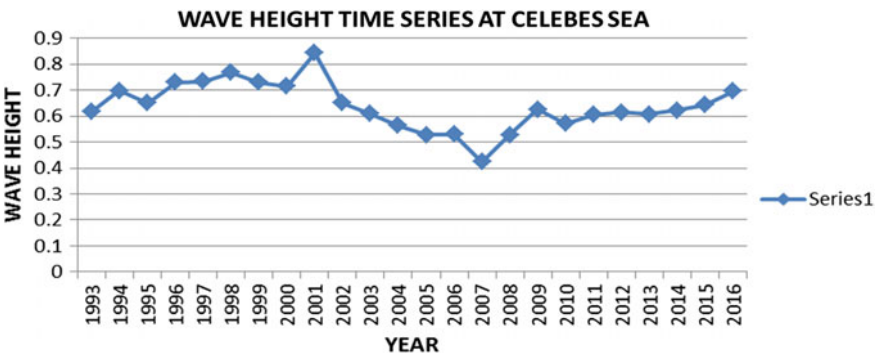


Fig. 15 Time series of monthly wave height for the Celebes Sea from 1993 to 2016

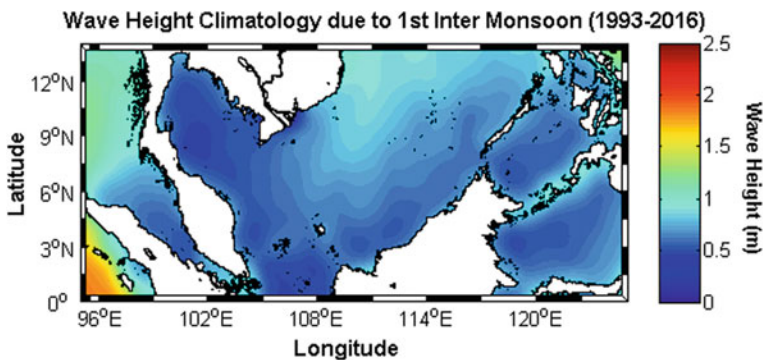
### 3.4 Wave Height Pattern Due to Seasonal Effects

Every year, Malaysian seas will experience four types of monsoon seasons, which will affect the wave height pattern. The monsoon seasons are as follows:

- First Inter-monsoon Season (March–April)
- Southwest Monsoon Season (May–August)
- Second Inter-monsoon Season (September–October)
- Northeast Monsoon Season (November–February)

**First Inter-Monsoon.** First inter-monsoon is a season that marks the transition between Northeast monsoon and Southwest monsoon. During inter-monsoon season, usually the wave height and wind are very mild, the wind direction is also flexible and the patterns tend to be in a disordered manner [17]. During this season also, the wind tension induces persistent coastal upwelling. Based on Fig. 16, it is noticeable that the wave height during first inter-monsoon is not more than 1 m, except on certain isolated areas such as in Sarawak shores and around Terengganu shores that have a reading of wave height around 1 m. Other than that all of the areas of Malaysian seas show a very calm of the wave climate.

**Southwest Monsoon.** During the Southwest monsoon, strong wind will travel from Indian Ocean and it will hit the west coast of Peninsular Malaysia. However, this case has never happened because of Sumatra Island (Indonesia) that has blocked the path of the strong wind. As the result in Fig. 17, the wave height around Malacca straits during this period does not rise as it happens in East coast of peninsular Malaysia. The wave climate in Malacca straits during this period is still a little bit higher than during the first inter-monsoon season. Some part of the South China Sea rises during the Southwest monsoon but, in the Celebes Sea and the Sulu Sea, the wave heights have lowered a little bit than during the first inter-monsoon. Wave height around the North or entrance of Straits of Malacca has been recorded to be at 1.5 m. This shows that it does not have a good protection from the Southwest monsoon compared to the other areas of Straits of Malacca at the south [12].



