SEA LEVEL RISE QUANTIFICATION AND PROJECTION USING MULTI-MISSION SATELLITE ALTIMETER OVER MALAYSIAN SEAS

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DEDICATION

In memory of my beloved Umi,

Puan Nik Rayan binti Nik Mat

إِنَّا لِلّهِ وَإِنَّـا إِلَيْهِ رَاجِعُونَ

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ABSTRACT

The increase of anthropogenic activities has triggered rising global sea levels and threatens many low-lying and unprotected coastal areas. Without countermeasures, global sea levels will continue to rise at an accelerating rate in the 21^{st} century. Geographically, Malaysia is epitomized by its unique geographical settings and is surrounded by water, hence a comprehensive study of the seas is vital for local management to take significant measures to understand and protect Malaysian coastline from threatening disasters. This study makes a significant effort to quantify and project sea level trends for this region by taking into account regional sea temperature changes. It presents an approach to quantify sea level trends based on multi-mission satellite altimeters over Malaysian seas. Future projection of sea levels was performed for every 20 years from 2020 to 2100. Multi-mission satellite altimetry data for Sea Level Anomalies and Sea Surface Temperature was processed using the Radar Altimeter Database System. Radar Altimeter Database System performs enhanced processing strategies for the derivation of sea level anomalies, including filtering, gridding, and moving average. The daily solutions of this data were combined into monthly average solutions for sea level rise quantification and projection. The assessment results show similar sea level anomaly patterns of high correlation coefficients (>0.9) and small (few cm) Root mean square errors between sea level anomalies from altimetry and tide gauges over the same period. Subsequently, sea level trends were determined using robust fit regression analysis for the sea level anomaly time series, where the sea level rise trends around Malaysia ranged from 3.37 ± 0.13 mm yr^{-1} off Peninsular Malaysia to 5.00 ± 0.10 mm yr^{-1} off Sabah and Sarawak with an overall mean of 4.17 ± 0.16 mm yr^{-1}. From 1993 to 2015, cumulative sea level rise was 4.86 cm. During the 21^{st} century, Malaysian seas will encounter a rise of 6.07 cm by 2020, 13.15 cm by 2040, 20.23 cm by 2060, 27.31 cm by 2080, and 34.39 cm by 2100. Information on sea level changes in this region is valuable for a wide variety of climate applications and for studying environmental issues such as global warming in Malaysia. It is also important for its relevance to predicting future regional climates for disaster adaptation measures.

