

Heatwave Effects on Sea Level and Sea Surface Temperature Variations: A Multi-Decadal Satellite Altimetry Study in Malaysia

Muhammad Zulhaikal Abdul Razak^{a*}, Mohammad Hanif Hamden^{a*}, Ami Hassan Md Din^a, Fatin Nabihah Syahira Ridzuan^a, Amalina Izzati Abdul Hamid^a, Mohd Fadzil Mohd Akhir^b, Ku Nor Afiza Asnida Ku Mansor^b, Muhammad Syahrullah Fathulhuda^c, Muhammad Faiz Pa'suya^d, Nur Adilla Zulkifli^e & Mat Nizam Uti^f

^a*Geospatial Imaging and Information Research (GI2RG), Faculty of Built Environment and Surveying,
Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia*

^b*Institute of Oceanography and Environment, Universiti Malaysia Terengganu,
21030 Kuala Nerus, Terengganu, Malaysia*

^c*Geomatics Engineering, Faculty of Mineral and Energy Technology, Universitas Pembangunan Nasional Veteran Yogyakarta,
Jl. Padjajaran, Ring Road Utara No. 104, Ngropoh, Condongcatur, Depok, Sleman,
Daerah Istimewa Yogyakarta 55283, Indonesia*

^d*Ocean Mapping and Marine Geospatial Research Group (OMMAR), Faculty of Built Environment,
Universiti Teknologi MARA, Perlis Branch, 02600 Arau, Perlis, Malaysia*

^e*Faculty of Civil Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor*

^f*Department of Built Environment Studies and Technology, Faculty of Built Environment, Universiti Teknologi MARA Perak
Branch, Seri Iskandar Campus, 32610 Seri Iskandar, Perak, Malaysia*

*Corresponding author: muhammadzulhaikal@graduate.utm.my, mohammad.hanif@utm.my

Received 11 November 2025, Received in revised form 22 June 2026
 Accepted 22 July 2026, Available online 30 September 2026

ABSTRACT

Heatwaves events is one of the consequences from the global warming and climate change. In a warming ocean temperature, sea level variations are expected to increase in correlation with the temperature fluctuations. Coastal flooding and erosion also occur significantly due to the sea level fluctuation, giving impacts towards economic and marine ecosystem. This study aims to investigate the impacts of heatwaves towards sea level and sea surface temperature using multi-mission satellite altimetry. The satellite altimetry missions derived Sea Level Anomaly (SLA) and Sea Surface Temperature (SST) around the Malaysian Seas from 1993 until 2023. Celebes Sea have showed a mixed correlation coefficient from -0.4223 to 0.8960. Sulu Sea have a small to strong positive correlation with coefficient from 0.2548 to 0.8481. Malacca Straits showed weak to moderate correlation coefficient from -0.020 to 0.4365. South China Sea show a significant and strong negative correlation from -0.5540 to -0.8107. Seasonal variations by the Australian-Asian monsoon system and local current flow played a significant role for the correlation of SLA and SST. In conclusion, this study is important in creating awareness for potential future climate change events, particularly heatwaves that could have a significant impact on the country.

Keywords: Satellite altimetry; sea level anomaly; sea surface temperature; climate change; correlation

INTRODUCTION

According to the National Weather Service from the National Oceanic and Atmospheric Administration (NOAA), a heatwave is defined as an extended duration of exceptionally hot weather. In the marine context, a Marine Heatwave (MHW) is more specifically defined as a prolonged anomalously warm ocean event exceeding the 90th percentile threshold or at least five consecutive days (Hobday et al. 2016), which is now widely adopted as the standard definition in oceanographic studies. Heatwave events are one of the consequences of global warming and climate change.

Recent studies show that global warming is a primary driver of marine heatwaves, contributing to nearly half of the observed MHW events and significantly increasing their frequency, duration, and intensity. This trend raises serious concerns about the long-term impacts on marine ecosystems, fisheries, and coastal communities, as more frequent and prolonged heatwaves can disrupt biodiversity, alter species distribution, and exacerbate coral bleaching events. For example, Marcos et al. (2025) reported a threefold increase in MHW persistence and approximately a 1°C rise in intensity due to global warming. Similarly, Zhang et al. (2022) observed frequent occurrences of MHWs across most ocean regions during the last two decades. The increase in global air temperature is therefore expected to cause heatwave events to become more frequent and intense in the future (Awang & Hamid, 2013).

The affected area by heatwave is not only limited to land but also extends to ocean parameters due to the adjustment from increased global air temperature (Chen et al. 2022). Marine heatwaves are further influenced by complex air–sea interactions, including changes in surface heat fluxes, enhanced ocean stratification, and atmospheric blocking patterns (Paredes-Fortuny et al. 2025). These processes can modulate the intensity and duration of MHWs and have significant implications on regional climate variability. Therefore, elevated Sea Surface Temperature (SST) contributes to thermal expansion, which leads to long-term sea level rise (Awang & Hamid, 2013). As a result, SST becomes an important variable in local and global weather systems (Merchant et al. 2019).

Meanwhile, Sea Level Anomalies (SLA) represent the difference between instantaneous Sea Surface Height (SSH) and Mean Sea Surface (MSS) heights at a specific period and location. Seasonal sea level anomalies have become more common in recent years due to the increased frequency of extreme weather and climate events (J. Feng et al. 2018). Studies by Awang & Hamid (2013) and Affandi et al. (2022) indicate that sea level fluctuations are influenced by rising SST and ocean heat content. Malaysia

is characterized by a tropical climate as a result of its equatorial location. SST and SLA patterns fluctuate in accordance with the monsoon seasons (Isa et al. 2020) and both SST and SLA are important oceanographic parameters for understanding global climate change and its regional manifestations.

Sea level trends are influenced by multiple climate processes. As a result of climate change, the global mean SST has increased from decade to decade, and the frequency and intensity of climate variability have also intensified. Global Mean Sea Level (GMSL) has shown an increasing rate of 3.37 mm yr⁻¹ from 1993 to 2015 based on AVISO's Sea Level Research Team (AVISO, 2016; Hamid, 2018). During the warm phase of the El Niño–Southern Oscillation (ENSO), increasing SST is frequently accompanied by higher-than-average annual SLA in the eastern tropical Pacific (Liu et al. 2020). Projected warming scenarios further indicate amplification of marine heatwaves in several ocean basins (Athanasopoulos et al. 2024), suggesting that SST–SLA interactions may intensify under future climate conditions.

In the Malaysian context, SST variations in the South China Sea significantly impact extreme weather events and regional climate variability over various timescales (Liu et al. 2020). Past El Niño and La Niña events in Malaysia provide a foundation for understanding ocean dynamics and associated impacts (Tangang et al. 2019). Malaysia is influenced by the Australian–Asian monsoon system (Tangang et al. 2019). From November to March, the northeast monsoon dominates the Southern South China Sea region, resulting in intense northeasterly wind stress, high rainfall, and relatively lower SST values along the east coast of Peninsular Malaysia. Meanwhile, from April to August, the southwest monsoon dominates, bringing drier conditions and warmer SST values (Akhir, 2014). These monsoonal wind reversals alter ocean circulation and contribute to seasonal SLA variability (How et al. 2020).

Coastal flooding and erosion occur significantly due to sea level fluctuations, affecting economic activities and marine ecosystems. For example, coastal flooding occurred in Singapore in 1999 was attributed to the combination of wind direction and sea level fluctuation during the Northeast monsoon (Tkalic et al. 2013). In a warming ocean, sea level variations are expected to increase in correlation with temperature fluctuations (Widlansky et al. 2020). Sea level rise rates in Malaysia vary from 3.27 ± 0.12 mm yr⁻¹ off the eastern coast to 4.95 ± 0.15 mm yr⁻¹ off the western coast (Hamid et al. 2018).

The conventional method of measuring long-term sea level change relies on tide gauge stations attached to the Earth's crust. However, these measurements are affected by geophysical effects such as local land subsidence and

uplift (Hannah, 2010; Liu et al, 2025), making them observations of relative sea level. In addition, tide gauge and in-situ SST measurements are point-based. Although accurate, they are costly and offer limited spatial resolution (Feng et al. 2023). Therefore, large-scale datasets with reliable spatial-temporal resolution are required to support climate mitigation and coastal protection planning.

Satellite altimetry has continuously observed the ocean since 1991 by TOPEX-class and ERS-class missions. These missions provide highly precise sea surface height measurements due to accurate orbit determination (Din, 2012). By combining multi-mission datasets and applying cross-over adjustment techniques, spatial-temporal resolution can be enhanced while minimizing orbital errors and inconsistencies (Din et al. 2015; Bosch et al. 2014).

Despite increasing global research on marine heatwaves, limited studies have comprehensively investigated the linkage between marine heatwaves, SST, and SLA in Malaysian waters using multi-mission satellite altimetry. Most regional studies remain descriptive and focus on either SST or sea level independently. A clearer

understanding of the SST–SLA response during marine heatwave conditions in monsoon-influenced tropical seas remains insufficiently explored.

The main goal of this research is therefore to investigate the impacts of marine heatwaves on sea level and sea surface temperature using multi-mission satellite altimetry data. Understanding these interactions is essential for improving regional climate assessment, coastal hazard mitigation, and adaptation strategies under ongoing climate change.

DATA AND METHODS

RESEARCH AREA IDENTIFICATION

The research area encompassed the Malaysian Seas, namely the Straits of Malacca, Southern of South China Sea, Sulu Sea & Celebes Sea. The spatial extend of the study ranged 1° N to 14° N latitude and 96° E to 124° E longitude.



