

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

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MISSION SATELLITE ALTIMETER OVER MALAYSIAN SEAS

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DEDICATION

In memory of my beloved Umi,

Puan Nik Rayan binti Nik Mat

إِنَّا لِلَّهِ وَإِنَّا 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 21st 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 $3.37 \pm 0.13 \text{ mm yr}^{-1}$ off Peninsular Malaysia to $5.00 \pm 0.10 \text{ mm yr}^{-1}$ off Sabah and Sarawak with an overall mean of $4.17 \pm 0.16 \text{ mm yr}^{-1}$. From 1993 to 2015, cumulative sea level rise was 4.86 cm. During the 21st 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 $3.37 \pm 0.13 \text{ mm tahun}^{-1}$ dari Semenanjung Malaysia hingga $5.00 \pm 0.10 \text{ mm tahun}^{-1}$ bagi Sabah dan Sarawak dengan purata keseluruhan $4.17 \pm 0.16 \text{ mm tahun}^{-1}$. 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.

TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
	DECLARATION	ii
	DEDICATION	iii
	ACKNOWLEDGEMENT	iv
	ABSTRACT	vi
	ABSTRAK	vii
	TABLE OF CONTENTS	viii
	LIST OF TABLES	xii
	LIST OF FIGURES	xv
	LIST OF SYMBOLS	xxii
	LIST OF ABBREVIATIONS	xxiv
	LIST OF APPENDICES	xxvii
1	INTRODUCTION	
1.1	Background of study	1
1.2	Problem Statement	2
1.3	Aim and Objectives of Study	4
1.4	Scope of Study	4
1.5	Significance of Study	7
1.6	General Research Methodology	8
1.7	Thesis Outline	10
2	LITERATURE REVIEW	
2.1	Introduction	12
2.2	Climate Change	12

2.2.1	Climate Change in Malaysia	15
2.2.2	Rising Sea Levels due to Thermal Expansion	18
2.3	Sea Level Change	22
2.3.1	Influence of ENSO and Monsoon seasons toward Sea Level	24
2.3.2	Sea Level Change in Malaysia	26
2.3.3	Holocene, Present and Future Projection of Rising Sea Levels	27
	2.3.3.1 Holocene Sea Level	27
	2.3.3.2 Present Rising Sea Levels	29
	2.3.3.3 Emissions Scenarios and Future Projection of Rising Sea Levels	30
2.4	Satellite Altimeter	36
2.4.1	Fundamental of Satellite Altimeter to Derive Sea Level Data	38
2.4.2	Single Mission Satellite Altimeter and Multi- mission Satellite Altimeter	41
2.5	Rising Sea Levels : Previous and Current Research Approach	42
2.6	Summary	44
3	RESEARCH METHODOLOGY	
3.1	Introduction	45
3.2	Research Flow	45
3.3	Sea Level Anomaly Determination from Tidal Data	50
3.4	Radar Altimeter Database System (RADS)	53
	3.4.1 RADS Framework	53
	3.4.2 Multi-mission Satellite Altimeter	54
	3.4.3 Crossover Adjustment	56
	3.4.4 RADS Processing Strategy for Sea Level Anomaly (SLA) and Sea Surface Temperature (SST) Determination	57
	3.4.4.1 Sea Surface Temperature (SST)	60

	Derivation from Satellite Altimeter	
	3.4.4.2 Data Filtering	61
	3.4.4.3 Data Gridding	62
	3.4.4.4 Moving Average	64
3.5	Robust Fit Regression for Rising Sea Levels Analysis	65
3.6	Summary	66
4	MULTI-MISSION SATELLITE ALTIMETER DATA OPTIMIZATION FOR SEA LEVEL TREND ANALYSIS	
4.1	Introduction	67
4.2	Default Processing of Multi-mission Satellite Altimeter	67
4.3	Multi-mission Satellite Altimeter Data Filtering	69
4.4	Multi-mission Satellite Altimeter Data Gridding	71
4.5	Moving Average of Altimetry Data Processing	73
4.6	Data Verification : Satellite Altimeter versus Tide Gauge	74
4.7	Summary	77
5	INTERPRETATION OF RISING SEA LEVELS QUANTIFICATION ANALYSIS	
5.1	Introduction	78
5.2	Relative Sea Level from Tide Gauge	78
	5.2.1 Analysis of Relative Sea Level Variation	79
	5.2.2 Analysis on Relative Sea Level Rate	86
	5.2.3 Analysis on Relative Sea Level Magnitude	89
5.3	Absolute Sea Level from Multi-mission Satellite Altimeter	92
	5.3.1 Analysis of Absolute Sea Level Variation	93
	5.3.2 Analysis on Absolute Sea Level Rate and Trend using Robust Fitting	101
	5.3.3 Analysis of Absolute Sea Level Magnitude from Year 1993 to 2015	109