ABSTRAK

Peningkatan aktiviti antropogenik telah mencetuskan kenaikan paras laut global dan telah mengancam banyak kawasan pantai yang rendah dan yang tidak dilindungi. Tanpa langkah pengawasan, paras laut global akan terus meningkat pada kadar yang pantas pada abad ke-21. Secara geografi, Malaysia bercirikan persekitaran geografi yang unik dan dikelilingi oleh perairan, maka kajian komprehensif di laut Malaysia adalah penting bagi pengurusan kawasan setempat dan untuk mengambil langkah penjagaan dalam memahami dan melindungi pantai Malaysia daripada ancaman bencana. Kajian ini merupakan usaha dalam mengukur dan mengunjur trend paras laut di rantau ini dengan mengambil kira perubahan suhu laut serantau. Kajian ini turut membentangkan pendekatan untuk mengukur paras laut berdasarkan kombinasi pelbagai misi satelit altimeter ke atas laut Malaysia. Unjuran paras laut di masa depan akan dilaksanakan pada setiap 20 tahun, bermula dari tahun 2020 dan sehingga 2100. Data daripada pelbagai kombinasi satelit altimeter yang terdiri daripada anomali paras laut dan suhu permukaan laut diproses dengan menggunakan Sistem Pangkalan Data Altimeter Radar. Sistem Pangkalan Data Altimeter Radar melakukan strategi pemprosesan yang dipertingkatkan dalam menerbitkan anomali paras laut, termasuk penapisan data, pemplotan titik data dan purata data harian. Data harian ini digabungkan menjadi purata bulanan untuk kuantifikasi dan unjuran bagi kenaikan paras laut Malaysia. Dapatan penilaian menunjukkan corak anomali paras laut yang sama dengan pekali korelasi yang tinggi (> 0.9) dan hanya sedikit (beberapa cm) ralat punca minimum kuasa dua, antara anomali paras laut dari altimeter dan tolok pasang surut dalam tempoh yang sama. Seterusnya, trend paras laut ditentukan oleh analisis regresi *robust fitting* untuk siri masa anomali paras laut, di mana paras kenaikan laut sekitar Malaysia adalah dari 3.37 ± 0.13 mm tahun^{-1} dari Semenanjung Malaysia hingga 5.00 ± 0.10 mm tahun^{-1} bagi Sabah dan Sarawak dengan purata keseluruhan 4.17 ± 0.16 mm tahun^{-1}. Dari tahun 1993 hingga 2015, kenaikan paras laut kumulatif Malaysia ialah pada 4.86 cm. Pada abad ke-21, laut Malaysia akan mengalami kenaikan 6.07 cm pada tahun 2020, 13.15 cm pada tahun 2040, 20.23 cm pada tahun 2060, 27.31 cm pada tahun 2080 dan pada akhir abad ke-21, 34.39 cm pada tahun 2100. Maklumat tentang perubahan paras laut di rantau ini amat bernilai dalam pelbagai aplikasi terhadap iklim dan untuk mengkaji isu-isu alam sekitar seperti pemanasan global di Malaysia. Ia juga penting dalam perkaitannya dengan meramalkan iklim serantau pada masa depan untuk langkah-langkah penyesuaian bencana.

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LIST OF SYMBOLS

c	-	Speed of the radar pulse neglecting refraction (approximate 3 x 10^8 m/s)
^{14}C	-	Radiocarbon-dated
d	-	Distance between known point, x_i to the arbitrary point, x
e	-	Unit vector
F_w	-	Weighting function
h	-	Sea surface height
h_{atm}	-	Dynamic atmospheric correction
h_D	-	Dynamic sea surface height
h_i	-	Leverage
h_{tides}	-	Tides correction
H	-	The height of the mass centre of the spacecraft above the reference ellipsoid, estimated through orbit determination
K	-	A tuning constant whose default value of 4.685 provides for 95% asymptotic efficiency as the ordinary least squares assuming Gaussian distribution
r	-	Distance between the data point and the grid point
r_i	-	Residuals
R	-	Altimeter range
R	-	Correlation of coefficient
R^2	-	Correlation of determination
S	-	Mean absolute deviation divided by a factor 0.6745 to make it an unbiased estimator of standard deviation
t	-	Altimeter travel time
x	-	An interpolated (arbitrary point)
x_i	-	A known point

$\Delta\zeta^{m}_{esl}$	-	Modified eustatic curve
ΔR_{dry}	-	Dry tropospheric correction
ΔR_{wet}	-	Wet tropospheric correction
ΔR_{iono}	-	Ionospheric correction
ΔR_{ssb}	-	Sea-state bias correction
μm	-	Micrometer
σ	-	Sigma

LIST OF ABBREVIATIONS

ABM	:	Australian Bureau of Meteorology
AOGCM	:	Atmosphere-Ocean Global Circulation Models
AATSR	:	Advanced Along-Track Scanning Radiometer
AMSR-E	:	Advanced Microwave Scanning Radiometer on the Earth Observing System
AR3	:	IPCC Third Assessment Report
AR5	:	IPCC Fifth Assessment Report
ATSR	:	Along-Track Scanning Radiometer
AVHRR	:	Advanced Very High Resolution Radiometer
AVISO	:	Archiving, Validation and Interpretation of Satellite Oceanographic data
BP	:	Before Present
CEOS	:	Committee on Earth Observation Satellites
CH_4	:	methane
CO_2	:	Carbon Dioxide
CS	:	Celebes Sea
DEOS	:	Delft Institute for Earth-Oriented Space Research
DSMM	:	Department of Survey and Mapping Malaysia
ECMWF	:	European Centre for Medium-Range Weather Forecasts
Envisat	:	Environmental Satellite
ENSO	:	El Niño–Southern Oscillation
ERS	:	European Remote Sensing Satellite
ESA	:	European Space Agency
GIA	:	Glacial isostatic adjustment
Geosat	:	Geodetic/Geophysical Satellite
GHG	:	Greenhouse Gases

