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RESEARCH ARTICLE

EVALUATING SEA LEVEL CHANGES IN SOUTHEAST ASIA: INSIGHTS FROM CMIP6 PROJECTIONS UNDER THE SSP3-7.0 SCENARIO

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ABSTRACT

The anticipated rise in sea levels presents a profound threat to coastal regions worldwide, including Malaysia, where about 70% of the population live in vulnerable coastal areas. This study analyses sea level projections for Malaysia's coastal regions up to the year 2100, incorporating key contributors outlined by the Intergovernmental Panel on Climate Change, namely Thermal Expansion, Ice Sheet and Glacier Melting, Groundwater Discharge, and Glacial Isostatic Adjustment (GIA). Results indicate that sea level rise in the South China Sea (SCS), particularly in the South China Sea Peninsular Malaysia (SCSPM) and the South China Sea East Malaysia (SCSEM), is expected to exceed that of other Malaysian coastal areas such as the Straits of Malacca (SM) and the Sulu Sea (SS). Specifically, by 2100, projections suggest a maximum increase of 366.6 mm and 370.7 mm for SCSPM and SCSEM, respectively, compared to 324.2 mm for the SM and 343.5 mm for SS. In addition, the analysis reveals spatial disparities in sea level rise across Malaysian regions, with the SCS experiencing the most pronounced changes. The study also highlights shifts in the relative contributions of various factors to overall sea level rise by the end of the century. Sterodynamic processes, glacier melting, and groundwater discharge are expected to increase, accounting for 49.1%, 8.6%, and 1.4% of total sea level rise, respectively, compared to 2020 levels. Conversely, the contribution from ice sheets is projected to decline, constituting 43% of total sea level rise. Notably, GIA is anticipated to mitigate sea level rise slightly, with a projected contribution of -2.1% by 2100. These findings provide valuable insights into the differential impacts of sea level rise on Malaysian coastal regions and underscore the urgency of adaptive strategies to mitigate the potential consequences of rising sea levels throughout the twenty-first century.

KEYWORDS

Ice sheet melting, glacier melting, sterodynamic processes, groundwater discharge, glacial isostatic adjustment.

1. INTRODUCTION

Sea-level rise is one of the most significant consequences of climate change driven by global warming, which will inevitably impact coastal areas worldwide (Sarkar et al., 2014) . Over the past 15 years, there has been a marked increase in sea-level rise, and it is expected to accelerate further by the end of the 21st century (Sung et al., 2021).

Climate-induced sea-level rise poses a severe threat to low-lying coastal regions and communities worldwide, a concern that has persisted since the concept of human-induced global warming emerged in the 1980s (Nicholls and Cazenave, 2010; Nicholls, 2011; Ashrafuzzaman, 2023; Doorga et al., 2024). This global phenomenon has shown marked increases over the last 15 years and is expected to accelerate towards the end of the 21st century (Sung et al., 2021). Sea-level rise is influenced by multiple factors, including thermal expansion, the melting of the Antarctic and Greenland ice sheets, and land water storage (Nicholls, and Cazenave, 2010; Church et al., 2013). However, various regional factors also influence sea-level rise, making it challenging to estimate its effects on coastal regions and communities using global projections (Jennath et al., 2021). These regional variations in sea-level rise are driven by factors such as glacier melt rates in regions outside of Antarctica and Greenland, atmospheric processes, isostatic adjustment, thermal expansion, as well as other localized processes (Grinsted et al., 2015; Hamlington et al., 2020).

Unlike large-magnitude storms that can alter coastal areas rapidly, the effects of sea-level rise are slow, recurring, and cumulative (Passeri et al., 2015). Projections indicate a significant rise in sea levels by the end of the 21st century (Griggs and Reguero, 2021). Once sea levels increase, they will remain elevated for centuries, even with mitigation efforts. Without proactive intervention, this rise will likely continue unabated, leading to

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long-term and potentially irreversible impacts on coastal regions and communities. In Malaysia, approximately 1,972 km of coastline in Peninsular Malaysia and 2,873 km in East Malaysia (Sarawak and Sabah) are at risk (Ghazali, 2006). With 70% of the population residing near coastal zones these areas are particularly vulnerable to climatic and geophysical hazards, including storms and storm-induced flooding (Nicholls, 2011; Ehsan et al., 2019). Malaysia's extensive coastline and densely populated coastal areas heighten its vulnerability to sea-level rise, which contributed to coastal erosion, increasingly frequent and severe flooding, and damage to infrastructure (Nazarnia et al., 2020; Oppenheimer et al., 2019; Lyu et al., 2020).

