DERIVATION OF TIDAL CONSTITUENTS FROM SATELLITE ALTIMETRY DATA FOR COASTAL VULNERABILITY ASSESSMENT IN MALAYSIA

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DEDICATION

To my beloved father Ainee Kem and mother Habsah Mansor

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ABSTRACT

Sea level rise has posed a serious threat particularly to the coastal environment due to its prominent association to the land inundation. The rise of global sea level might be inevitable, however the assessment of the impending impacts of the sea level rise is a vital approach to mitigate the incoming impacts. This study is an initiative to assist coastal vulnerability assessment due to the sea level rise impacts specifically across Malaysian coastal regions by using Mean Tidal Range parameter derived from tidal models. The tidal models were generated from merged along-track TOPEX and Jason-1 sea level anomalies (SLA) data retrieved in Radar Altimeter Database System (RADS) for South China Sea region covering latitude 0° N to 13° N and longitude 98° E to 120° E. Tidal harmonic analysis was performed by using t-tide Matlab programme to estimate amplitude and phase for tidal constituents M2, S2, K1 and O1 from altimetry data. The corresponding tidal constituents were subsequently interpolated into 0.25° square grids. The overall accuracy of the tidal models is Root Sum Square (RSS) whose value is 8.59 cm, while the Root Mean Square (RMS) of Mean Tidal Range values derived from the tidal models is 17.12 cm. Subsequent to the derivation of Mean Tidal Range from the corresponding tidal models, it can be inferred that Mean Tidal Range values for Malaysian coastal regions vary from 81.95 cm to 158.97 cm. There is a consensus in various coastal vulnerability studies that a region whose Mean Tidal Range value less than 2 meters is the most susceptible region to the sea level rise impacts. Therefore, Malaysian coastal regions can be generally categorized as vulnerable due to the sea level rise threats. The use of tidal models are expected to complement the existing coastal management system in order to monitor level of coastal severity caused by the sea level rise impacts especially for Malaysian coastal regions.

ABSTRAK

Kenaikan aras laut telah mengakibatkan ancaman yang serius terutamanya kepada kawasan pantai disebabkan oleh perkaitan rapatnya dengan banjir. Kenaikan aras laut sejagat mungkin tidak dapat dielakkan, walau bagaimanapun penilaian impak kenaikan aras laut adalah penting untuk mengurangkan impak yang mendatang. Kajian ini adalah suatu inisiatif bertujuan untuk membuat penilaian kerentanan kawasan pantai terhadap kesan kenaikan aras laut khususnya sepanjang kawasan pantai Malaysia menggunakan pemboleh ubah min julat pasang surut yang diperoleh daripada model pasang surut. Model pasang surut telah dihasilkan daripada gabungan data anomali aras laut (SLA) sepanjang trek TOPEX dan Jason-1 yang diperolehi daripada sistem pangkalan data altimeter radar (RADS) untuk kawasan Laut China Selatan yang merangkumi latitud 0° N hingga 13° N dan longitud 98° E hingga 120° E. Analisis harmonik pasang surut telah dilakukan dengan menggunakan program Matlab T-TIDE untuk menganggar amplitud dan fasa bagi juzuk-juzuk pasang surut M2, S2, K1 dan O1 daripada data altimeter. Juzuk-juzuk pasang surut tersebut kemudiannya diinterpolasi kepada petak grid 0.25°. Ketepatan keseluruhan bagi model pasang surut dinyatakan dengan punca jumlah kuasa dua (RSS) dimana nilainya adalah 8.59 cm, manakala nilai punca min kuasa dua (RMS) bagi min julat pasang surut yang diperoleh daripada model pasang surut adalah 17.12 cm. Berikutan dengan penerbitan min julat pasang surut daripada model pasang surut tersebut, nilai-nilai min julat pasang surut bagi kawasan pantai Malaysia boleh disimpulkan berbeza-beza daripada 81.95 cm ke 158.97 cm. Terdapat satu kesepakatan dalam banyak kajian kerentanan pantai iaitu sesuatu kawasan yang mempunyai nilai min julat pasang surut kurang daripada 2 meter adalah kawasan yang paling terdedah kepada impak kenaikan aras laut. Oleh itu, kawasan-kawasan pantai Malaysia secara umumnya boleh dikategorikan sebagai berbahaya kepada ancaman kenaikan aras laut. Penggunaan model pasang surut dijangka dapat saling melengkapi sistem pengurusan pantai sedia ada untuk memantau tahap keterukan kawasan pantai disebabkan kesan-kesan kenaikan aras laut terutamanya untuk kawasan-kawasan pantai Malaysia.