GISS	:	Goddard Institute for Space Studies
GMSL	:	Global Mean Sea Level
GMST	:	Global mean surface temperature
GPS	:	Global Positioning Satellite
GUIDE	:	Graphical User Interface Development Environment
IDW	:	Inverse Distance Weighting
InSAR	:	Interferometric Synthetic Aperture Radar
IRLS	:	Iteratively re-weighted least squares
IPCC	:	Intergovernmental Panel on Climate Change
LGM	:	Last Glacial Maximum
LGP	:	Late Glacial Period
MATLAB	:	Matrix Laboratory
MJO	:	Madden–Julian Oscillation
MMD	:	Malaysian Meteorological Department
MS	:	Malacca Strait
MSS	:	Mean sea surface
MySLS	:	Malaysian Sea Level System
NAHRIM	:	National Hydraulic Research Institute of Malaysia
NASA	:	National Aeronautics and Space Administration
NCDC	:	National Climatic Data Centre
NCEP	:	National Centers for Environmental Prediction
NOAA	:	National Oceanic and Atmospheric Administration
N_2O	:	Nitrous oxide
OISST	:	Optimum Interpolation Sea Surface Temperature
ONI	:	Oceanic Niño Index
PGP	:	Post Glacial Period
PODAAC	:	Physical Oceanography Distributed Active Archive Centre
PSMSL	:	Permanent Service for Mean Sea Level
RADS	:	Radar Altimeter Database System
RCP	:	Representative Concentration Pathway
REMSS	:	Remote Sensing Systems SST
RMSE	:	Root mean square error
RSS	:	Remote Sensing System

SARAL	:	Satellite with ARgos and ALtiKa
SCS	:	South China Sea
SLA	:	Sea level anomaly
SRES	:	Special Report on Emissions Scenarios
SSH	:	Sea surface height
SS	:	Sulu Sea
SST	:	Sea surface temperature
USO	:	Ultra-stable oscillator
VLM	:	Vertical land motion
WGS	:	World Geodetic System

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Rising sea levels is a major concern nowadays due to anthropogenic effects. Increasing atmospheric concentrations of heat-trapping gases has occurred because human activities, like cutting down tropical trees, as well as burning coal and oil have caused the earth to warm since the 1880s (NASA, 2016). A study by a marine physicist, Tim Barnett at the Scripp Institution of Oceanography showed that 90% of greenhouse warming ends up in the seas. According to the recent synthesis report of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2014), one of the major challenges in the 21st century is rising global sea levels. Due to this change, sea levels worldwide are now constantly rising and eventually threatening many low-lying and unprotected coastal areas (Nicholls and Cazenave, 2010).

AVISO's Sea Level Research Team conducted a study to investigate Global Mean Sea level (GMSL) from January 1993 to December 2015, it showed that GSMSL has increased to a rate of 3.37 mm year^{-1} (AVISO, 2016). An increase in sea level significantly increases the impact of storms on low-lying coastal areas as well as the economic and social burdens or the severely affected. Immediate action needs to be taken to quantify forthcoming sea levels so that mitigation activities will be able to commence as soon as possible.

This study presents an effort to quantify and project sea level trends over Malaysian seas from 1993 to 2015 using a multi-mission satellite altimeter and tide gauges. The quantification of this region sea level is also associated with sea surface temperature (SST) by reason of past and present-day rising sea levels is thought to be a consequence of global warming (Church *et al.,* 2008), causing the oceans to warm.