FIGURE 1. Study area over Malaysian sea.

DATA ACQUISITION

This research focused on 30 years' period of data from 1993 – 2023. The satellite altimetry data were extracted from Radar Altimeter Database System (RADS). RADS was installed in Universiti Teknologi Malaysia (UTM) since 2005 as part of SEAMERGES project (Din, 2012). The multi-mission satellites altimetry data were used to obtain SST and SLA. However, the data extraction for SST only available until 31st December 2022 in RADS server. The in-situ data for SST and SLA were acquired by UMT and DSMM respectively.

Satellite Altimeter Data: The satellite-derived SLA and SST were extracted through RADS server by using PuTTY software. PuTTY extracts the SST and SLA data from RADS and the data is converted to ASCII format. The multi-missions satellite altimetry used in this research study are TOPEX/Poseidon, Jason-1, Jason-2, Jason-3, Sentinel-6A, ERS-1, ERS- 2, Cryosat-2, SARAL Altika and Sentinel-3A. Table 1 shows selected satellite altimetry mission.

In-situ Data: The DSMM Tide Gauge Stations were used to obtain SLA from tidal data for validation. It comprises of 9 stations located along Malaysia's coast. The

data were acquired from the Permanent Service for Mean Sea Level (PSMSL), National Oceanography Centre, United Kingdom. Monthly tidal data for each station acquired from PSMSL website (<https://psmsl.org/>). The

monthly tide gauge data were used to verify the corresponding monthly data obtained from satellite altimeter. Table 2 shows the coordinate of 9 in-situ data from DSMM Tide Gauge Stations.

TABLE 1. Selected satellite altimetry mission.

Altimeter	Sponsor	Phase	Period	Cycle
ERS-1	ESA	C	28/11/1992-20/12/1993	090-101
		D	25/12/1993-10/04/1994	103-138
		E	11/04/1994-27/09/1994	139-140
		F	28/09/1994-21/03/1995	141-143
		G	24/03/1995-02/06/1996	144-156
TOPEX	NASA/CNES	A	25/09/1992-10/08/2002	001-364
		N	11/08/2002-19/09/2002	365-368
		B	20/09/2022-08/10/2005	369-481
ERS-2	ESA	A	03/05/1995-28/04/2011	000-167
GFO-1	US Navy	A	07/01/2000-25/09/2007	037-202
Jason-1	NASA/CNES	A	15/01/2002-26/01/2009	001-260
		B	11/02/2009-03/03/2012	262-374
		C	08/05/2012-20/06/2013	382-425
Envisat	ESA	B	25/05/2002-19/10/2010	006-094
		C	27/10/2010-08/04/2012	095-113
Jason-2	NASA/CNES	A	04/07/2008-02/10/2016	000-303
		B	13/10/2016-05/12/2016	305-310
			11/07/2017-17/07/2018	332-355
			25/07/2018-01/10/2019	356-383
Cryosat-2	ESA	A	16/07/2010-18/11/2021	004-150
SARAL	ESA	A	14/03/2013-04/07/2016	001-035
		B	04/07/2016-22/08/2022	036-099
Jason-3	NASA/CNES	A	12/02/2016-07/04/2022	000-227
Sentinel-3A	ESA	A	01/03/2016-07/11/2023	001-105
Sentinel-6A	ESA	A	17/12/2020-19/01/2024	004-117

TABLE 2. Coordinates of 9 in-situ data from DSMM Tide Gauge Stations.

Stations	Latitude (°N)	Longitude (°E)
TANJUNG GELANG	3.975000	103.430000
CENDERING	5.265000	103.186667
LUMUT	4.240000	100.613333
PULAU TIOMAN	2.807222	104.140000
TANJUNG SEDILI	1.931667	104.115000
GETING	6.226389	102.106667
KOTA KINABALU	5.983333	116.066667
BINTULU	3.262222	113.063889
LABUAN 2	5.272778	115.250000

Meanwhile, two datasets for in-situ data for SST verification were acquired from the Institute of Oceanography and Environment (INOS), University Malaysia Terengganu (UMT). The first dataset spanned from October 2019 to January 2021. Figure 2 depicts the first dataset's position in the South China Sea near Terengganu, Malaysia. The dataset's coordinates are 4.872°

N and 104.830° E. The second dataset was also located in the southern part of the South China Sea, on Tioman Island, Pahang. It was collected from 20 to 21 August 2014. There are around 14 SST verification stations located throughout the island. The coordinates of all stations of the second dataset are shown in Table 3.

DATA PROCESSING

The RADS server allows users to define geophysical corrections and models to be applied during data extraction. In this study, the extracted data adopted the default correction and model configurations recommended for each

satellite altimetry mission, ensuring consistency across multi-mission datasets. Each correction or model contributes to improving the accuracy of SLA derived from multi-mission satellite altimetry during data processing. Table 4 summarises the corrections and models applied to each satellite mission during the RADS extraction process.

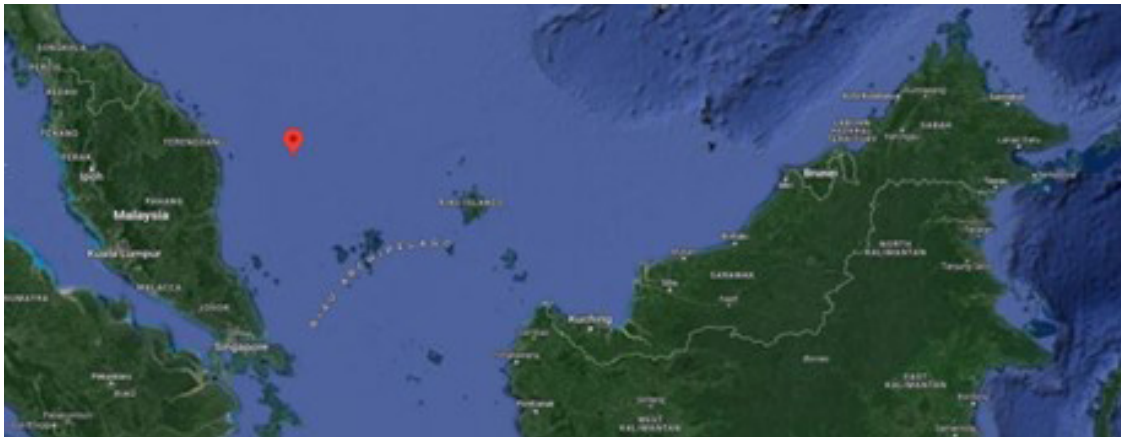


FIGURE 2. Location of the in-situ station for first dataset.

TABLE 3. Coordinates of 9 in-situ data from DSMM Tide Gauge Stations.

Stations	Latitude (°N)	Longitude (°E)
77	3.05812	103.48817
78	3.06182	103.62312
79	3.06553	103.75807
80	3.07047	103.938
81	3.07541	104.11794
82	3.08036	104.29787
83	3.08530	104.47780
84	3.09024	104.65773
85	2.86526	104.66069
86	2.64045	104.66365
87	2.63544	104.48372
88	2.63043	104.30379
89	2.62542	104.12386
90	2.62166	103.98891

In order to obtain reliable and consistent SLA estimates from multi-mission satellite altimetry, several processing steps were applied within the RADS environment. The process of modifying the parameter during RADS processing, including data filtering and gridding as well as crossover adjustment between ERS and TOPEX class (Din et al. 2014). Crossover adjustment is a process used to correct the orbital positions of ERS-class satellites to match the TOPEX satellite orbit at their nearest crossover points. The adjustment is referenced to the TOPEX class because it has higher accuracy compared to the ERS class (Hamid,

2018; Hamden et al. 2021). The data processing was performed using a 1.5-sigma outlier filtering threshold, a moving average window of ± 18 days, and a spatial gridding resolution of 0.25° , following recommendations from previous regional altimetry studies. Figure 3 and Figure 4 show an overview optimization of data processing for SLA and SST.

Data Validation: The analysis focused on the pattern, correlation, and Root Mean Square Error (RMSE) between the satellite-derived and in-situ datasets. The coefficient of determination (R^2) evaluates the extent to which a

statistical model explains the variability of the observed data, while RMSE measures the standard deviation of the residuals (Hamid, 2018). RMSE provides a more informative assessment of deviation by quantifying the differences between satellite-derived and in-situ

measurements. In contrast, R^2 indicates the strength of the relationship between the two datasets. However, some in-situ data from the DSMM tide gauge and CTD measurements were unavailable for certain periods.

TABLE 4. Correction/model applied for each satellite altimetry during RADS extraction.

Correction/Model	Editing (m)		Description
	Lower	Upper	
Dry Troposphere	-2.40	2.10	All satellites: Atmosphere pressure grid (ECMWF)
Wet Troposphere	-0.60	0.00	All satellites: Radiometric measurement
Ionosphere	-0.40	0.04	All satellites: Smoothed dual- frequency ERS: NIC09 GFO/Saral/Envisat: JPL GIM
Dynamic Atmosphere	-1.00	1.00	All satellites: MOG2D
Ocean Tide	-5.00	5.00	All satellites: FES2014b
Load Tide	-0.50	0.50	All satellites: FES2014a
Solid Earth Tide	-1.00	1.00	Applied (Elastic response to tidal potential)
Pole Tide	-0.10	0.10	Applied (Tide produced by Polar Wobble)
Sea State Bias	-1.00	1.00	All satellites: CLS non- parametric ERS: BM3 parametric
Reference	-1.00	1.00	DTU15 mean sea surface
Engineering Flag	-	-	Applied
Reference Surface			TOPEX Jason-1 Jason-2 Jason-3 Sentinel-6A

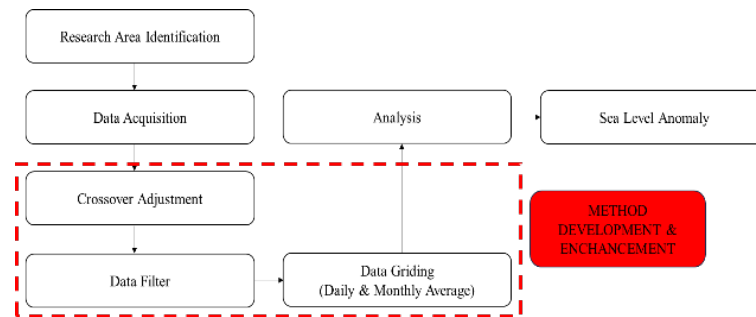


FIGURE 3. Overview of optimization data processing for SLA.