5.3.4	Analysis on the Sea Level Trend and Magnitude between Tide Gauge and Satellite Altimeter	112
5.3.5	Analysis of the Sea Level Changes With Sea Surface Temperature from Satellite Altimeter	114
5.4	Summary	118
6	RISING SEA LEVELS PROJECTION FROM MULTI-MISSION SATELLITE ALTIMETER	
6.1	Introduction	120
6.2	Rising of Sea Levels Projection from Year 2020 to 2100	120
6.3	Comparison of Rising Sea Levels Projection	126
6.3.1	Comparison of Rising Sea Levels Projection with IPCC global-predicted	126
6.3.2	Comparison of Rising Sea Levels Projection with NAHRIM	128
6.4	Malaysian Sea Level System (MySLS)	132
6.5	Summary	134
7	CONCLUSION AND RECOMMENDATION	
7.1	Conclusion	135
7.2	Recommendations for Future Research	137
	REFERENCES	139
	Appendices(A-M)	149-176

LIST OF TABLES

TABLE NO.	TITLE	PAGE
1.1	Altimetry data selected for this study	6
1.2	List of tide gauge station selected for this study	7
2.1	The estimation of global sea level rate for each contribution (Bindoff <i>et al.</i> , 2007)	24
2.2	Holocene time in quaternary system (Roberts, 1998; Mackay <i>et al.</i> , 2003)	28
2.3	AOGCM simulated mean sea level (m) predictions around Peninsular Malaysia coastlines (NAHRIM, 2010)	35
2.4	AOGCM simulated mean sea level (m) predictions around Sabah and Sarawak coastlines (NAHRIM, 2010) (NAHRIM, 2010)	36
2.5	Satellite altimeter past missions up till today and their approximated range precision and radial orbit accuracy (summarised from Chelton <i>et al.</i> , 2001 and Din, 2014; AVISO, 2018)	37
2.6	The characteristic of the latest mission of altimeter employed in this study (AVISO, 2018)	38
2.7	Previous related climate change and sea level rise studies and this study	43
3.1	Arrangement in study phases	46
3.2	Yearly mean sea level average above zero tide gauge and its mean (in metre) for Peninsular Malaysia	51

3.3	Yearly mean sea level average above zero tide gauge and its mean (in metre) for East Malaysia	52
3.4	Recent status of RADS (RADS, 2017)	54
3.5	Altimetry data selected for deriving SLA	57
3.6	Corrections and models applied to RADS altimeter processing	58
4.1	R^2 value and RMSE value (in cm) for data filtering	71
4.2	R^2 value and RMSE value (in cm) for data gridding	72
4.3	R^2 value and RMSE (in cm) value for moving windows	74
4.4	Comparison value of R^2 and RMSE between default Parameter 1, Parameter 2 of sigma 2.0, size of block of 0.25° and moving average of ± 9 days and Parameter 3 i.e. sigma 2.5, size of block of 0.25° and moving average of ± 2 days.	75
5.1	Relative sea level rate (mm yr^{-1}) computed from robust fit regression analysis from tide gauges data of Malaysian coastlines	87
5.2	Relative sea level magnitude (cm) computed from tide gauges data of Malaysian coastlines	91
5.3	Absolute sea level rate (mm yr^{-1}) computed from altimeter data at the tide gauge location of Malaysian coastlines	102
5.4	Summary of the absolute sea level rate over Malaysian seas	108
5.5	Absolute sea level magnitude (cm) computed from altimetry data of Malaysian coastlines	109
5.6	Summary of the absolute sea level rise over Malaysian seas from year 1993 to 2015	112
5.7	Summary of the sea level trend from tide gauge and satellite altimeter for the Malaysian coastlines from year 1993 to 2015	113