With the advancement of new technology, measuring sea level changes and identifying its causes has remarkably progressed in recent years. As tide gauges are attached to land and can only be found in coastal areas, satellite altimeters have been used to acquire sea level data. As satellite altimeter gives absolute sea level, the Radar Altimeter Database System (RADS) developed by the Technical University of Delft was used for altimeter data acquisition and processing in this study (Naeiji *et al.*, 2000). RADS provides Sea Level Anomaly (SLA) and SST data from multi-mission satellite altimeters. This study also provides an enhanced RADS processing strategy to optimize sea surface heights (SSHs) for the derivation of SLAs.

With an enhanced altimetry data from RADS in measuring Malaysian sea level information, these results are expected to be valuable for a multidisciplinary environmental studies in Malaysia like flooding, global warming, and climate applications.

1.2 Problem Statement

Wide-ranging signs indicate that the climate system has been warmed. This is as the result of global warming, initiating rising sea levels. Population, economy, and a very existence of archipelago countries are endangered by this phenomena, as rising sea levels and ocean temperatures are the consequence of global warming. Due to this, this study provides a recent information on regional sea level behavior and as an evidence of the ongoing 21st century rising sea level on this region.

Global warming causes ocean temperature to warm. As the ocean warm, the water expands, ultimately increasing the sea level. This condition is called thermal expansion, one of the alarming contributors to the 21^{st} rising sea level worldwide (Church *et. al*, 2008). Therefore, while measuring the present rising sea level of Malaysian seas, this study investigates whether there is an affiliation between Malaysian sea temperatures and the current sea level, which may contribute to the rising of sea level in this region.

Geographically, the Southeast Asian region is exemplified by its unique geographical settings. It is bounded by the Pacific and Indian Oceans. The Malaysia region is bordered by the South China Sea, Malacca Strait, Sulu Sea, and Celebes Sea. It has large populations inhabiting low lands in coastal areas. Hence, a comprehensive study on regional seas is vital for local authorities to take significant measure for efficient management and protection of Malaysian coastal zone from threatening disasters.

Multi-mission satellite altimeter techniques (absolute sea level) have been widely used in recent years to quantify sea level changes in order to overcome the uneven geographical distribution of tide gauge stations (relative sea level) in coastal areas and a lack of long-term tidal records for the deep ocean (Azhari, 2003; Din, 2014). Though the principle of satellite altimeter is simple, the approach for estimating precise sea level measurements is actually can be very complex, demanding an optimization in altimetry data processing. This study is also focused on optimizing RADS processing procedures in order to determine the finest sea level data for computing sea level trend and magnitude in this region.

Besides, sea level prediction information for all Malaysian seas is vital for the management of the coastal zone in longer term. Thus, by providing sea level projection information across all Malaysian seas, which is possible due to the technology of satellite altimeter, the authorities can make an appropriate adaptation measures of Malaysian coastal zones from future disaster caused by rising sea levels.

This study performs a thorough analysis of sea level interpretations in the Malaysia region, by using satellite altimeters to obtain precise sea level data and associating ocean temperatures to the current sea level trend. It is expected to assist more comprehensive studies on sea levels for this region in the future.

1.3 Aim and Objectives of Study

This study has the following aim and objectives.

The aim of this study is to quantify sea level trends by relating present ocean temperatures and to project rising sea level over Malaysian seas. From this there are three (3) specific objectives:

i) *To derive sea level anomalies (SLAs) in the Malaysian seas, within a 23-year period beginning 1993 to 2015, from optimized RADS processing strategy.*

ii) *To quantify the sea level rate and magnitude using multi-mission satellite altimeter while associating sea surface temperature (SSTs) from RADS to the current absolute sea level trend.*

iii) *To project the rising sea levels in the Malaysian seas for every 20 years, starting from the year 2020 until the 2100.*

1.4 Scope of Study

This sections involves the scope and limitations of this study to establish a complete methodology for interpreting, quantifying, and projecting rising sea levels in the Malaysian region.

1) Area of Study

Rising sea levels due to climate change are often investigated at the global level. However, this study was conducted locally to see whether or not the cause of rising global sea levels is affecting the rise of local sea levels.