Low-lying areas in Peninsular Malaysia, Sabah, and Sarawak face additional risks such as land loss and saltwater intrusion, which threaten communities, agriculture, and freshwater resources. Without accurate regional projections and effective adaptation strategies, these challenges will continue to grow, adversely affceting both the environment and livelihoods. Therefore, reliable sea-level rise projections are essential for developing mitigation and adaptation strategies in coastal cities. Coastal communities are likely to be significantly impacted, with flood risks in specific areas often assessed using historical tide gauge data over decades or numerical modelling (Majumder et al., 2025).

Although many studies have been conducted on sea-level rise in Southeast Asia, there has been limited research on the factors contributing to sea-level rise in the region, which include thermal expansion, ice sheet and glacier melting, groundwater discharge, and glacial isostatic adjustment (Dong et al., 2024). Understanding the relative contributions of these factors is crucial for improving regional projections and developing effective adaptation strategies.

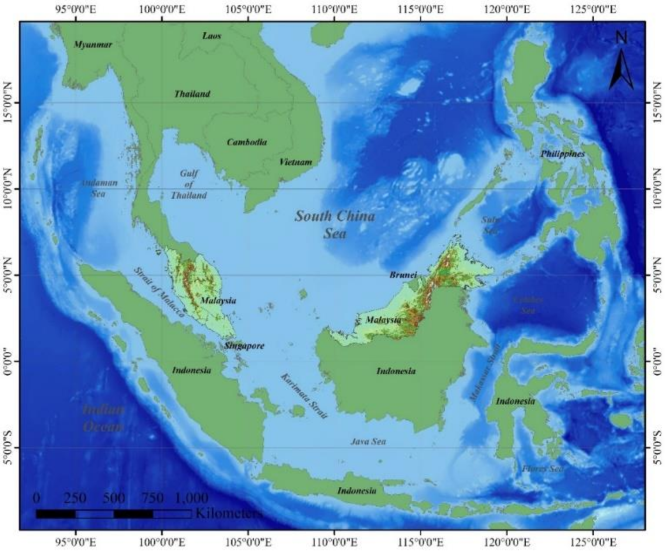

Figure 1: A map of Southeast Asia depicting the Sulu Sea (to the east of Sabah), the Southern South China Sea (off the east coast of Peninsular Malaysia and west of Sarawak and Sabah), and the Strait of Malacca (off the west coast of Peninsular Malaysia), surrounding Malaysia and illustrating key maritime regions in proximity to the country.

This study aims to analyse sea-level changes in Southeast Asia – South China Sea (SCS) throughout the 21st century, with a specific focus on South China Sea Peninsular Malaysia (SCSPM) and South China Sea East Malaysia (SCSEM), Straits of Malacca (SM), and Sulu Sea (SS) (Figure 1). The key contrutors, namely thermal expansion, ice sheet and glacier melting, groundwater discharge, and glacial isostatic adjustment, are examined in detail. The analysis is based on data from the Coupled Model Intercomparison Project phase 6 (CMIP6) under the SSP3-7.0 scenario. By considering region-specific contributing factors beyond global estimates, our findings aim to enhance the accuracy of sea-level projections for Malaysia. This information will support policymakers, urban planners, and coastal managers in developing targeted adaptation strategies to safeguard coastal communities, infrastructure, and ecosystems from the impacts of sea-level rise.

2. Methodology

Table 1: Summary of datasets used in this study, including sources, temporal coverage, spatial resolution, and key variables relevant to sea level change projections.

Dataset	Temporal resolution	Spatial Resolution	Time coverage
AVISO	Monthly	1° x 1°	1993 – 2010
CMIP6 Models	Monthly	Varies	Historical (1993 – 2010)

The Earth System Grid Federation (ESGF) provided monthly averages of CMIP6 models (Table 1). Historical and projection data were obtained for variables including sea surface height above geoid (zos), global average thermosteric sea level change (zostoga), and surface temperature (ts). Additionally, data on glacier melting, land water discharge, and glacial isostatic adjustment (GIA) were sourced from the IPCC AR6 Sea Level Projection Tool available at https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool. This tool utilizes sea level projections from the IPCC 6th Assessment Report.