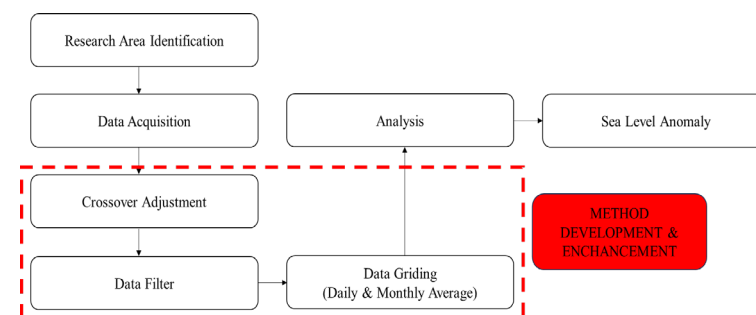


FIGURE 4. Overview of optimization data processing for SST

Data Analysis: Pearson's correlation coefficient (R) was applied to quantify the statistical relationship between SLA and SST using temporally matched datasets to ensure consistency in the analysis period. A correlation coefficient approaching +1 indicates a strong positive relationship between SLA and SST, whereas a value approaching -1 indicates a strong negative relationship (Oktaviani et al. 2021). Once the correlation coefficient was obtained, both datasets were presented in time-series graphs to visualise

and better understand their relationship. The correlation analysis was conducted across four sea regions: the Straits of Malacca, the South China Sea, the Celebes Sea, and the Sulu Sea. Table 5 provides a description of the correlation coefficient values between the two variables. Figure 5 illustrates the locations of the correlation analysis between SLA and SST during heatwave events, and their corresponding coordinates (Table 6).

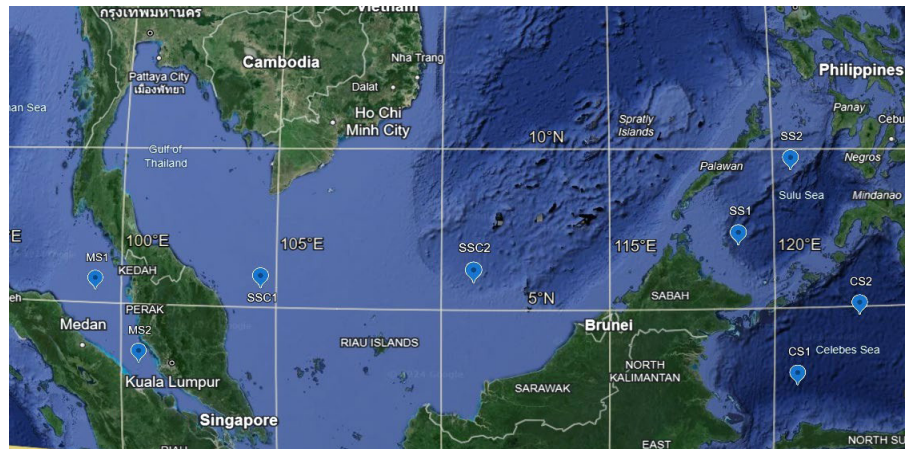


FIGURE 5. Coordinates of correlation study between SLA and SST during heatwave events.

TABLE 5. Description of correlation coefficient value between two variables

No	Correlation Coefficient	Description
1	$0 < r < 0.2$	Weak or no correlation
2	$0.2 < r < 0.4$	Small relationship
3	$0.4 < r < 0.7$	Moderate relationship
4	$0.7 < r < 0.9$	Close relationship
5	$0.9 < r < 1$	Very high correlation

TABLE 6. Description of correlation coefficient value between two variables

Point	Latitude (°N)	Longitude (°E)
MS1	5.25	99.25
MS2	3.00	100.25
SCS1	5.50	104.50
SCS2	5.75	111.00
CS1	2.50	120.75
CS2	4.75	122.75
SS1	7.00	119.00
SS2	9.25	120.50

DERIVATION OF SLA AND SST FROM MULTI-MISSION SATELLITE ALTIMETRY DATA:

The raw data extracted from the RADS server were processed through crossover adjustment, data filtering, gridding, and visualisation for the 30-year period from

1993 to 2023. The analysis of satellite-derived SLA and SST was conducted based on seasonal variations and annual mean changes. The factors that affected the result from both SLA and SST were discussed to obtain further understanding on oceanic process.

SEA LEVEL ANOMALY

Figure 6 shows the annual mean SLA from 1993 to 2023 over the Malaysian Seas. The overall SLA range varies from -0.1 to 0.3 m. The annual mean SLA in 2022 recorded the highest value, with almost all areas experiencing sea level rise. In contrast, 1997 exhibited the lowest SLA during the study period. Across the Straits of Malacca, the South China Sea, the Celebes Sea, and the Sulu Sea, sea level shows a steady increasing trend over time. This positive trend indicates that the Malaysian Seas have experienced sea level rise (SLR) from 1993 to 2023. Hamid et al. (2018) reported a mean SLR of approximately 4.22 ± 0.12 mm/year in the Malaysian Seas for the period 1993–2015. One of the primary factors contributing to SLR is thermal expansion of the oceans (Widlansky et al. 2020).

Figure 7 shows the seasonal climatology of SLA derived from 30 years of data (1993–2023). The Gulf of

Thailand and the east coast region exhibit high positive SLA during the Northeast Monsoon and lower (negative) SLA during the Southwest Monsoon. These variations are influenced by monsoonal wind patterns (Luu et al. 2015). During the Northeast Monsoon, winds generally blow from the northeast to the southwest (Rizal et al. 2012; Isa et al. 2020), pushing water toward the basin and resulting in positive sea level anomalies along the Gulf of Thailand and the east coast of Peninsular Malaysia. In contrast, during the Southwest Monsoon, sea level decreases as monsoon winds draw water from the Sunda Shelf toward the northwestern South China Sea (Tklich et al. 2013; Luu et al. 2015). However, the Straits of Malacca display a different pattern compared to the South China Sea, as sea level variations in this region are more strongly influenced by the larger oceanic processes of the Indian Ocean.

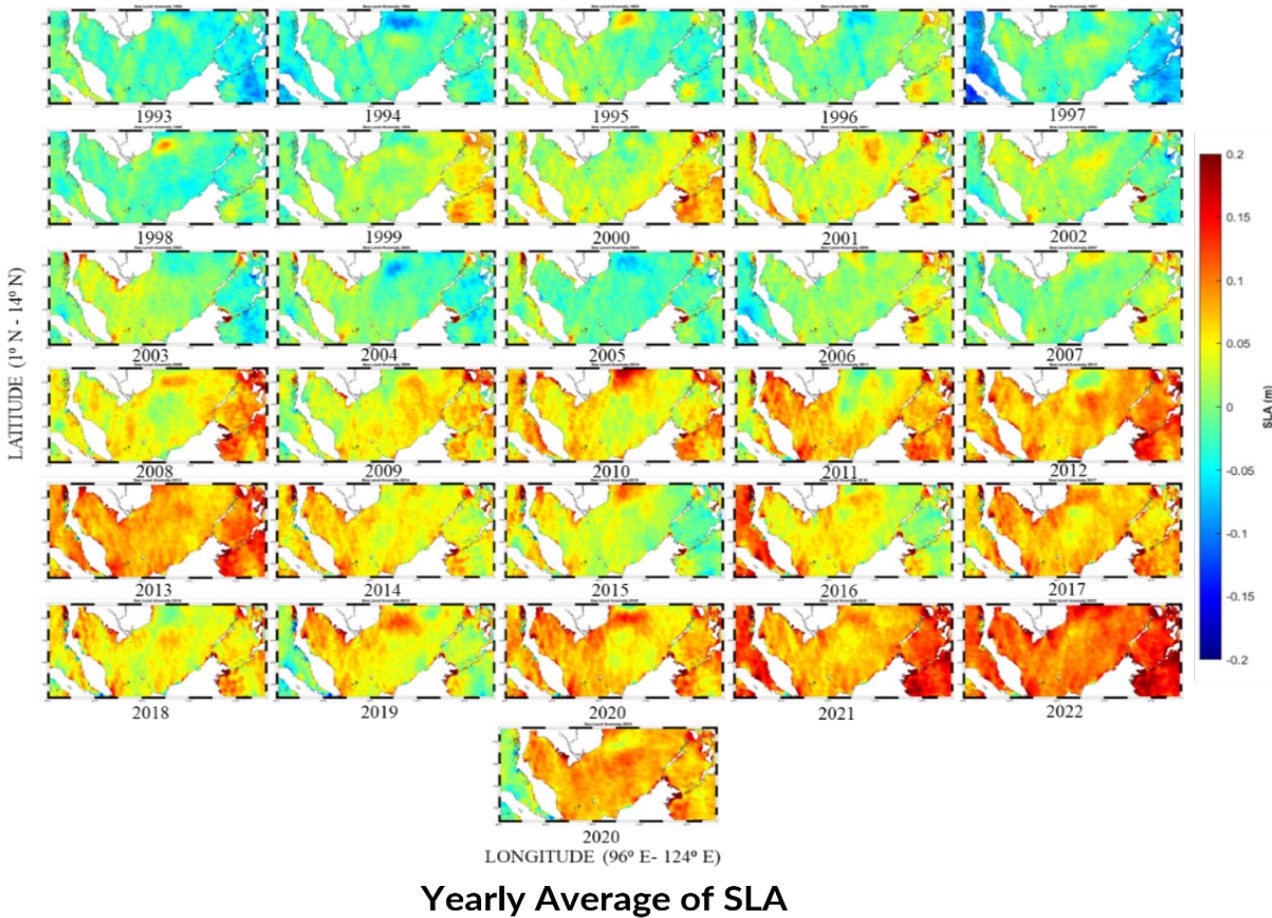


FIGURE 6. Yearly Average of SLA.