5.8	Summary of the sea level magnitude from tide gauge and satellite altimeter for the Malaysian coastlines from year 1993 to 2015	113
6.1	Rising of sea levels projection magnitude year 2015 to 2100 (every 20 years) at Malaysian seas	121
6.2	Average magnitude of sea level projection over Malaysian seas	123
6.3	Comparison of rising sea levels projection from this study and from IPCC global-predicted (all contributions) from the year 2015 to 2100	127
6.4	Comparison of rising sea levels projection from this study and from IPCC global-predicted (thermal expansion only) from the year 2015 to 2100	127
6.5	Magnitude differences of this study rising sea levels projection versus NAHRIM for Peninsular Malaysia in cm	129
6.6	Magnitude difference of this study rising sea levels projection versus NAHRIM for Sabah and Sarawak in cm	129

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
1.1	Map of study area (Google Map, 2018)	5
1.2	The general flowchart of this study	9
2.1	Effects of Global Warming (NOAA 2010)	13
2.2	Average of greenhouse gas concentrations worldwide (IPCC, 2014)	14
2.3	Global CO ₂ emissions from anthropogenic effects (IPCC, 2014)	14
2.4	Average anomaly of global combined land and ocean surface temperature (IPCC, 2014)	15
2.5	Temperature trend at 4 selected meteorological stations (MMD, 2009)	16
2.6	Annual Rainfall Anomaly around Malaysia (MMD, 2009)	17
2.7	Observation of the sea level from satellite altimeter within the time span of 1993-2010 (NASA, 2013)	18
2.8	The mean acceleration of sea level in ranges uncertainty and its estimated contributions (Church <i>et al.</i> , 2001)	19
2.9	Thermal expansion of the ocean	20
2.10	Spatial patterns of ocean thermal expansion trend for 1955-2003 (a) and 1993-2003 (b) (Nerem <i>et al.</i> , 2006)	21
2.11	(Upper) GISS (red) and the Hadley Centre/	22

	Climatic Research Unit (blue) surface temperature of combined mean land and ocean globally.	
	(Lower) Sea-level change mostly from annually tidal data (red) and a 3-month data spacing altimetry data (blue) (Rahmstorf <i>et al.</i> , 2007)	
2.12	The reference mean sea level (AVISO, 2016)	23
2.13	ONI map in detecting El Niño (red line) and La Niña (blue line) (NOAA, 2017)	25
2.14	Map of Malaysian sea level trend over the Malaysian seas from multi-satellite altimeter and absolute coastal tide gauges (Din, 2014)	26
2.15	Holocene combined eustatic changes in sea level according to Fleming <i>et al.</i> (1998)	28
2.16	Holocene sea level for the east and west coast of Peninsular Malaysia (Tjia, 1996)	29
2.17	IPCC global averaged sea level change (IPCC, 2014)	30
2.18	Projected GMSL rise relative to 1986-2005 (IPCC, 2013)	33
2.19	Projected GMSL rate and its causes (IPCC, 2013)	34
2.20	Rising of global sea level at the end of the 21 st century	34
2.21	Schematic view of satellite altimeter measurement (modified from Watson, 2005; Din 2014)	39
3.1	Tide gauge measurement system schematic (modified from DSMM, 2012; Md Din, 2014)	50
3.2	Altimeter tracks of Jason-1(a), Jason-2 (b), CryoSat-2 (c) and SARAL (d)	55
3.3	The combination of 4 multi-mission satellite altimeter across Malaysia region Jason-1(red), Jason-2 (black), CryoSat-2 (green) and SARAL (blue)	55
3.4	The area for the crossover minimization (left) and	56