Total sea level rise (TSL) and dynamic sea level rise (DSL) represent distinct but related components of sea level change. TSL projections account for all contributing factors, including thermal expansion, ice sheet and glacier melt, groundwater discharge, and glacial isostatic adjustment, providing a comprehensive estimate of sea level variations. In contrast, DSL is solely based on the 'zos' variable, which represents sea surface height above the geoid. Consequently, while TSL captures the full spectrum of sea level drivers, DSL isolates dynamic ocean processes, offering insights into regional sea level variability.

For the purpose of this study, sea level variability will be examined based on TSL and DSL will not be considered. A comprehensive assessment of sea level variability using DSL has been previously reported complementing the present study by highlighting the role of dynamic ocean processes in shaping regional sea level patterns (Azran et al., 2023).

2.1 The Shared Socioeconomic Pathway (SSP) framework

The Shared Socioeconomic Pathway (SSP) is a framework used to explore and analyse future global developments in socioeconomic factors, such as population growth and economic trends, and their implications for greenhouse gas emissions and climate change. Included in the SSPs framework, SSP3-7.0 represents a scenario used in climate modelling to project future socio-economic trends and their impact on greenhouse gas emissions and climate change. Generally referred to as the "Regional Rivalry" scenario, SSP3 envisions a world characterized by high challenges to both mitigation and adaptation. It assumes a fragmented world with increasing nationalism, regional conflicts, and slower economic growth, leading to limited international cooperation on environmental policies. The "7.0" denotes the approximate level of radiative forcing (in watts per square meter) by the year 2100. Under this scenario, continued reliance on fossil fuels and slower technological advancements results in high greenhouse gas emissions, significant global warming, and substantial impacts on sea level rise and other climate-related phenomena.

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2.2 Sea Level Projection in Southeast Asia using CMIP6 models

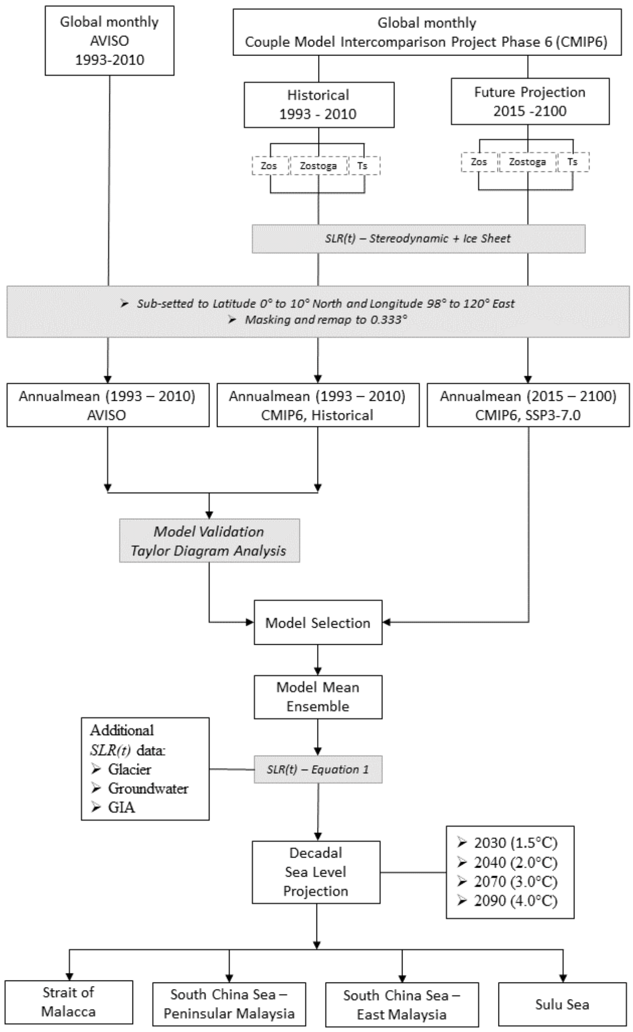

Figure 2: General framework for sea level change projections based on CMIP6 simulations under the SSP3-7.0 scenario.