SEA SURFACE TEMPERATURE

Figure 8 shows the annual mean of SST from 1993 to 2022 over Malaysian Seas. The data were available only until

2022. The overall SST range within the study area varies between 26 and 31°C . In general, SST over the Malaysian Seas shows a steady increasing trend over time. The highest annual mean SST values were recorded in 1998, 2010,

2016, and 2022. These years coincided with El Niño–Southern Oscillation (ENSO) events. This finding is consistent with Tangang et al. (2019), who reported that Malaysia experienced El Niño events during 1997/1998, 2009/2010, and 2015/2016. Rising SST can significantly affect Malaysia’s economic sectors by enhancing evaporation over seawater and reducing precipitation (Supatra & Norazhar, 2019). Tangang et al. (2019) also demonstrated the relationship between ENSO phenomena and SLA variations over the Malaysian Seas. Figure 9 shows the seasonal climatology of SST based on data from

1993 to 2022. During the Northeast Monsoon, SST over the Malaysian Seas records lower temperatures ranging from 26 to 29°C compared to other seasons, whereas during the Southwest Monsoon, SST increases to approximately 29.5 to 31°C. SST generally becomes warmer, particularly in the Gulf of Thailand and the Straits of Malacca (30–31°C). The Second Inter-Monsoon period (October–November) shows a decrease in SST, with temperatures ranging between 28 and 29.5°C. During the Northeast Monsoon, rainfall reaches its maximum, particularly over Sabah, Sarawak, and the east coast of Peninsular Malaysia.

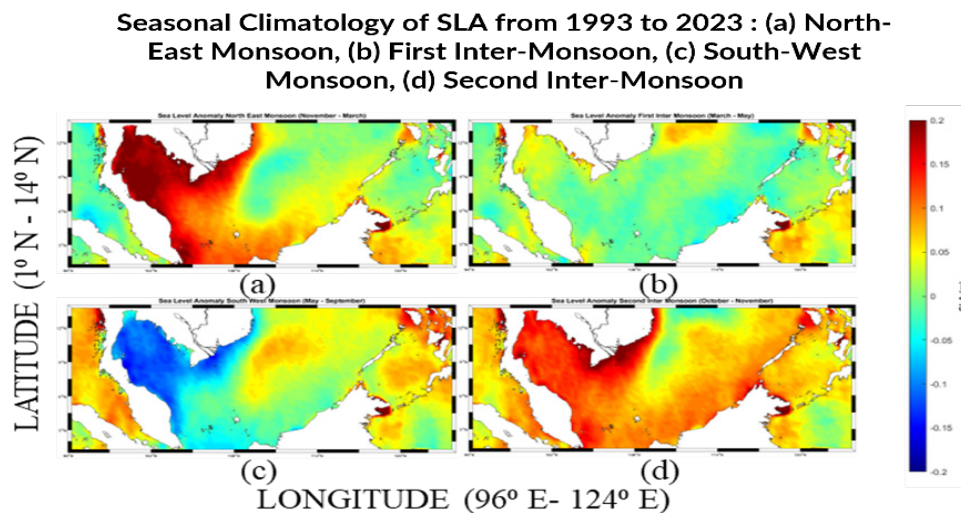


FIGURE 7. Seasonal Climatology of SLA from 1993 to 2023 (a) North East Monsoon, (b) First Inter-Monsoon, (c) South West Monsoon, (d) Second Inter-Monsoon.

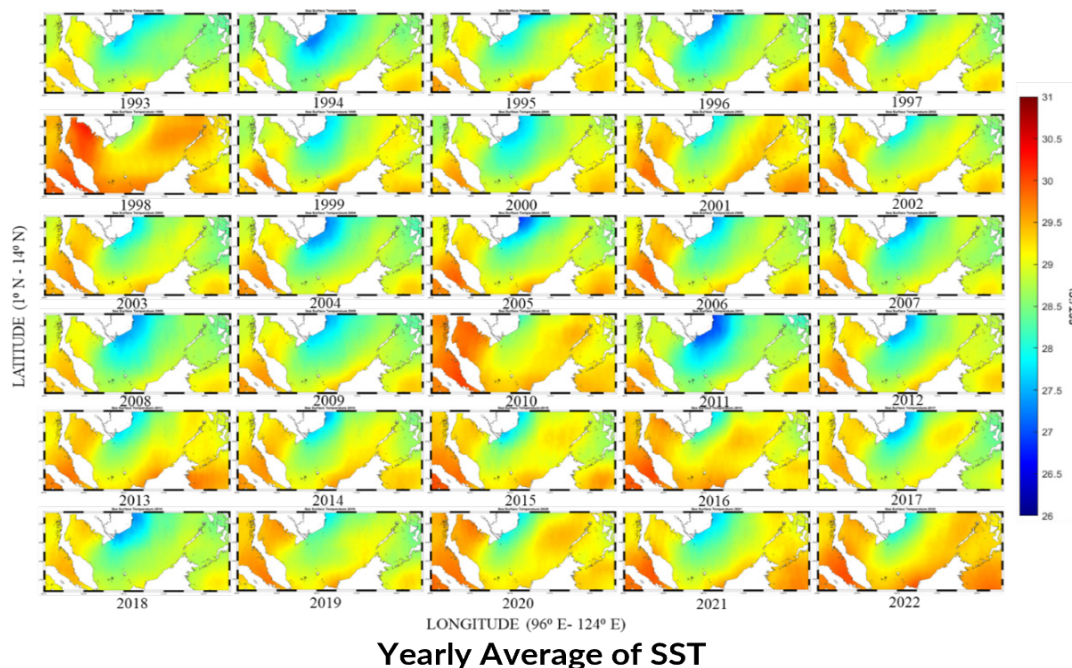


FIGURE 8. Yearly Average of SST.

This pattern is attributed to the Borneo vortex and cold surges, which converge moisture-laden air and result in high precipitation over the South China Sea (Chang et al. 2005; Tangang et al. 2019). This explains the relatively cooler SST (26–29.5°C) observed during the Northeast Monsoon. During the First Inter-Monsoon period, the significant temperature changes in the Straits of Malacca

and the Gulf of Thailand are influenced by weaker surface winds, reduced cloud cover over the ocean, and increased sensible and latent heat fluxes (Isa et al. 2020).

SST during the Southwest Monsoon is generally warmer (29.5–30.5°C), primarily due to the inflow of warm tropical waters from Indonesia, which are transported and distributed throughout the South China Sea (Akhir, 2012).

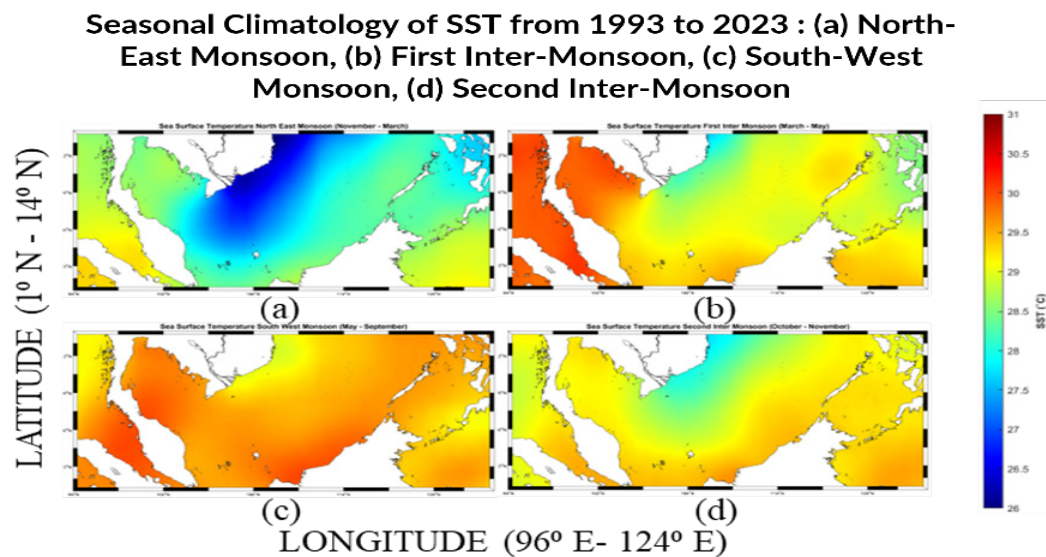


FIGURE 9. Seasonal Climatology of SST from 1993 to 2022 (a) North East Monsoon, (b) First Inter-Monsoon, (c) South West Monsoon, (d) Second Inter-Monsoon

VALIDATION OF MULTI-MISSION SATELLITE ALTIMETRY DERIVED SLA AND SST

Sea Level Anomaly: Satellite altimetry measures the sea surface relative to the satellite orbit at repeat cycles of 9 or 35 days, resulting in approximately three observations per month or one observation per month, depending on the mission. In contrast, tide-gauge stations provide continuous

measurements at fixed coastal locations. Therefore, it is essential to ensure consistency between satellite-derived monthly SLA and tide-gauge monthly SLA (Trisirisatayawong et al. 2011; Hamid 2018). Any differences exceeding 10 cm between satellite-derived and in-situ SLA were considered outliers and subsequently removed.