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LIST OF SYMBOLS

r	-	Earth radius
D	-	Distance from point on earth to the centre of moon
R	-	Distance from centre of earth and centre of moon
θ	-	Latitude of point on earth
G	-	Universal gravitational constant
m1	-	Mass of the earth
m2	-	Mass of the moon
σ	-	Moon inclination from the equator
α	-	Declination of moon orbit and the ecliptic
ω	-	Speed of a tidal constituent
Z_o	-	Mean Sea Level (MSL)
H_{SALT}	-	Altitude of satellite altimeter above reference ellipsoid
N	-	Geoid heights
fc	-	Nyquist frequency
Ta	-	Aliasing period of tidal constituents
Δt	-	Altimetry sampling interval
F	-	Actual period of tidal constituents
h_{atm}	-	Atmospheric corrections for range improvement
h_{ssb}	-	Sea state bias correction for range improvement
h_{IB}	-	Inverse Barometer (IB) correction for range improvement
h_{tides}	-	Tide corrections for range improvement
h_{MSS}	-	Inverse Barometer (IB) correction for range improvement

LIST OF ABBREVIATIONS

IPCC	-	Intergovernmental Panel on Climate Change
ERS	-	European Remote Sensing Satellite
CVI	-	Coastal Vulnerability Index
SLA	-	Sea level anomalies
MSL	-	Mean sea level
RADS	-	Radar Altimeter Database System
DSMM	-	Department of Surveying and Mapping Malaysia
IDW	-	Inverse Distance Weighting
FRIS	-	Filchner-Ronne Ice Shelf
USGS	-	U. S. Geological Survey
AHP	-	Analytical Hierarchy Process
LSE	-	Least Square Estimation
SSH	-	Sea surface height
DORIS	-	Doppler Orbitography and Radiolocation Integrated by Satellite
SLR	-	Satellite Laser Ranging
GPS	-	Global Positioning System
SST	-	Sea Surface Topography
MSS	-	Mean sea surface
SSB	-	Sea State Bias
IB	-	Inverse barometer
RMS	-	Root Mean Square
RSS	-	Root Sum Square

ECMWF	-	European Centre for Medium-Range Weather Forecasts
GOT	-	Global Ocean Tide
CLS	-	Collecte Localisation Satellites
MOG2D	-	2 Dimensions Gravity Waves Model
DTU	-	Denmark Technical University
FFT	-	Fast Fourier Transformation

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

The increase in sea level around the world attracts global attention. The increase in global sea level is prominently known as sea level rise has been studied by many researchers. The escalation in awareness regarding the sea level rise phenomenon leads to numerous studies in related fields to assess the future impacts as well as improving the understanding related to the sea level rise.

According to Church *et. al.* (2010), data from coastal and island tide gauges indicate that the average rate of global sea level rise was 1.7 mm per year during 1900s. However, recent satellite records has demonstrated a dramatic change in the trend of the sea level rise whose rate is accelerated to 0.18 meter to 0.59 meter (Intergovernmental Panel on Climate Change, 2007) (IPCC). Such acceleration can be anticipated due to recent rate of environmental pollutions whose the impacts alter the climate patterns.

Sea level rise is a result from the increase in global temperature. This has introduced the world to a threat called global warming. Due to the temperature gradient, the rise in global temperature transfers the heat to the ocean's surface and subsequently causing the ocean's volume to increase. Theoretically, the water particles gain energy when each of the particles receives heat and causing the water volume to expand. In this context heat is absorbs from the sea surface. Consequently, the increase in ocean's volume is called ocean's thermal expansion and many believed that this phenomenon is the main driver to sea level rise phenomenon.

Apart from ocean's thermal expansion, another factor whose the impact contributing to the sea level rise is the melting glaciers (Church *et. al.*, 2010). Similarly to the ocean's thermal expansion, the melting glaciers and polar ice caps are also triggered by the global warming. As mentioned earlier, those factors contributing to sea level rise are the resultant from global warming phenomenon. The rise in global temperature is yielded by the increase in greenhouse gas to the air (Church *et. al.*, 2010). The increase in greenhouse gas amount to the air is believed to be the primary factor to amplify the rate of sea level rise in future.