The area of interest covers Malaysian seas, namely the Malacca Straits, South China Sea, Celebes Sea, and Sulu Sea, between 0° N ≤ Latitude ≥ 14° N and 95° E ≤ Longitude ≥ 126° E, covering the entire Malaysian seas as shown in Figure 1.1.

Figure 1.1 Map of study area (Google Map, 2018)

2) Multi-mission Satellite Altimeter

Eight (8) satellite missions were used in this study, TOPEX, Jason-1, Jason-2, ERS-1, ERS-2, Envisat, CryoSat-2, and SARAL as shown in Table 1.1. The period of the altimetry data covers January 1993 to December 2015 (~23 years).

Table 1.1 Altimetry data selected for this study

Satellite	Phase	Sponsor	Period	Cycle
TOPEX	A, B, N	NASA/Cnes	Jan 1993 - Jul 2002	11 - 363
Jason-1	A, B, C	NASA/Cnes	Jan 2002 - Jun 2013	1 - 425
Jason-2	A	NASA/Cnes	Jul 2008 - Mac 2016	0 - 282
ERS-1	C, D, E, F, G	ESA	Jan 1993 - Jun 1996	91 - 156
ERS-2	A	ESA	Apr 1995 - Jul 2011	0 - 169
Envisat	B, C	ESA	May 2002 - Apr 2012	6 - 113
CryoSat	A	ESA	Jul 2010 - Dec 2015	4 - 77
SARAL	A	ESA	Mac 2013 - Dec 2015	1 - 31

3) Tide Gauges Data

Monthly tidal data was obtained from The Permanent Service for Mean Sea Level (PSMSL) website (http://www.psmsl.org/). Over 20 years of data of tidal data from 1993 to 2015 were used in this study in order to synchronize the altimetry data. Tide gauge data was used to estimate sea level trends and magnitudes at each tide gauge station. There were 21 Malaysian coastal tide gauges used in this study as listed in Table 1.2. Figure of tide gauge distribution can be found in Chapter 5, Figure 5.1.

4) Software

a. Radar Altimeter Database System (RADS)

Multi-mission satellite altimetry data was processed using RADS. RADS is a processing tool which performs almost entirely in retrieving the altimetry data. The final output of altimetry processing was absolute SLA and SST data with respect to DTU13 Mean Sea Surface (MSS) in daily and monthly solutions.

b. MATLAB Software

MATLAB analysed sea level data for sea level quantification and projection, for mapping purposes, and to develop a system called the Malaysian Sea Level System (MySLS).

Table 1.2 List of tide gauge station selected for this study

Number	Tide Gauge Name	Latitude	Longitude
1.	Geting	6° 13’ 35”	102° 06’ 24”
2.	Cendering	5°15’ 54”	103° 11’ 12”
3.	Tanjung Gelang	3° 58’ 30”	103° 25’ 48”
4.	Pulau Tioman	2° 48’ 26”	104° 08’ 24”
5.	Port Klang	3° 03’ 00”	101° 21’ 30”
6.	Pulau Pinang	5° 25’ 18”	100° 20’ 48”
7.	Lumut	4° 14’ 24”	100° 36’ 48”
8.	Johor Bahru	1° 27’ 42”	103° 47’ 30”
9.	Kukup	1° 19’ 31”	103° 26’ 34”
10.	Pulau Langkawi	6° 25’ 51”	99° 45’ 51”
11.	Tanjung Sedili	1° 55’ 54”	104° 06’ 54”
12.	Tanjung Keling	2° 12’ 54”	102° 09’ 12”
13.	Bintulu	3° 15’ 44”	113° 03’ 50”
14.	Kudat	6° 52’ 46”	116°50’ 37”
15.	Kota Kinabalu	5° 59’ 00”	116° 04’ 00”
16.	Sandakan	5° 48’ 36”	118° 04’ 02”
17.	Tawau	4° 14’ 00”	117° 53’ 00”
18.	Labuan	5° 16’ 22”	115° 15’ 00”
19.	Lahad Datu	5° 01’ 08”	118° 20’ 46”
20.	Miri	4° 32’ 00”	113° 58’ 00”
21.	Sejingkat	1° 34’ 58”	110° 25’ 20”