The general framework for sea level change projections in Southeast Asia, using CMIP6 modelling based on the SSP3-7.0 scenario, is illustrated in Figure 2. Considering all contributions, the total sea level rise is expressed by the following equation (Sung et al., 2021):

$$SLR(t) = SLR(t)_{ocean} + SLR(t)_{ice-sheet} + SLR(t)_{glacier} + SLR(t)_{groundwater} + SLR(t)_{GIA} \quad (1)$$

The total sea level rise (SLR(t)) from ocean processes comprises density changes and ocean thermal expansion, which are represented by the combination of sea surface height above the geoid (zos, see Section 2.3) and global thermosteric change (zostoga, see Section 2.4) variables from CMIP6. SLR(t) from ice-melting refers to the ice sheet contribution, which is divided into surface mass balance (SMB) and dynamical (DYN) contributions. SMB refers to the surface mass change due to the formation or loss of ice sheets through temperature changes and precipitation, as described in Equations (2) and (3), where δTatm is the projected global mean surface temperature obtained from the surface temperature (ts) variable (see Section 2.5) in CMIP6:

$$\Delta SMB_{Antarctic} = -0.0105 - 0.01759 \times \delta T_{atm} - 0.0412 \quad (2)$$

$$\Delta SMB_{Greenland} = 0.0153 + 0.01493 \times \delta T_{atm} - 0.00094 \quad (3)$$

The DYN was calculated using Equations (4) and (5), accounting for the differences in dynamic changes of ice sheets between Antarctica and Greenland. Here, r represents a scenario-independent term (0.32 mm year-1) as obtained from Meehl et al. (2022) (Meehl et al., 2007):

$$\Delta DYN_{Antarctic} = \Delta SMB_{Antarctica} \times 0.95 + \tfrac{2}{3} \times r \quad (4)$$

$$\Delta DYN_{Greenland} = \Delta SMB_{Greenland} + \tfrac{1}{3} \times r \quad (5)$$

These equations suggest differential melting scenarios occurring in Antarctica and Greenland (Sung et al., 2021). In Antarctica, incoming solar energy melts the ice shelf, creating water pools on its surface, which weakens and eventually shatters the ice shelf. Additionally, ice shelves may melt due to changes in bottom balance caused by warmer water circulation. In Greenland, the mechanisms observed are calving and melting of marine-terminating glaciers. The contributions from DYNAntarctic and DYNGreenland are combined to calculate the ice sheet contribution to sea level rise (SLR(t)ice-sheet). The sea level rise contribution from glaciers (i.e., SLR(t)glacier) pertains to the melting of glaciers excluding the ice sheets in polar regions. The sea level rise contribution from groundwater (i.e., SLR(t)groundwater) involves changes in land water storage, and SLR(t)GIA accounts for GIA. All models are standardized to a resolution of 0.33° (approximately 36.97 km) using the bilinear interpolation method, which is chosen for its balance between computational efficiency, processing time, and accuracy. This method ensures smooth spatial transitions by weighting adjacent grid points, reducing errors compared to other interpolation methods while maintaining a faster processing speed than higher-order techniques.

2.3 Sea Surface Height Above Geoid (zos)

Sea surface height above the geoid (zos) refers to the elevation of the ocean surface relative to an equipotential surface known as the geoid, which represents the mean sea level in the absence of thermal expansion, currents, tides, and atmospheric pressure variations. This variable is crucial for understanding sea level changes as it captures the combined effects of mass distribution, salinity variations, and ocean circulation patterns on sea level, providing a comprehensive measure of oceanic responses to climatic and environmental changes. The 'zos' variable measures variations in sea level patterns relative to the ocean geoid, which represents the resting state of the ocean at z = 0, with global mean thermosteric effects removed to isolate ocean dynamics (Griffies et al., 2016). As a key indicator of dynamic sea level, 'zos' captures spatial variability driven by oceanic and atmospheric processes (Griffies and Greatbatch, 2012). This makes it essential for refining regional sea level projections, improving coastal impact assessments, and informing adaptation strategies. The static equilibrium of sea level, referring to the fluid dynamic state of the ocean influenced by geophysical factors, is affected by numerous elements, including ocean currents, seawater density, mass flux boundaries, buoyancy impacts, Earth's gravity, deformation, rotation, tectonic uplift, thermal subsidence, and shoreline morphology (Griffies and Greatbatch, 2012;Kopp et al., 2010; Mitrovica et al., 2011).