Sea level rise does not occur uniformly all around the world due to the influence of the winds, variation in earth gravitational force and currents (Feng *et. al.*, 2013). Thus, some regions may experience severe sea level rise while other regions may experience less. Based on a study conducted by Din (2014), sea level data derived from TOPEX, Jason-1, ERS-1, ERS-2 and Envisat satellite altimeter from 1993 to 2008 the result has indicated that Malaysia is also experiencing sea level rise at 4.47±0.71mm per year. Another study done by Reyes and Blanco (2012) has predicted 100 cm sea level increase in future will inundate 5000 hectares of the Manila Bay. Thus, having safety measures to assess potential threats due to sea level rise impacts is vital especially in the coastal regions.

1.2 Problem Statement

Coastal areas are the most affected areas due to the sea level rise phenomenon. In fact, the sea level rise has the potential to permanently alter the coastal areas due to its association to land inundation, flooding in low-lying areas, contributes to coastal erosion and leads to saltwater intrusion into fresh water (Church *et. al.*, 2010). Thus, it is important to evaluate the susceptibility of a coastal area to provide mitigation measures and subsequently alleviate the impending impacts of sea level rise.

One of most important coastal parameter used to assess the vulnerability of a coastal area to the impacts of sea level rise is the Mean Tidal Range. Mean Tidal Range parameter is commonly derived from tide gauge data. The use of tide gauge data is inarguably accurate and feasible to conduct site specific coastal vulnerability study. However, in order to conduct coastal vulnerability study over a larger area for instance conducting study at national level, the distribution of tidal stations along coastal regions is apparently insufficient. The inadequacy of tidal stations distribution is exacerbated by the fact that tides in shallow water region is extremely localized to the location where the tidal station is located (Hok, 2012).

Hence, in this study Mean Tidal Range is derived from tidal models generated from satellite altimetry data. The proposition of using tidal models to derive Mean Tidal Range is basically to compensate the scarcity of tidal stations along coastal regions. Therefore, Mean Tidal Range parameter can be derived anywhere within area of study even though in the area where tide gauge data is absent. The combination of satellite altimetry and tide gauge sea level data provides a tremendous potential to monitor global sea level rise, facilitates coastal vulnerability assessment and subsequently benefits the authority, environmentalists and private agencies to develop a systematic coastal management and planning to mitigate future sea level rise impacts on coastal area where most human settlements are located.

1.3 Objectives of the Study

The aim of the study is to generate tidal models from TOPEX and Jason-1 SLA data to assess the impending sea level rise threats particularly in Malaysian coastal regions. Three objectives have been outlined in order to achieve the aim of the study. The objectives are as follows:

i) To generate tidal models for South China Sea from TOPEX and Jason-1 SLA data.

ii) To validate the tidal models from tide gauges data.

iii) To derive Mean Tidal Range from tidal models for Malaysian coasts.

1.4 Scope of the Study

Climate change has triggered gradual increase in global mean sea level (MSL) and the subsequent impacts may permanently affect coastal areas. Thus, the assessment on the physical threats due to sea level rise phenomenon is necessary for coastal planning and management purposes. Therefore, Mean Tidal Range is derived from tidal models generated from satellite altimetry sea level data to further assess the susceptibility of Malaysian coastal regions to the impending sea level rise threats. The following Table 1.1 enlists the important elements and processes involved throughout the study.

Table 1.1 : Scope of the study

Research phases	Research scope			
Literature study and planning	Climate change	Satellite altimetry principles		
	Coastal vulnerability assessment	Tidal study		
Data acquisition and processing	Radar Altimeter Database System (RADS)	Preliminary data filtering	Coastal tide gauges data	
		Altimetric data corrections		
		Along-track SLA time series		
SLA data assessments	SLA trend validation	12 hours mean of coastal tidal data		
		Mean difference of altimetric SLA and relevant coastal tidal data		
		Altimetric SLA and tidal data correlation		
	Harmonic analysis	Coastal altimetry data performance		
		Altimetry Phase A and B data precision		
Tidal modelling	Spectral Analysis	Along track SLA time series		
	Harmonic analysis	Interpolation	Inverse Distance Weighting	
			Kriging method	
		Models validation		
Mean Tidal Range computation	Mean Tidal Range Computation	Mean Tidal Range validation		
Data analysis and discussion	Altimetry data processing	SLA validation	Models validation	
	Altimetry data precision and performance at coastal regions			
	Mean Tidal Range assessments for the study area			

The whole flow of the study comprises six phases such as literature study and planning, data acquisition and processing, SLA data assessment, modelling the tides, Mean Tidal Range derivation and data analysis and discussion. The input data and area selected for the study are discussed in the next section.