**Fig. 16** The average of significant wave height first inter-monsoon season over Malaysian seas

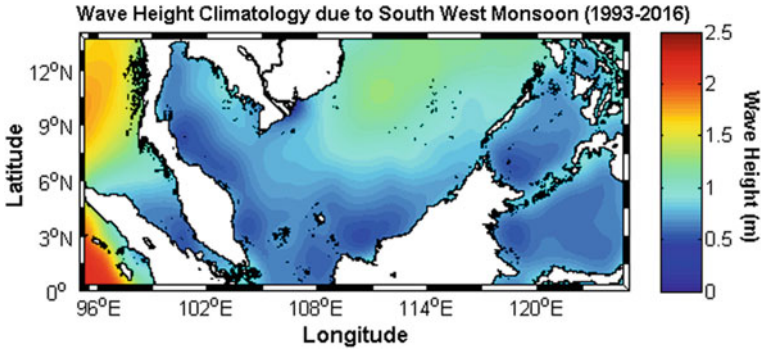


Fig. 17 The average of significant wave height Southwest monsoon season over Malaysian seas

**Second Inter-Monsoon.** Second inter-monsoon is the transition period of Southwest monsoon and Northeast monsoon. Figure 18 shows the Second inter-monsoon phase in Malaysian seas. During this season, the wave height is not as calm as the first inter-monsoon season. It can be seen in the middle of South China Sea, where the wave rose to be as high as 1.5 m. Only a few spots are below 1 m while the other areas of the seas are facing an increase of the wave height. The high wave starts to travel from Philippine towards East Coast, Sarawak and Sabah. It shows that the Northeast monsoon is on its way to Malaysia especially on the East Coast of Peninsular Malaysia.

**Northeast Monsoon.** November is the starting point for Northeast monsoon. However, sheltered area like Malacca straits remains calm during this time. The average of wave height for most of the Malacca straits areas is below 0.8 m. During this period of time, wave height in Malaysian seas starts to rise rapidly, especially in the open seas. Figure 19 shows that in East Coast of peninsular Malaysia, Sarawak shores and Sabah shores have the average wave height of above 1 m. On average, the wave height in the offshore areas is around 1.8 m and can be up to 2.5 m.

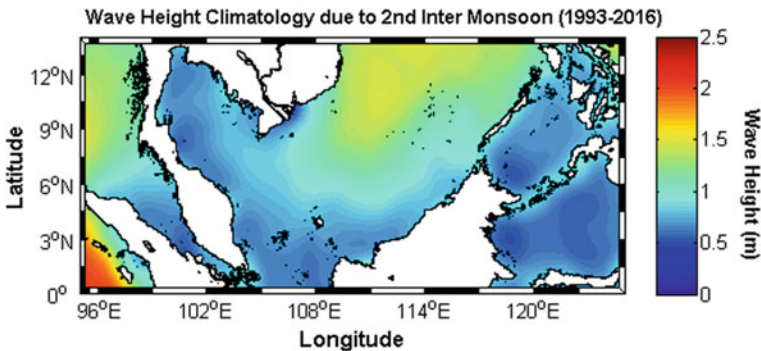
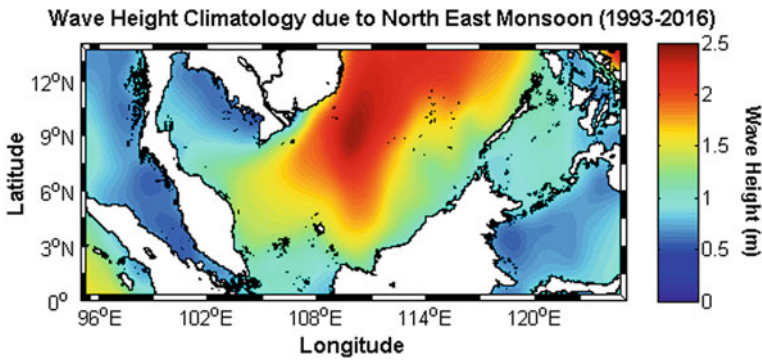


Fig. 18 The average of significant wave height second Inter-monsoon season over Malaysian seas



**Fig. 19** The average of significant wave height Northeast monsoon season over Malaysian seas

From the result, it is clearly seen that there are several places that can be taken into consideration in implementing the renewable energy, which are in the areas of Terengganu shores and Sabah shores because both regions have a consistent measurement of wave height. The regions are facing a firm wave height for every year which is 1 m and above. Based on previous researches, the stronger the wind speed will produce the stronger the wave height.

## 4 Conclusions

The main purpose of the study is to provide the information on wave height climatology over Malaysian seas, where the climatology of wave height was made and analysed. The map shows the wave height of Malaysian seas throughout the 24 years evaluated in this study. The study also provides important information which can be used in the decision of developing the potential wave energy technology in Malaysia. The reliability of satellite altimeter data in wave height studies over Malaysian seas was also evaluated. The correlation of satellite altimeter and in situ measurement shows a good relative relationship because all of the correlation results are more than 0.7 for altimetry versus buoy using 9 days moving windows. The 24 years of satellite altimeter data that was taken from 1993 until 2016 are used to analyse the wave height climatology over Malaysian Seas. The effects of monsoon events towards the characteristics of the seas and wave height are also observed and analysed. From the results, it is shown that the wave heights in Malaysian seas are not very consistent because of the effect of the monsoon seasons. In conclusion, there are a few potential areas for the renewable energy from wave height such as in Terengganu and Sabah shores can be proposed for the future study.