TABLE 7. RMSE and Correlation of satellite-derived SLA with in-situ

Stations	RMSE (cm)	R ²
TANJUNG GELANG	4.75	0.9162
CENDERING	4.78	0.9015
LUMUT	5.86	0.8588
PULAU TIOMAN	4.99	0.9168
TANJUNG SEDILI	6.69	0.9085
GETING	5.47	0.9374
KOTA KINABALU	4.38	0.8489
BINTULU	4.35	0.7408
LABUAN 2	3.76	0.8281

The RMSE between the tide-gauge stations and satellite altimetry ranged from 3.76 cm to 6.69 cm. RMSE represents the average deviation between satellite-derived SLA and tide-gauge SLA. The relatively low RMSE values obtained in this study indicate the high accuracy of satellite-derived SLA in estimating sea-level variations. These results also demonstrate the reliability of satellite altimetry as an alternative method for sea-level estimation, particularly for open-ocean applications.

Figure 10 show a correlation of satellite-derived SLA with DSMM tide gauge over Malaysian seas. In this study, a correlation coefficient above 0.70 was considered indicative of a strong correlation. Overall, the results show strong correlations between the two datasets, ranging from 0.80 to 0.93. Bintulu recorded the lowest correlation value (0.74) compared to the other stations; however, this value is still classified as a strong correlation. The high positive correlations and overall consistency indicate a strong relationship between the two datasets (Hamid, 2018).

Sea Surface Temperature: Based on the data validation presented in Table 8, the difference between monthly in-situ SST (Dataset 1) and satellite-derived SST from October 2019 to January 2021 ranged from 0.001 to 0.800°C, which is less than 1°C. The RMSE was 0.294°C, indicating that the average deviation between the in-situ measurements (Seabird sensor) and the satellite-derived SST was approximately 0.300°C. The correlation coefficient for Dataset 1 was 0.9677, demonstrating a strong positive correlation and high consistency between the two datasets.

Similarly, Table 9 presents the validation results for Dataset 2, which consists of daily in-situ SST data collected from 20 to 21 August 2014 around Tioman Island, Pahang. The differences between daily in-situ and satellite-derived SST ranged from 0.050 to 0.440°C, also remaining below 1°C. The RMSE was 0.245°C, which is lower than that obtained for Dataset 1. Overall, these results demonstrate good agreement between satellite-derived SST and in-situ observations, indicating reliable satellite performance.

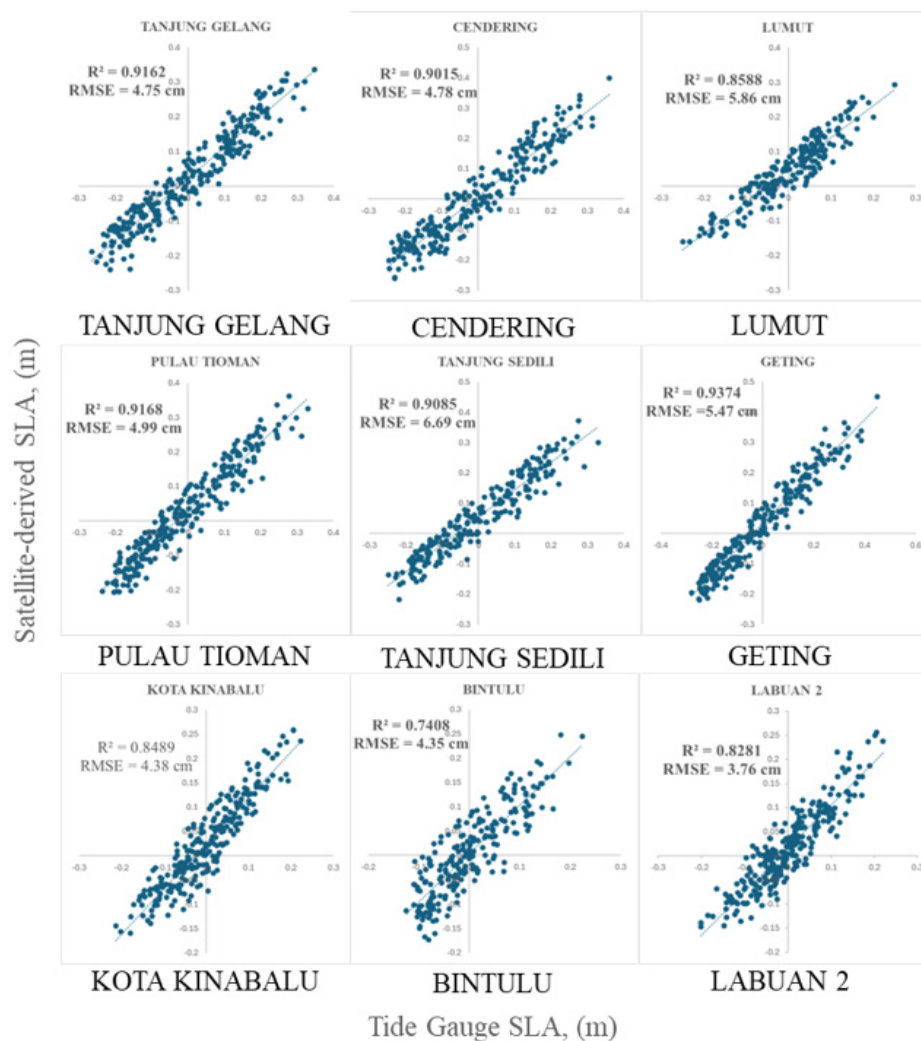


FIGURE 10. Correlation of satellite-derived SLA with tide gauge.

TABLE 8. Verification of satellite-derived SST with in-situ dataset 1.

Years	Months	SST (°C)		Difference (°C)
		In-situ	Sat-derived	
2019	10	30.361	29.560	-0.801
	11	29.452	29.172	-0.280
	12	27.433	27.224	-0.209
2020	1	26.844	27.071	0.227
	2	27.238	27.123	-0.115
	3	28.384	28.095	-0.289
	4	29.686	29.871	0.185
	5	30.623	30.431	-0.192
	6	30.139	30.200	0.061
	7	30.009	29.651	-0.358
	8	29.763	29.762	-0.001
	9	29.736	29.621	-0.115
	10	29.445	29.158	-0.287
	11	28.919	28.516	-0.403
	12	27.696	27.634	-0.062
2021	1	26.282	26.319	0.037
			RMSE	0.294

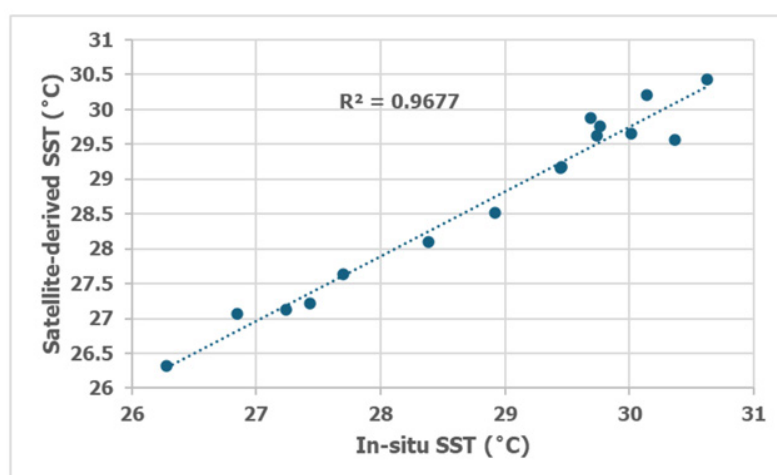


FIGURE 11. Correlation of satellite-derived SST with in-situ dataset 1.

TABLE 9. Verification of satellite-derived SST with in-situ dataset 2.

Stations	SST (°C)		Difference (°C)
	In-situ	Sat-derived	
77	29.422	29.184	-0.238
78	29.072	29.122	0.050
79	28.946	29.088	0.142
80	28.910	29.111	0.201
81	29.208	29.242	0.034
82	29.078	29.102	0.024
83	28.789	29.137	0.348
84	28.767	29.207	0.440

continue...

...cont.

85	28.906	29.238	0.332
86	29.116	29.258	0.142
87	28.914	29.173	0.259
88	29.450	29.362	-0.088
89	29.681	29.276	-0.405
90	28.933	29.127	0.194
		RMSE	0.245

CORRELATION BETWEEN SLA AND SST DURING THE HEATWAVE EVENTS

Malacca Straits: Figure 12 and Figure 13 show a correlation of satellite-derived SLA and SST during heatwave events (a) 1998, (b) 2010, (c) 2016, (d) 2022 at MS1 and MS2 respectively. Both figures indicate weak to no correlation between SLA and SST overall. However, Figure 12 shows a moderate positive correlation between SLA and SST during heatwave events in 1998 and 2022, with correlation coefficients of 0.4162 and 0.4365, respectively. In contrast, during 2010 and 2016, the correlation was weak or negligible, with values of -0.020 and 0.1956 , respectively. Figure 13 indicates weak or

negligible correlations between SLA and SST during heatwave events across all years, with correlation coefficients of 0.1199, -0.3621 , -0.0507 , and -0.2192 , respectively. The correlation between SLA and SST gradually decreases from the upper section (MS1 to MS2) of the Straits of Malacca toward the Singapore Strait, as the northern part is more strongly influenced by the Indian Ocean Dipole (IOD) (Luu et al. 2015). Overall, even during heatwave events, no significant correlation between SLA and SST is observed. These findings are consistent with Wisna et al. (2023), who reported that sea-level fluctuations in the Straits of Malacca are not solely dependent on heatwave events, but are more strongly influenced by regional current dynamics.