	the actual study area	
3.5	Altimeter ground tracks over the Malaysian seas for completing one cycle from Jason-2 and ENVISAT separate missions (two from the left) and Jason-2 + ENVISAT combination (right) (Din, 2014)	57
3.6	Overview of optimization of altimetry data processing in RADS for SLA	59
3.7	Overview of optimization of altimetry data processing in RADS for SST	59
3.8	Gaussian weighting function is used to limit the datasets to a certain data range that appropriate for the precise computation of sea level (Din, 2014)	62
3.9	Gridded points based on block sizes of 0.125° (a), 0.25° (b), 0.5° (c) and 1° (d) over Malaysian seas	63
3.10	The scenario of moving window of ± 9 days for optimizing altimetry data processing	64
3.11	The comparison between robust fit regression and ordinary least squares	66
4.1	Geographical distribution of tide gauge station employed in altimetry data processing	68
4.2	Comparison between SLA time series from tide records (blue) and altimetry (red) at four tide gauge stations around Malaysia, and their correlation determinations, based on the choice of sigma 1.5, block size 0.25° and moving average ± 18 days.	69
4.3	Comparison time series plots between tidal monthly time series (blue) and altimetry monthly time series (red) as well as the altimetry and tidal sea level correlation analysis of sigma 2.0 at Malaysian tide gauge stations.	70
4.4	Comparison time series plots between tidal	72

	monthly time series (blue) and altimetry monthly time series (red) as well as the altimetry and tidal sea level correlation analysis of block size 0.25° at Malaysian tide gauge stations.	
4.5	Comparison time series plots between tidal monthly time series (blue) and altimetry monthly time series (red) as well as the altimetry and tidal sea level correlation analysis of moving window ± 9.0 days at Malaysian tide gauge stations.	73
4.6	Evaluation plots between Geting tidal (blue) time series and altimetry (red) time series with its correlation respectively. Plot (a) indicates default Parameter 1, plot (b) represents a Parameter 2 while plot (c) represents Parameter 3	76
4.7	Evaluation plots between Kota Kinabalu tidal (blue) time series and altimetry (red) time series with its correlation respectively. Plot (a) indicates default Parameter 1, plot (b) represents Parameter 2 while plot (c) represents Parameter 3	76
5.1	The distribution of tide gauge stations in Malaysia	79
5.2	Monthly tidal sea level anomaly at West Coast of Peninsular Malaysia tide gauges stations	82
5.3	Monthly tidal sea level anomaly at East Coast of Peninsular Malaysia tide gauges stations	83
5.4	Monthly tidal sea level anomaly at Sarawak tide gauges stations	84
5.5	Monthly tidal sea level anomaly at Sabah tide gauges stations	85
5.6	Plot of the relative sea level trend of Geting and Cendering tide gauges monthly-average time series by using robust fit regression analysis	86
5.7	Relative sea level trend vector overspread along the Malaysian coastlines calculated over 23-year	89

	tidal data. Units are in mm yr^{-1}	
5.8	Relative sea level magnitude vector overspread along the Malaysian coastlines calculated over 23-year tidal data. Units are in centimetre	92
5.9	Absolute sea level anomalies variation during the South-west Monsoon (May to August) over the Malaysian seas. Unit is in centimetre	94
5.10	Absolute sea level anomalies variation during the North-east Monsoon (November to February) over the Malaysian seas. Unit is in centimetre	95
5.11	Absolute sea level anomalies variation during the First Inter-Monsoon (March to April) over the Malaysian seas. The time span is from 1993 to 2015. Unit is in centimetre	95
5.12	Absolute sea level anomalies variation during the Second Inter-Monsoon (September to October) over the Malaysian seas. The time span is from 1993 to 2015. Unit is in centimetre	96
5.13	Absolute sea level anomalies variation during the Very Strong 1997-1998 El Niño Phenomena over the Malaysian seas. Unit is in centimetre	97
5.14	Absolute sea level anomalies variation during the Moderate 2002-2003 El Niño Phenomena over the Malaysian seas. Unit is in centimetre	98
5.15	Absolute sea level anomalies variation during the Strong 2009-2010 El Niño Phenomena over the Malaysian seas. Unit is in centimetre	98
5.16	Absolute sea level anomalies variation during the Strong 1998-1999 La Niña Phenomena over the Malaysian seas. Unit is in centimetre	99
5.17	Absolute sea level anomalies variation during the Strong 1999-2000 La Niña Phenomena over the Malaysian seas. Unit is in centimetre	99