**Acknowledgements** The authors would like to thank TU Delft, NOAA, Altimetry's Lilac, the oil and Gas Company and University Malaysia Terengganu (UMT) for providing altimetry, buoy and ADCP data, respectively. We are grateful to the Ministry of Education (MOE) Malaysia and University Technology Malaysia for funding this research under Research University Grant (Vot number: Q.J130000.2527.12H99).

## References

1. Yaakob, O., Hashim, F.E., Omar, K.M., Din, A.M., Koh, K.K.: Satellite-based wave data and wave energy resource assessment for South China Sea. In: International Conference on Marine Technology Kuala Terengganu, Malaysia, 359–371 (2012)
2. Zheng, C.W., Li, C.Y.: Variation of the wave energy and significant wave height in the China Sea and adjacent waters. *Renew. Sustain. Energy Rev.* **43**, 381–387 (2014)
3. Aziz, W.A.: Wave height and wave energy mapping in Malaysian seas using satellite altimetry data. Master thesis, University Teknologi Malaysia (2014)
4. Samrat, N.H., Rahaman, M.H., Mamun, A., Adib, R., Ahmed, M.T.A.B.M.I.: Wave energy in Bangladesh, ECERE2015-P005 (2015)
5. Shanass, P.R., Sanil Kumar, V., Hithin, N.K.: Comparison of gridded multi-mission and along-track mono-mission satellite altimetry wave heights with in situ near-shore buoy data. *Ocean. Eng.* **83**, 24–35 (2014)
6. Fernando, S.P., Helen, A.F., Laurie, P.: Constructing improved decadal records of Antarctic ice shelf height change from multiple satellite radar altimeters. *Remote Sens. Environ.* 192–205 (2016)
7. Jarihani, A.A., Callow, J.N., Johansen, K., Gouweleeuw, B.: Evaluation of multiple satellite altimetry data for studying inland water bodies and river floods. *J. Hydrol.* **505**, 78–90 (2013)
8. Aziz, W.A.W.A., Yaakob, O., Omar, K.M., Din, A.M.: Satellite altimeter ocean wave height data in South China Sea. In: International Conference on Marine Technology, Kuala Terengganu, Malaysia (ID: MTP-21) (2012)
9. Andersen, O.B., Scharroo, R.: *Coastal Altimeter*. Springer, Berlin (2010)
10. Rosmorduc, V., Benveniste, J., Bronner, E., Dinardo, S., Lauret, O., Maheu, C., Milagro, M., Picot, N., Ambrozio, A., Escolà, R., Garcia-Mondejar, A., Restano, M., Schrama, E., Terra-Homem, M.: Radar altimetry tutorial. In: Benveniste, J., Picot, N. (eds.) *ESA & CNES* (2016)
11. Guido, V.: Model and Its Application to Cassini Mission. Department of Aerospace and Mechanical Engineering, Second University of Naples, Aversa, Italy (2007)
12. Liong, P.C.: Hydrography of the straits of Malacca. *Malays. Agric. J.* **49**(3), 381–391 (1974)
13. Work, P.A.: Nearshore directional wave measurements by surface-following buoy and acoustic Doppler current profiler. *Ocean. Eng. Elsevier*, **35**, 727–737, <https://doi.org/10.1016/j.physletb.2003.10.071>. (2008)
14. OSW Hydroacoustics: Acoustic Doppler profiler homepage. <https://hydroacoustics.usgs.gov/indexvelocity/instruments.shtml#adp>, last accessed 13 May 2017
15. Ashton, I.G.C., Johanning, L.: On errors in low frequency wave measurements from wave buoys. *Ocean. Eng.* **95**, 11–22 (2014)
16. Worst, J.S., Donohue, K.A., Rossby, T.A.: Comparison of vessel-mounted acoustic doppler current profiler and satellite altimeter estimates of sea surface height and transports between New Jersey and Bermuda along the CMV oleander route. *J. Atmos. Oceanic Technol.* **31**, 1422–1433 (2014)
17. Corrigan, C.E., Ramanathan, V., Schauer, J.J.: Impact of monsoon transitions on the physical and optical properties of aerosols. *J. Geophys. Res.* **111**, 1–15, D18208, <https://doi.org/10.1029/2005JD006370>. (2006)