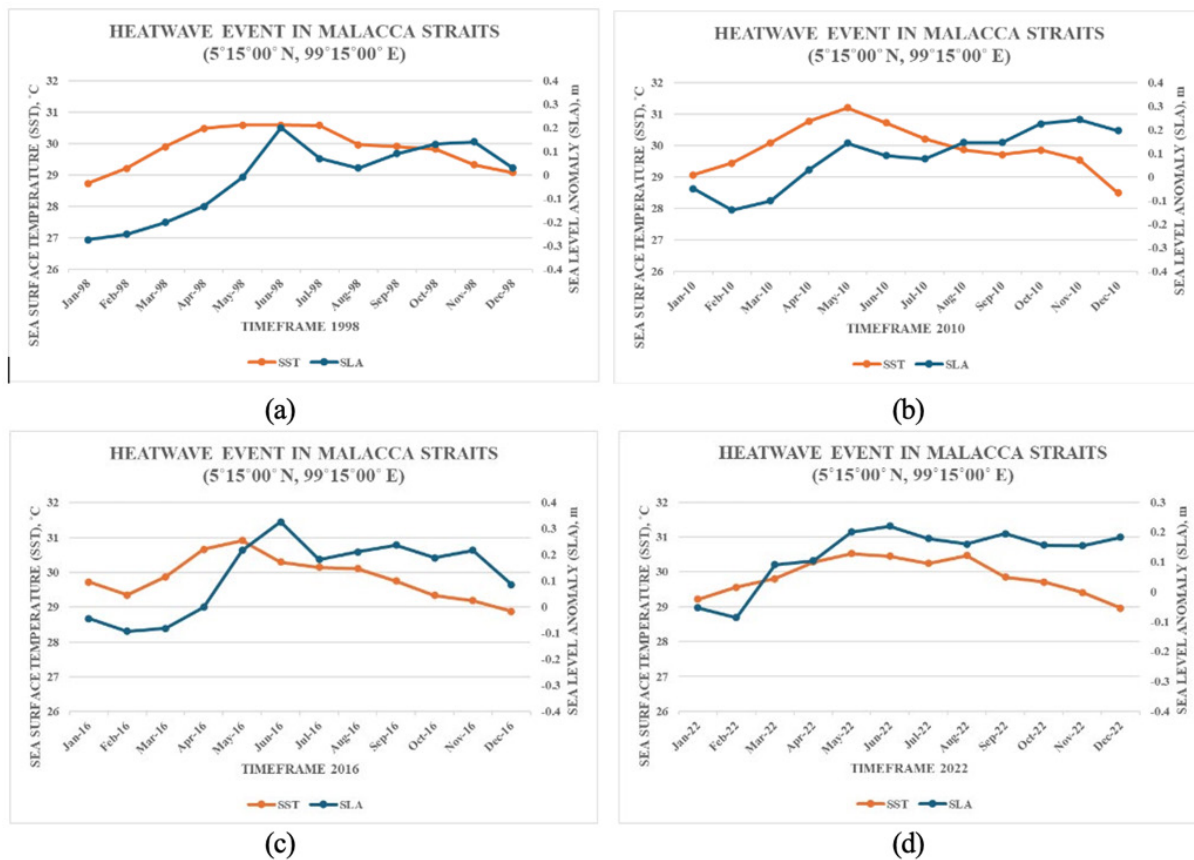


FIGURE 12. Correlation of satellite-derived SLA and SST during heatwave events(a) 1998, (b) 2010, (c) 2016, (d) 2022 at MS1.

South China Sea: Figure 14 and Figure 15 shows a correlation of satellite-derived SLA and SST during heatwave events (a) 1998, (b) 2010, (c) 2016, (d) 2022 at SCS1 and SCS2 respectively. Both figures show a strong negative correlation between SLA and SST, indicating that when temperature increases, sea level decreases. The correlation coefficients during the heatwave years at SCS1 were -0.7733 , -0.7245 , -0.7100 , and -0.8107 , respectively. Meanwhile, the corresponding correlation coefficients at SCS2 were -0.5412 , -0.4485 , -0.7153 , and -0.5540 , respectively.

In both figures, the heatwave years of 1998, 2010, 2016, and 2022 recorded peak temperatures of up to

30.5°C , particularly during May and June. During these months, sea level reached its lowest values, dropping to approximately -0.1 m. The highest temperatures generally occurred between May and July, corresponding to the First Inter-Monsoon period. During this period, the significant temperature changes in the Gulf of Thailand are attributed to weaker surface winds, reduced cloud cover over the ocean, and increased sensible and latent heat fluxes (Isa et al. 2020). The correlation at SCS1 is slightly stronger than at SCS2, likely because SCS1 is located closer to the Gulf of Thailand.

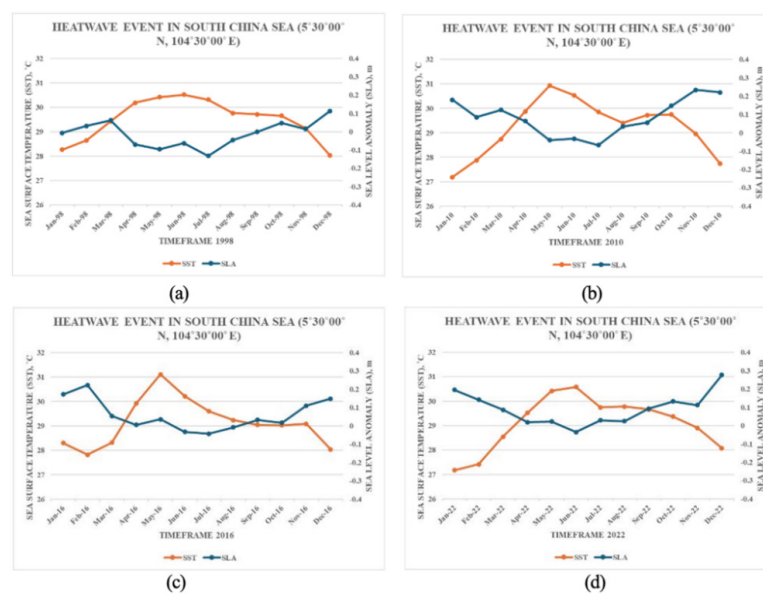


FIGURE 14. Correlation of satellite-derived SLA and SST during heatwave events (a) 1998, (b) 2010, (c) 2016, (d) 2022 at SCS1.

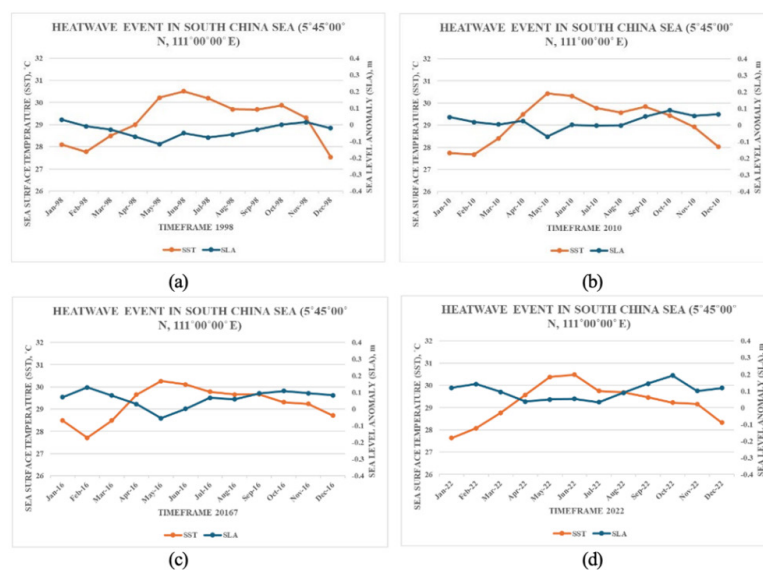


FIGURE 15. Correlation of satellite-derived SLA and SST during heatwave events (a) 1998, (b) 2010, (c) 2016, (d) 2022 at SCS2.

Celebes Sea: Figure 16 and Figure 17 shows a correlation of satellite-derived SLA and SST during heatwave events (a) 1998, (b) 2010, (c) 2016, (d) 2022 at CS1 and CS2 respectively. In both figures, the 1998 heatwave shows an increasing trend in both SLA and SST from January to October at SC1 and SC2. This indicates moderate to strong positive correlations, with coefficients of 0.4260 and 0.8960, respectively. Figure 16 shows a

mixed trend between SLA and SST during the 2010, 2016, and 2022 heatwaves at CS1. The correlation coefficients for these years were 0.2274, -0.3440 , and -0.4233 , respectively, indicating weak to moderate correlations. However, at CS2, a generally positive correlation was observed during the same years, with correlation coefficients of 0.7438, 0.1479, and 0.6124, respectively.