1.4.1 Input Data

There are 3 main input data used such as SLA obtained from satellite altimeter, tide gauge data for various locations provided by Department of Surveying and Mapping Malaysia (DSMM) and tidal constituents from Tide Table 2015 produced by National Hydrographic Centre. These data are used for tidal modelling and data validation purposes. Table 1.2 describes the input data involve in tidal modelling and data validations.

Table 1.2 : Input data

Data	Description
Satellite altimetry SLA	i) Obtained from TOPEX and Jason-1 altimeter. ii) Data retrieved from RADS. iii) Processed from 1993 to 2011. iv) Main input data for tidal modelling.
Tide gauge	i) Provided by the DSMM. ii) 7 tidal stations are selected. iii) Data available starting from 1993 to 2011 for each tidal station. iv) Dedicated for SLA data assessments.
Tide Table 2015	i) Produced by National Hydrographic Centre. ii) 8 tidal stations are selected. iii) Used for tidal models and Mean Tidal Range validation.

Referring to Table 1.2, satellite altimetry SLA data from 1993 to 2011 are selected to match the tide gauge data provided by the DSMM. The selection of these common years between satellite altimetry data and tide gauge data is an important feature to facilitate further analysis.

1.4.2 Area of the Study

South China Sea is located in South East Asia region and bordered by several countries such as China, Philippines, Brunei, Malaysia, Singapore and Vietnam. It also interacts with Pacific Ocean in north-east region and Celebes Sea in the eastern part. The southern region of the South China Sea is selected for further tidal modelling purpose due to its immense influence to Malaysia coastal regions. The area subject for tidal modelling covers from latitude 0° N to 13° N and longitude 98° E to 120° E. Figure 1.1 shows the southern part of the South China Sea.

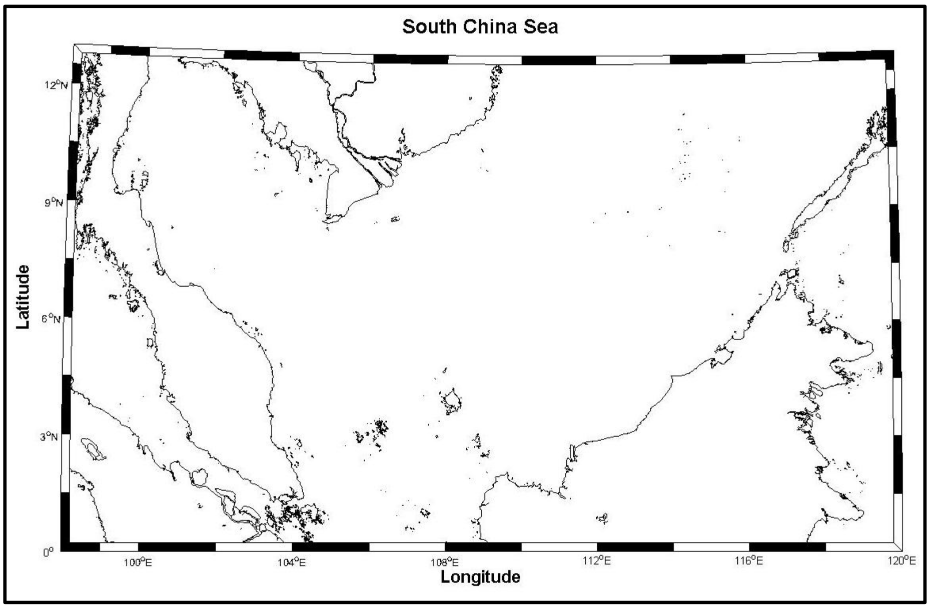

Figure 1.1 South China Sea (Source: M-map)

The South China Sea is selected due to the availability of satellite altimetry tracks in the region and the suitability of its location to conduct the study. The availability of altimetry tracks is vital since altimetry data is the sole data input used to model the tides in the region. Furthermore, the presence of heavy industries, dense human settlements and tourism activities across Malaysian coasts increase the demand to monitor coastal regions particularly to alleviate the impacts to coastal hazards and subsequently contribute to a better coastal management and planning.