2.4 Global Average Thermosteric Change (zostoga)

Global average thermosteric sea level change (zostoga) quantifies the contribution of ocean water thermal expansion to sea level rise. This metric reflects changes in sea level due to temperature-induced density variations in seawater, with warmer temperatures causing water to expand and occupy more volume. Unlike zos, zostoga isolates the effect of thermal expansion alone, providing insight into the direct impact of global warming on sea level rise without the influence of dynamic and mass-related changes. The CMIP6 models include the variable zostoga, which represents a component of global mean sea level change attributable to variations in ocean density caused by temperature changes (Griffies et al., 2016; Jevrejeva et al., 2021; Gregory et al., 2019). Zostoga specifically relates to ocean surface temperature anomalies and is a standard output provided by climate models participating in CMIP6 simulations. This variable denotes deviations from the average sea surface temperature over a specified period and is commonly used to analyse oceanographic and climate variability in model outputs.

2.5 Surface Temperature (ts)

In the CMIP6 model, the surface temperature (ts) variable represents the temperature at the Earth's surface. This variable is crucial for understanding and projecting climate change impacts, as it directly influences the melting of ice sheets. By analysing ts, the contribution of ice sheet melt to sea level rise can be estimated. The ts data provide essential inputs for models calculating the extent of ice melt, enabling more accurate predictions of future sea level changes driven by temperature variations. The ice sheet contribution was calculated by combining the surface mass balance (SMB) contribution and the dynamical (DYN) contribution, as demonstrated in Equations (2), (3), (4), and (5) in section 2.4 (Sung et al., 2021).

2.6 Model Validation

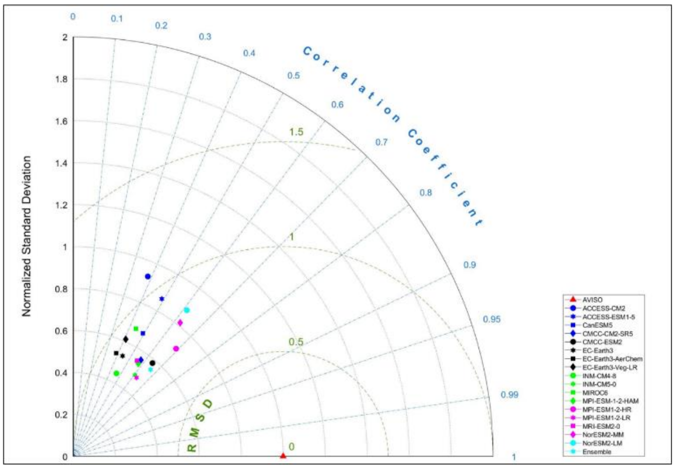

Figure 3: Taylor diagram illustrating the statistical performance of 15 models in simulating various CMIP6 variables compared to satellite-derived AVISO data. CMCC-ESM2, MPI-ESM1-2-HR, and MPI-ESM1-2-LR were selected as the optimal models for generating an ensemble mean to project future sea level changes in Malaysian waters.

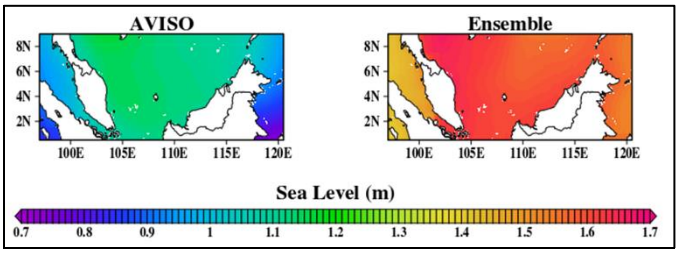

Figure 4: Spatial distribution of total sea level (TSL) from AVISO observations and the multi-model mean ensemble for the time-mean period 1993–2010.

A comparison of simulated sea level contributions using various CMIP6 variables against satellite-derived AVISO data from 1993 to 2010 is shown in Figure 3. The Taylor diagram selected the models CMCC-ESM2, MPI-ESM1-2-HR, and MPI-ESM1-2-LR due to their alignment with AVISO satellite data in terms of standard deviation, correlation coefficient, and RMSD. These metrics were given priority as they collectively assess the models' ability to replicate observed sea level variability, capturing both the magnitude and pattern of changes. By selecting models that closely align with observed data, the study ensures more reliable projections, making these models better suited for assessing regional sea level changes with higher confidence. The RMSD indicated the degree of variation from the observation, with most models scoring between 0.5 and 1, indicating proximity to observations, except for the ACCESS-CM2 model, which exhibited a higher RMSD score (>1). The correlation coefficient values ranged from 0.2 to 0.7, with values greater than 0.6 used to assess model performance. Standard deviation analysis showed that most models clustered around or below 0.8, except for ACCESS-CM2, which had a higher standard deviation of approximately 0.9. Model selection was based on three statistical criteria: highest correlation coefficients, lowest root mean square deviation (RMSD), and lowest standard deviations. The analysis identified CMCC-ESM2, MPI-ESM1-2-HR, and MPI-ESM1-2-LR as the optimal models. These models were utilized to generate a multi-model ensemble mean for projecting future sea levels in Malaysian seas (Figure 4).