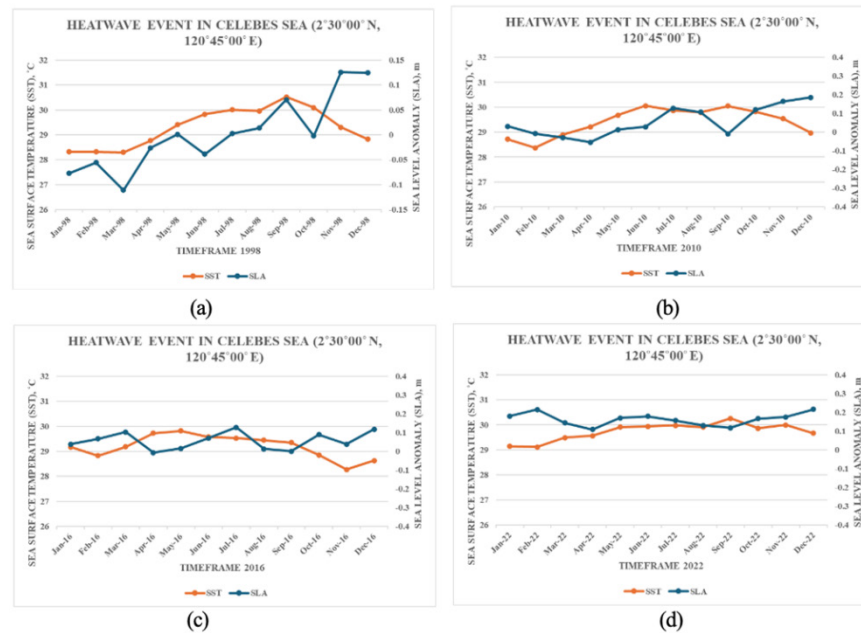


FIGURE 16. Correlation of satellite-derived SLA and SST during heatwave events (a) 1998, (b) 2010, (c) 2016, (d) 2022 at CS1.



FIGURE 17. Correlation of satellite-derived SLA and SST during heatwave events (a) 1998, (b) 2010, (c) 2016, (d) 2022 at CS2.

Sulu Sea: Figure 18 and Figure 19 shows a correlation of satellite-derived SLA and SST during heatwave events (a) 1998, (b) 2010, (c) 2016, (d) 2022 at SS1 and SS2 respectively. Generally, the correlation of all SLA and SST during heatwaves year show a positive correlation. The correlation coefficients during the heatwave years at SS1 were 0.7427, 0.6630, 0.3591, and 0.4513, respectively. Meanwhile, the corresponding correlation coefficients at SS2 were 0.8481, 0.7774, 0.2548, and 0.6880, respectively.

A specific pattern of increasing SST and associated rises in SLAs can be seen throughout the heatwave year in both figures. The varying positive relationship observed between increased SST and elevated SLA suggests that heatwave conditions significantly influence sea-level fluctuations, primarily due to thermal expansion. However, additional factors may also contribute, including ocean currents and changes in water mass distribution.

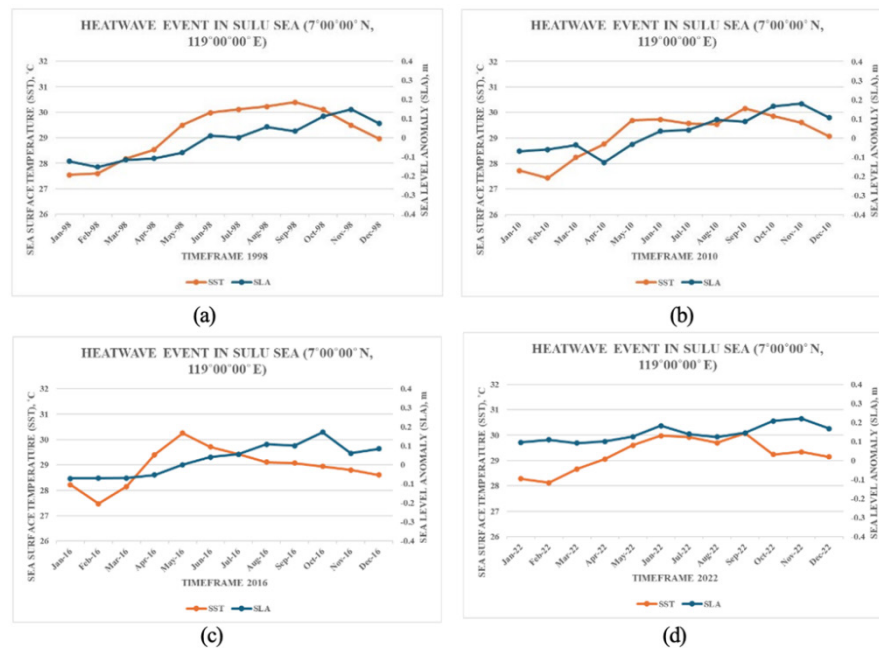


FIGURE 18. Correlation of satellite-derived SLA and SST during heatwave events (a) 1998, (b) 2010, (c) 2016, (d) 2022 at SS1.

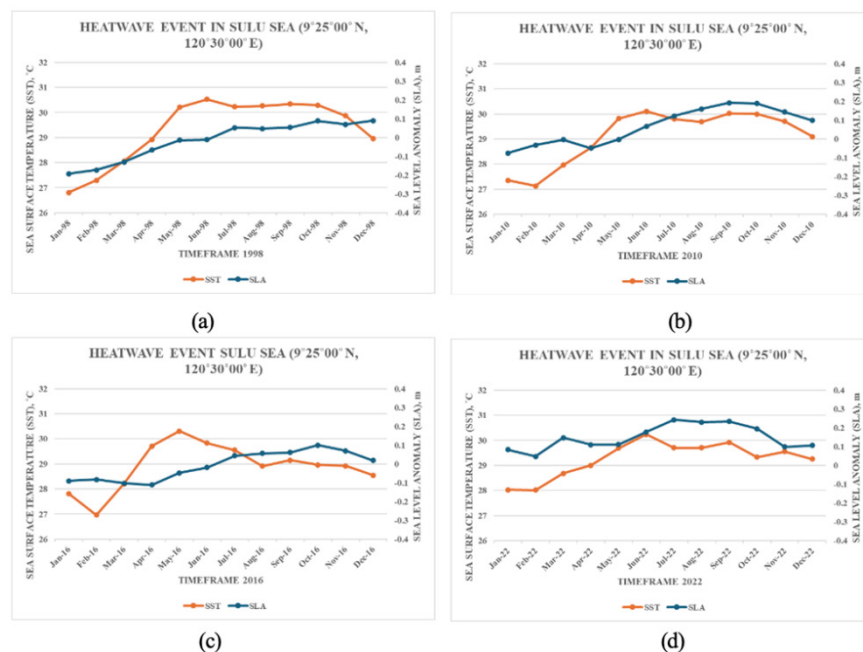


FIGURE 19. Correlation of satellite-derived SLA and SST during heatwave events (a) 1998, (b) 2010, (c) 2016, (d) 2022 at SS2

CONCLUSION

This study investigated the impacts of heatwave events on sea level anomalies (SLA) and sea surface temperature (SST) using multi-mission satellite altimetry over the Malaysian Seas. The correlation between heatwaves and sea level across the different seas in this study shows a mixed pattern. The Celebes Sea exhibits variable correlations between SLA and SST during each heatwave year, with correlation coefficients ranging from -0.4223 to 0.8960 . The Sulu Sea shows small to strong positive correlations, with coefficients ranging from 0.2548 to 0.8481 . The Straits of Malacca display negligible to moderate correlations, with coefficients between -0.020 and 0.4365 . In contrast, the South China Sea demonstrates a significant and strong negative correlation, with coefficients ranging from -0.5540 to -0.8107 . Variations in SLA and SST associated with climate variability demonstrate measurable impacts on coastal environments and human activities, particularly during monsoon seasons when ocean-atmosphere interactions intensify.

Continuous monitoring and analysis are essential to support evidence-based coastal mitigation strategies and long-term marine management planning. This study highlights the importance of increasing awareness regarding potential future climate-driven extreme events, particularly marine heatwaves that may significantly influence regional sea level variability. Multi-mission satellite altimetry can serve as a valuable tool for long-term monitoring and climate change studies. Although the temporal coverage of the dataset is relatively limited, it provides a reliable foundation for extended oceanographic and climate-related analyses.

ACKNOWLEDGEMENT

The authors would like to acknowledge the financial support from the Ministry of Education Malaysia under Fundamental Research Grant Scheme (FRGS) (FRGS/1/2023/WAB05/UTM/02/1). The authors would also like to extend their sincere appreciation to TU Delft, NOAA, and Altimetric LLC for supplying satellite altimetry data via the Radar Altimeter Database System (RADS), as well as the Department of Survey and Mapping Malaysia (DSMM) and the Permanent Service for Mean Sea Level (PSMSL) for the coastal tide gauge data.

Special thanks are due to the Institute of Oceanography and Environment (INOS), Universiti Malaysia Terengganu (UMT), for providing the in-situ sea surface temperature (SST) data.

DECLARATION OF COMPETING INTEREST

None.