1.5 Significance of Study

Rising sea levels due to anthropogenic climate change is a global issue. Due to the heat-trapping effects of Greenhouses Gases (GHGs), climate scientists project that if emissions continue to grow unabated, it will affect people and the environment in many ways. Around the globe, seasons are shifting and humanity is seeing a rise in temperatures and sea levels. Air, water, food, and a safe place to live are provided by our planet for us and all living things. Lands and waters are shifting due to climate change, which will disturb the very existence of all living things in forthcoming years if action is not taken to overcome this issue, humankind will be leaving the earth for our heirs a very different world. The main contribution of this study are as follows:

1) A proper understanding of rising sea levels and variability will contribute to more effective flood mitigation, coastal inundation, coastal planning, and the management of this region.

2) This study intends to highlight the importance of precise sea level information by analyzing precise sea level data where data verification was conducted between conventional tide gauge data and altimetry data. Consequently, by using robust fit regression analysis, sea level quantification and projection was calculated.

3) The potential of multi-mission satellite altimeters has been proven practical by many studies for deriving sea level data and for understanding sea level trends. Therefore, this measurement should be adapted to estimate sea level changes in the Malaysian region. This technology complements traditional coastal tide gauge measurements in observing sea level changes, especially in the deep ocean.

1.6 General Research Methodology

The general methodology of this study is comprised of four (4) phases as follows and as illustrated in Figure 1.2:

Phase 1 provides a brief review on the initial stage of this study where all background knowledge was gathered to identify the research problems and objectives. **Phase 2** introduces how the data used in this study was acquired. Data verification was conducted to benchmark the precision of satellite altimeter data with tide gauge data.

Phase 3 presents the Malaysian Sea Level System (MySLS), which was developed in this stage as a byproduct of this study. It provides a sea level information system for this region. The performance of the system is presented in this phase as well**. Phase 4** deals with the completion of the objectives of this study, which are sea level quantification and projection. A detailed discussion of the analysis and results is described in this phase.