5.18	Absolute sea level anomalies variation during the Strong 2007-2008 La Niña Phenomena over the Malaysian seas. Unit is in centimetre	100
5.19	Absolute sea level anomalies variation during the Strong 2010-2011 La Niña Phenomena over the Malaysian seas. Unit is in centimetre	100
5.20	Plot of the absolute sea level trend of Cendering tide gauges monthly-average time series by using robust fit regression analysis	102
5.21	Map of absolute sea level trend (<i>upper</i>) and its standard error (<i>lower</i>) over the Malaysian Seas. Units are in mm yr ⁻¹	104
5.22	Satellite track of Cryosat-2 (yellow), Jason-1 (red), Jason-2 (black), and Saral (blue) while area concerned in the red circle in which around Malacca Straits (left) and Philippine archipelago (right)	105
5.23	Malacca Strait absolute sea level trend time series analysis using robust fit regression. The altimetry data is monthly averaged	106
5.24	South China Sea absolute sea level trend time series analysis using robust fit regression. The altimetry data is monthly averaged	106
5.25	Sulu Sea absolute sea level trend time series analysis using robust fit regression. The altimetry data is monthly averaged	107
5.26	Celebes Sea absolute sea level trend time series analysis using robust fit regression. The altimetry data is monthly averaged	108
5.27	Map of rising sea levels magnitude over the Malaysian seas from year 1993 to 2015	111
5.28	Map of sea surface temperature anomaly and sea level anomaly correlation coefficient	114

5.29	Time series of SLAs and SST anomalies (upper) and its correlation coefficient (lower) at latitude 5.25° N and longitude 99° E of Malacca Strait	116
5.30	Time series of SLAs and SST anomalies (upper) and its correlation coefficient (lower) at latitude 5° N and longitude 108° E of South China Sea	116
5.31	Time series of SLAs and SST anomalies (upper) and its correlation coefficient (lower) at latitude 9° N and longitude 121° E of Sulu Sea	117
5.32	Time series of SLAs and SST anomalies (upper) and its correlation coefficient (lower) at latitude 4° N and longitude 121° E of Celebes Sea	118
6.1	Time series of robust fitting linear trend projection of rising sea levels from year 1993 to 2100 over Malaysian seas	122
6.2	Map of the projection of rising sea levels over Malaysian seas from the year 2015 to 2020	124
6.3	Map of the projection of rising sea levels over Malaysian seas from the year 2015 to 2040	124
6.4	Map of the projection of rising sea levels over Malaysian seas from the year 2015 to 2060	125
6.5	Map of the projection of rising sea levels over Malaysian seas from the year 2015 to 2080	125
6.6	Map of the projection of rising sea levels over Malaysian seas from the year 2015 to 2100	126
6.7	Comparison of rising sea level projection with NAHRIM at Peninsular Malaysia	130
6.8	Comparison of rising sea level projection with NAHRIM at Sabah and Sarawak	131
6.9	The general process of MySLS development	133

LIST OF SYMBOLS

c	-	Speed of the radar pulse neglecting refraction (approximate 3×10^8 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

$\Delta\zeta_{\text{esl}}^{\text{m}}$	-	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 ₂ O	:	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

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	Default Processing strategy of RADS i.e. sigma 1.5, size of block of 0.25° and moving average of ±18 days	149
B	Sigma (σ) 1 of Data Filtering	150
C	Sigma (σ) 2.5 of Data Filtering	151
D	Block size 0.125° of Data Gridding	152
E	Block size 0.5° of Data Gridding	153
F	Block size 1° of Data Gridding	154
G	± 2.0 days of Moving Average	155
H	Data Verification: Satellite Altimeter	156
I	Plot of relative trend robust fit time series at tide gauge stations	162
J	Plot of Absolute trend robust fit time series at tide gauge stations	167
K	Malaysian Sea Level Rise System (MySLS) Interface	173
L	Research Activities	174
M	Research Publications	175

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 21st 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 $0^{\circ} \text{ N} \leq \text{Latitude} \leq 14^{\circ} \text{ N}$ and $95^{\circ} \text{ E} \leq \text{Longitude} \leq 126^{\circ} \text{ E}$, 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.