1.5 Significance of the Study

Current situation has indicated that the impacts of climate change are getting much severe than last few centuries. Sharp varying weather and the increase in storm intensity and frequency are the indications of weather responses to the climate change. Therefore, the implementation of coastal assessment due to the sea level rise phenomenon proposed in this study is expected to benefit coastal management and planning, providing alternative source of data for coastal assessment and introducing to the use to satellite altimetry data instead of sole dependency on tide gauge data.

Thus, this study is conducted to assess the susceptibility of Malaysian coastal regions to the coastal threats posed by the sea level rise phenomenon and roughly identify the affected areas. The assessments of future threats lead by the sea level rise phenomenon towards coastal areas are indispensable to support future coastal planning and management especially to the region like Bintulu and Chendering where various industries and dense human settlements are located. As a consequence, the authorities and environmentalists can take mitigation measures as well as providing alternatives to the region where the impacts of sea level rise is immense.

In term of the provision of sea level data for coastal assessment, the use of tide gauge alone is inefficient to study the Mean Tidal Range behaviour along Malaysian coastal regions due to its sparse distributions to compensate the locality of tidal behaviour (Hok, 2012), expensive operation and maintenance. Therefore, the proposition of the use of tidal models generated for the South China Sea is the most plausible solution as an alternative to accommodate the scarcity of tide gauge network along Malaysian coasts. The use of tidal models allows the computation of Mean Tidal Range parameter at any location along Malaysian coastal regions.

The satellite altimetry data is utilized to generate the tidal models such as TOPEX and Jason-1 SLA data. Satellite altimetry technique provides more reliable data to generate tidal models in term of providing long term sea level time series. Continuous sea level data is one of the criteria to produce a good tidal model. Moreover, sea level measured by the satellite altimeter is the absolute sea level which implies to vertical land motion free sea level data. As opposed to satellite altimetry data, tide gauge data is rarely continuous and hampered by the effect of vertical land motion (Feng *et. al.*, 2013). Absolute sea level data is an important feature in sea level rise study due to the fact that sea level rise is measured in milimeter level which the vertical land motions posed a great influence and consequently needs considerable attention.

Furthermore, utilizing altimetry technique benefits the tidal models through the fact that altimetry along track data provides dense in situ tidal measurement in the offshore regions. Formerly, tidal measurement in the offshore regions is extrapolated from coastal tide gauges data. As the distance from tide gauges increases, the accuracy of extrapolated tides deteriorates (Vella, 2000). Since the tidal behaviour is localized to the location where the measurement was made, extrapolation technique from coastal tide gauge is considered inappropriate. Hence, satellite altimetry has produced enormous contribution in providing in situ tidal measurement in the offshore regions whose data is used in this study to produce tidal models.

1.6 Summary of the Chapter

This Chapter 1 discusses the global and local sea level rise issues as well as the impacts induced by the sea level rise phenomenon particularly towards coastal vicinity. Consequently, coastal vulnerability assessment is indispensable in order to study the impending impacts of the sea level rise, identify the severity of an area due to the sea level rise impacts and assist local authority and decision makers to provide preventive and mitigation measures.

The use of Mean Tidal Range parameter in this study is justified by its influence and potential to exacerbate the impacts of sea level rise and posed permanent changes in coastal setting. The paucity of tidal stations distribution along has hindered the implementation of coastal vulnerability assessment at national level. Thus, this study has suggested the use of tidal models instead of the use of tide gauge data to compute Mean Tidal Range parameter for Malaysian coastal region.

The methodology of the study is briefly explained in this chapter. This methodology is basically introduced to achieve the objectives of the study, outline the scope of the study and provide justification of the input data involved and the significance of study area selected in this study.

The importance of this study is elaborated in this study to emphasize the motivations of conducting the study. The notion of conducting this study is basically to help the local authorities, environmentalists and researchers to provide an effective coastal managements and planning system to mitigate the impending impacts of sea level rise.

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