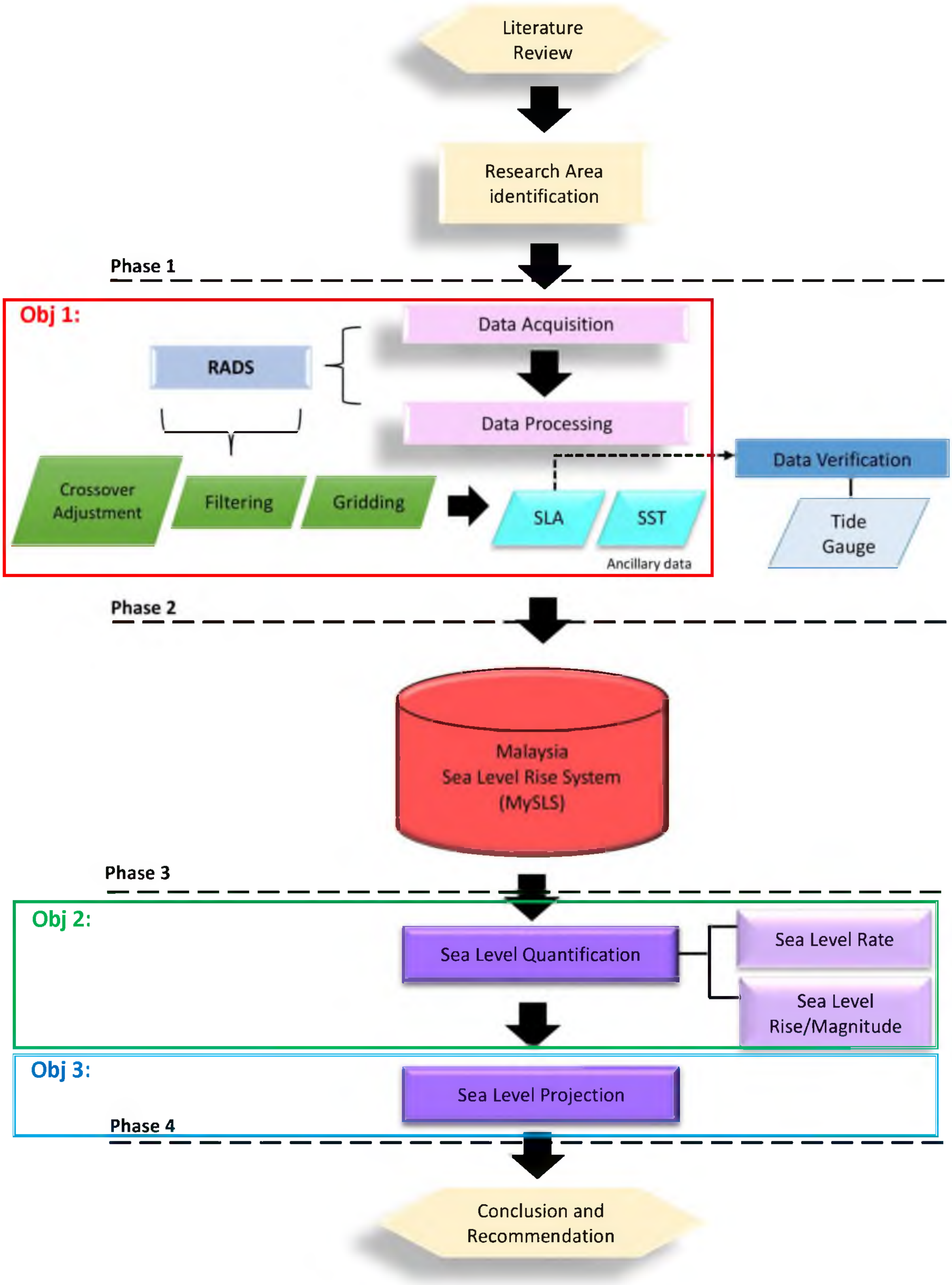

Figure 1.2 The general flowchart of this study

1.7 Thesis Outline

This thesis is categorized into general introduction, methodology, analysis, and conclusion, all of which are encompassed into seven (7) chapters as follows:

Chapter 1 begins with the main preamble comprising this study's problem statement, objectives, scope, and significance. A brief intro on research methodology is also included in this chapter.

Chapter 2 reviews fundamental topics and prior research on climate change, rising sea levels, and satellite altimeters. By reviewing this essential information, rising sea levels can be fully acknowledged while seeking new and updated information on climate change and rising sea levels.

Chapter 3 focuses on the research main methodology, which includes the data processing strategy, RADS, and tide gauge instrument descriptions. Multi-mission satellite altimeters are also comprehensively explained in this chapter. Robust fit regression analysis methods are explained here as well.

Chapter 4 discusses the optimization of altimetry data in RADS in order to achieve the finest SLAs. SLA data validation between altimeter and tide gauge instruments is also emphasized. By the end of chapter, a new set of parameters were generated for sea level trend analysis.

Chapter 5 presents sea level trend analysis from tide gauges and altimeters from January 1993 to December 2015. The relationship between ambient sea temperatures and rising sea levels in the Malaysian region was analysed using SST anomalies and SLAs. The sea level trends were then mapped.

Chapter 6 encompasses the projection of Malaysian seas from multi-mission satellite altimeters. Malaysian seas were forecasted every 20 years from year 2020 until 2100 from existing Malaysian sea levels. The projection of Malaysian seas from this study was compared with Intergovernmental Panel on Climate Change (IPCC) global-predicted sea levels and sea level study from National Hydraulic Research Institute of Malaysia (NAHRIM).

Chapter 7 presents the ultimate conclusion on Malaysian rising sea levels here. A few recommendations and ideas for future research are also explained to compliment future research on Malaysian sea levels.

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