3. Results

3.1 Total Sea Level projection (TSL) for Southeast Asia

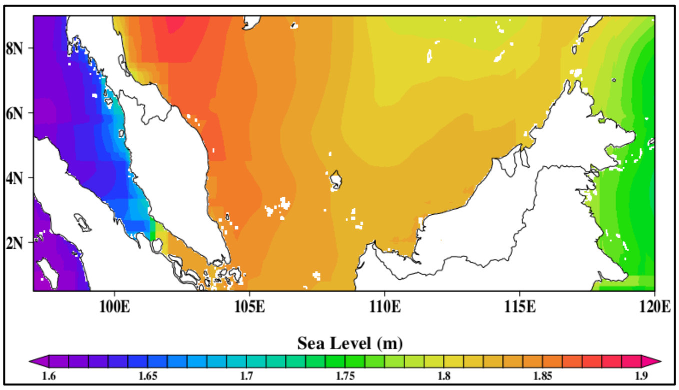

Figure 5: Spatial distribution of total sea level (TSL) from the mean model ensemble for the time-mean period.

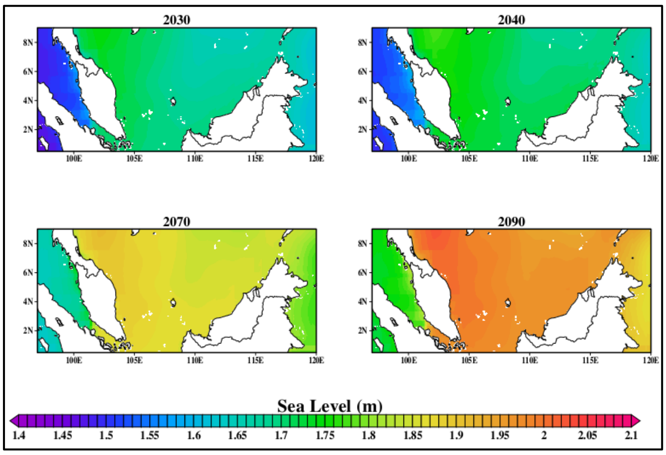

Figure 6: Spatial distribution of total sea level (TSL) from the mean model ensemble for the time-mean period, based on the warming year.

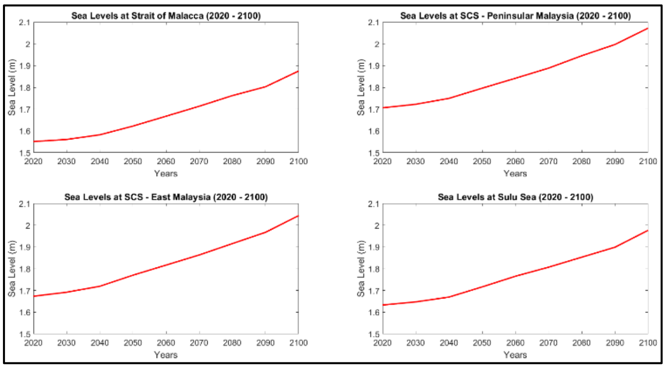

Figure 7: Total sea level (TSL) projections across Malaysia, showing regional variations for (a) the Strait of Malacca, (b) the South China Sea – Peninsular Malaysia, (c) the South China Sea – East Malaysia, and (d) the Sulu Sea.

Table 2: Decadal projections of total sea level (TSL) changes from the multi-model mean ensemble, showing sea level variations relative to the baseline year 2020.

Warming	Year	Strait of Malacca		SCS—Peninsular Malaysia		SCS—East Malaysia		Sulu Sea	
		Sea Level (m)	Sea Level Change (mm)	Sea Level (m)	Sea Level Change (mm)	Sea Level (m)	Sea Level Change (mm)	Sea Level (m)	Sea Level Change (mm)
1.5 °C	2030	1.561	9.5	1.722	16.5	1.692	18.5	1.648	14.3
2.0 °C	2040	1.582	30.9	1.749	43.5	1.719	45.8	1.670	36.4

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Table 2(Cont.): Decadal projections of total sea level (TSL) changes from the multi-model mean ensemble, showing sea level variations relative to the baseline year 2020.