REFERENCES

- Affandi, M.L.A., Md Din, A.H. & Rasib, A.W. 2022. A short review on causes of sea level rise for climate monitoring. *IOP Conference Series: Earth and Environmental Science* 1051(1): 012003. <https://doi.org/10.1088/1755-1315/1051/1/012003>
- Akhir, M.F.M. 2012. Surface circulation and temperature distribution of southern South China Sea from global ocean model (OCCAM). *Sains Malaysiana* 41(6): 701–714.
- Akhir, M.F. 2014. Review of current circulation studies in the southern South China Sea. *Journal of Sustainability Science and Management* 9(2): 21–30.
- AVISO. 2016. Satellite altimetry data. <http://www.aviso.altimetry.fr/en/data/products/ocean-indicator-products/mean-sea-level.html>. Accessed 23 February 2026.
- Awang, N.A. & Abd. Hamid, M.R. 2013. Sea level rise in Malaysia. *HydroLink* 2: 47–49.
- Bosch, W., Dettmering, D. & Schwatke, C. 2014. Multi-mission cross-calibration of satellite altimeters: Constructing a long-term data record for global and regional sea level change studies. *Remote Sensing* 6(3): 2255–2281. <https://doi.org/10.3390/rs6032255>
- Chang, C.P., Harr, P.A. & Chen, H.J. 2005. Synoptic disturbances over the equatorial South China Sea and western Maritime Continent during boreal winter. *Monthly Weather Review* 133(3): 489–503.
- Chen, W., Staneva, J., Grayek, S., Schulz-Stellenfleth, J. & Greinert, J. 2022. The role of heat wave events in the occurrence and persistence of thermal stratification in the southern North Sea. *Natural Hazards and Earth System Sciences* 22(5): 1683–1698. <https://doi.org/10.5194/nhess-22-1683-2022>
- Din, A.H.M., Naeije, M.C., Omar, K.M. & Ses, S. 2012. Long-term sea level change in the Malaysian seas from multi-mission altimetry data. *International Journal of Physical Sciences* 7(10): 1694–1712.
- Din, A.H.M., Reba, M.N.M., Omar, K.M., Pa'suya, M.F. & Ses, S. 2015. Sea level rise quantification using multi-mission satellite altimeter over Malaysian seas. *Proceedings of the 36th Asian Conference on Remote Sensing (ACRS 2015)*, Manila, Philippines, 19–23 October.
- Din, A.H.M., Ses, S., Omar, K.M., Naeije, M., Yaakob, O. & Pa'suya, M.F. 2014. Derivation of sea level anomaly based on the best range and geophysical corrections for Malaysian seas using Radar Altimeter

- Database System (RADS). *Jurnal Teknologi* 71(4): 83–91. <https://doi.org/10.11113/jt.v71.3830>
- Feng, C., Yin, W., He, S., He, M. & Li, X. 2023. Evaluation of SST data products from multi-source satellite infrared sensors in the Bohai-Yellow-East China Sea. *Remote Sensing* 15(10): 2493. <https://doi.org/10.3390/rs15102493>
- Feng, J., Li, D., Wang, H., Liu, Q., Zhang, J. & Li, Y. 2018. Analysis on the extreme sea levels changes along the coastline of Bohai Sea, China. *Atmosphere* 9(8): 324. <https://doi.org/10.3390/atmos9080324>
- Hamden, M.H., Din, A.H.M., Wijaya, D.D., Yusoff, M.Y.M. & Pa'suya, M.F. 2021. Regional mean sea surface and mean dynamic topography models around Malaysian seas developed from 27 years of along-track multi-mission satellite altimetry data. *Frontiers in Earth Science* 9: 665876. <https://doi.org/10.3389/feart.2021.665876>
- Hamid, A.I.A., Din, A.H.M., Hwang, C., Khalid, N.F., Tugi, A. & Omar, K.M. 2018. Contemporary sea level rise rates around Malaysia: Altimeter data optimization for assessing coastal impact. *Journal of Asian Earth Sciences* 166: 247–259. <https://doi.org/10.1016/j.jseaes.2018.07.034>
- Hamid, A.I.A. 2018. *Sea level rise quantification and projection using multi-mission satellite altimeter over Malaysian seas*. PhD thesis, Universiti Teknologi Malaysia.
- Hannah, J. 2010. The difficulties in using tide gauges to monitor long-term sea level change. *Proceedings of the XXIV FIG International Congress: Facing the Challenges—Building the Capacity*, Sydney, Australia, 11–16 April, pp. 1–11.
- Hobday, A.J., Oliver, E.C.J., Sen Gupta, A., Benthuisen, J.A., Burrows, M.T., Donat, M.G., Holbrook, N.J., Moore, P.J., Thomsen, M.S., Wernberg, T. & Smale, D.A. 2018. Categorizing and naming marine heatwaves. *Oceanography* 31(2): 162–173. <https://doi.org/10.5670/oceanog.2018.205>
- How, G.S., Din, A.H.M., Hamden, M.H., Uti, M.N. & Adzmi, N.H.M. 2020. Sea level anomaly assessment of SARAL/AltiKa mission using high- and low-resolution data. *Jurnal Teknologi* 82(4): 81–91. <https://doi.org/10.11113/jt.v82.13882>
- Isa, N.S., Akhir, M.F., Khalil, I., Kok, P.H. & Roseli, N.H. 2020. Seasonal characteristics of the sea surface temperature and sea surface currents of the Strait of Malacca and Andaman Sea. *Journal of Sustainability Science and Management* 15(4): 66–77. <https://doi.org/10.46754/jssm.2020.06.007>
- Liu, C., Li, X., Wang, S., Tang, D. & Zhu, D. 2020. Interannual variability and trends in sea surface temperature, sea surface wind, and sea level anomaly in the South China Sea. *International Journal of Remote Sensing* 41(11): 4160–4173.
- Liu, P., Din, A.H.M. & Hamden, M.H. 2025. Unveiling regional and seasonal sea level dynamics along China's coast: Insights from 30 years of multi-mission satellite altimetry data. *Science of Remote Sensing* 12: 100280. <https://doi.org/10.1016/j.srs.2025.100280>
- Luu, Q.H., Tkalich, P. & Tay, T.W. 2015. Sea level trend and variability around Peninsular Malaysia. *Ocean Science* 11(4): 617–628. <https://doi.org/10.5194/os-11-617-2015>
- Marcos, M., Amores, A., Agulles, M., Robson, J. & Feng, X. 2025. Global warming drives a threefold increase in persistence and 1 °C rise in intensity of marine heatwaves. *Proceedings of the National Academy of Sciences* 122(16): e2413505122. <https://doi.org/10.1073/pnas.2413505122>
- Merchant, C.J., Minnett, P.J., Beggs, H., Corlett, G.K., Gentemann, C., Harris, A.R., Hoyer, J. & Maturi, E. 2019. Global sea surface temperature. In Hulley, G.C. & Ghent, D. (eds.). *Taking the Temperature of the Earth: Steps towards Integrated Understanding of Variability and Change*, pp. 5–55. Elsevier. <https://doi.org/10.1016/B978-0-12-814458-9.00002-2>
- Oktaviani, F., Miftahuddin & Setiawan, I. 2021. Cross-correlation analysis between sea surface temperature anomalies and several climate elements in the Indian Ocean. *Parameter: Journal of Statistics* 1(1): 13–20. <https://doi.org/10.22487/27765660.2021.v1.i1.15354>
- Paredes-Fortuny, L., Pastor, F. & Khodayar, S. 2025. Concurrent atmospheric heatwaves intensify marine heatwaves through air-sea heat flux change in the Mediterranean Sea. *Communications Earth & Environment* 6: 638. <https://doi.org/10.1038/s43247-025-02633-2>
- Rizal, S., Damm, P., Wahid, M.A., Sundermann, J., Ilhamsyah, Y., Iskandar, T. & Muhammad, M. 2012. General circulation in the Malacca Strait and Andaman Sea: A numerical model study. *American Journal of Environmental Sciences* 8(5): 479–488. <https://doi.org/10.3844/ajessp.2012.479.488>
- Suparta, W. & Yatim, A.N.M. 2019. Characterization of heat waves: A case study for Peninsular Malaysia. *Geographia Technica* 14(1): 146–155. https://doi.org/10.21163/GT_2019.141.11
- Tangang, F., Juneng, L., Salimun, E. & Jamaluddin, A.F. 2019. Scientific understanding of El Niño-Southern Oscillation (ENSO) and its climatic impacts in Malaysia and surrounding region. In *El Niño—Review of Scientific Understanding and the Impacts of 1997/98 Event in Malaysia*, pp. 5–31. Kuala Lumpur: Academy of Sciences Malaysia.
- Tkalich, P., Vethamony, P., Babu, M.T. & Malanotte-Rizzoli, P. 2013. Storm surges in the Singapore Strait due to winds in the South China Sea. *Natural Hazards* 66(3): 1345–1362. <https://doi.org/10.1007/s11069-012-0211-8>

- Trisirisatayawong, I., Naeije, M., Simons, W. & Fenoglio-Marc, L. 2011. Sea level change in the Gulf of Thailand from GPS-corrected tide gauge data and multi-satellite altimetry. *Global and Planetary Change* 76(3–4): 137–151. <https://doi.org/10.1016/j.gloplacha.2010.12.010>
- Widlansky, M.J., Long, X. & Schloesser, F. 2020. Increase in sea level variability with ocean warming associated with the nonlinear thermal expansion of seawater. *Communications Earth & Environment* 1: 9. <https://doi.org/10.1038/s43247-020-0008-8>
- Wisha, U.J., Wijaya, Y.J. & Hisaki, Y. 2023. Sea level variability in the equatorial Malacca Strait: The influence of climatic–oceanographic factors and its implications for tidal properties in the estuarine zone. *Climate* 11(3): 70. <https://doi.org/10.3390/cli11030070>
- Zhang, X., Zheng, F., Zhu, J. & Chen, X. 2022. Observed frequent occurrences of marine heatwaves in most ocean regions during the last two decades. *Advances in Atmospheric Sciences* 39(9): 1579–1587.