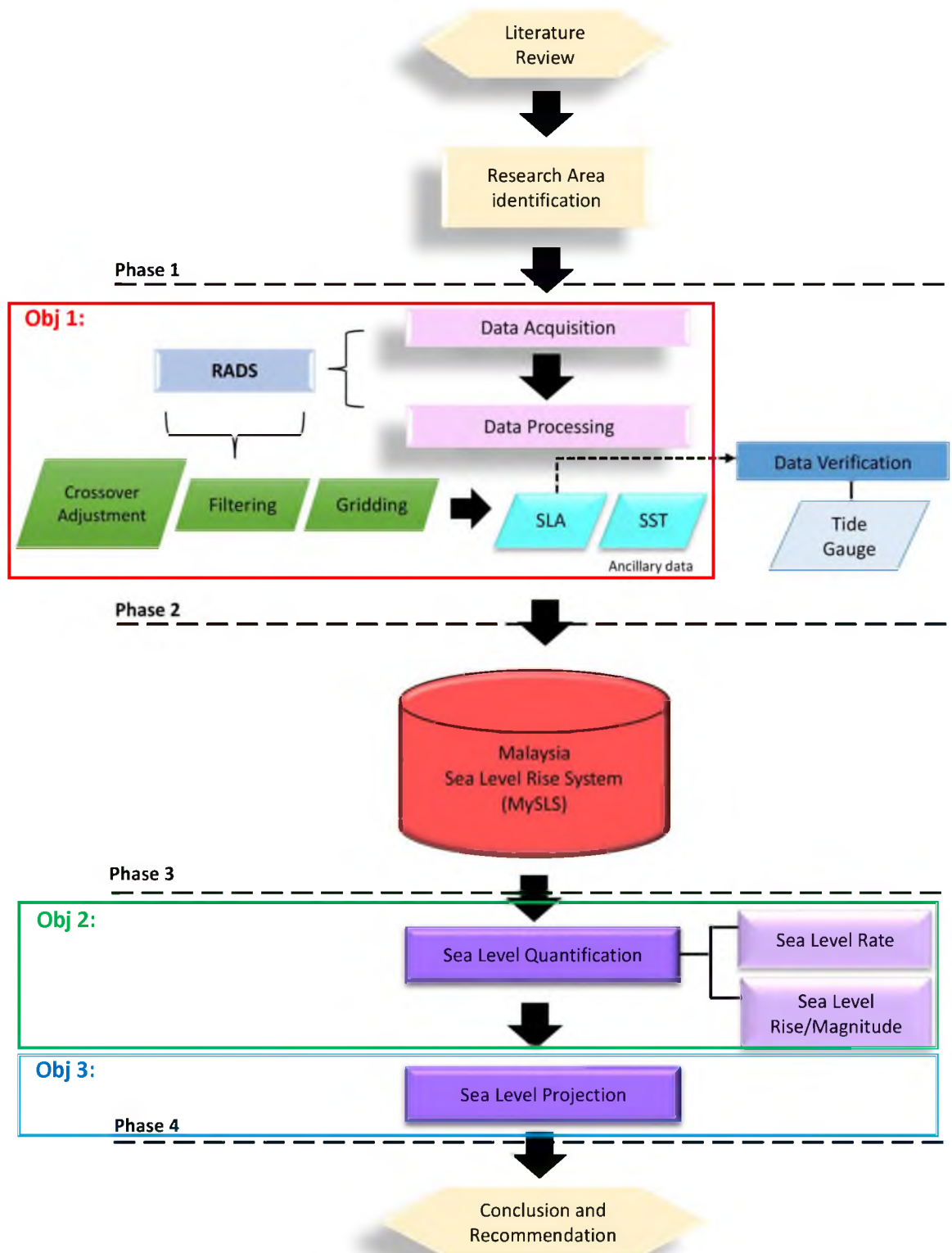


Figure 1.2 The general flowchart of this study

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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