3.0 °C	2070	1.713	162.2	1.888	182.5	1.863	189.8	1.807	173.9
4.0 °C	2090	1.803	251.8	1.997	291.2	1.967	293.9	1.899	265.6
	2100	1.875	324.2	2.073	366.6	2.044	370.7	1.977	343.5

An ensemble approach incorporates three high-performing models to project TSL trends in Malaysian waters (Figures 5, 6, and 7). The study focuses on four specific regions—SM, SCSPM, SCSEM, and SS—to evaluate future sea level projections. Table 2 presents a summary of the projected sea level ranges, changes, and trends under the SSP3-7.0 scenario, considering warming levels from 1.5°C to 4.0°C and projections extending to the end of the century (i.e., 2030, 2040, 2070, 2090, and 2100).

By 2030, under 1.5°C warming, projected sea levels for SM, SCSPM, SCSEM, and SS are estimated at 1.561 m, 1.722 m, 1.692 m, and 1.648 m, respectively. Prior to 2020, SCSPM, SCSEM, and SS are anticipated to experience sea level changes of 16.5 mm, 18.5 mm, and 14.3 mm, while SM shows a comparatively lower change of 9.5 mm. By 2040, under 2.0°C warming, sea level ranges are projected to increase to 1.582 m, 1.749 m, 1.719 m, and 1.670 m for SM, SCSPM, SCSEM, and SS, respectively. Comparing with the 1.5°C scenario, this represents changes of 30.9 mm, 43.5 mm, 45.8 mm, and 36.4 mm for SM, SCSPM, SCSEM, and SS, respectively. By 2070, under 3.0°C warming scenarios, projected sea levels for SM, SCSPM, SCSEM, and SS are anticipated to range from 1.713 m to 1.888 m. This period will see significant increases, with SM, SCSPM, SCSEM, and SS experiencing respective sea level changes of 162.2 mm, 182.5 mm, 189.8 mm, and 173.9 mm. By 2090, with global warming at 4.0°C, sea levels for SM, SCSPM, SCSEM, and SS are projected to range from 1.803 m to 1.997 m. These projections surpass those observed at 1.5°C (2030), 2.0°C (2040), and 3.0°C (2070), indicating substantial increases of 251.8 mm, 291.2 mm, 293.9 mm, and 265.6 mm for SM, SCSPM, SCSEM, and SS, respectively. Towards the end of the 21st century by 2100, projected sea levels at SM, SCSPM, SCSEM, and SS are estimated to range between 1.875 m and 2.073 m, reflecting continued escalation. These changes represent significant rises of 324.2 mm, 366.6 mm, 370.7 mm, and 343.5 mm for SM, SCSPM, SCSEM, and SS, respectively.

3.2 Comparison of Total Sea Level (TSL) and Dynamic Sea Level (DSL) Projections in Southeast Asia

A direct comparison between the decadal DSL and decadal TSL projections indicates that the inclusion of additional sea level rise contributions results in a significantly higher projected sea level range by the end of the 21st century. Notably, sea levels in the SCS, particularly SCSPM and SCSEM, are projected to be higher than those in SM and SS, indicating that there are distinct regional variations in sea level rise across Malaysian waters by the end of the 21st century. At SCSPM site, the decadal DSL projections indicate a sea level of 0.936 m with a change of 58.9 mm, whereas the decadal TSL projections suggest a sea level of 2.073 m with a change of 366.6 mm. Similarly, at SCSEM site, the decadal DSL projections estimate a sea level of 0.926 m with a change of 58.2 mm, while the decadal TSL projections indicate a sea level of 2.044 m with a change of 370.7 mm. These findings highlight the substantial impact of climate change on sea level rise, with significant implications for coastal and maritime nations.

Overall, TSL projections exceed those of DSL due to the inclusion of all sea level rise contributors, unlike DSL that only considers the 'zos' variable. Without considering other components of sea level rise, the multi-model mean ensemble indicates a consistent annual increase in sea level (Azran et al., 2023). Consequently, TSL projection exhibits a higher projected range compared to DSL.

3.3 Sea Level Change from CMIP6 Key Contributors in TSL

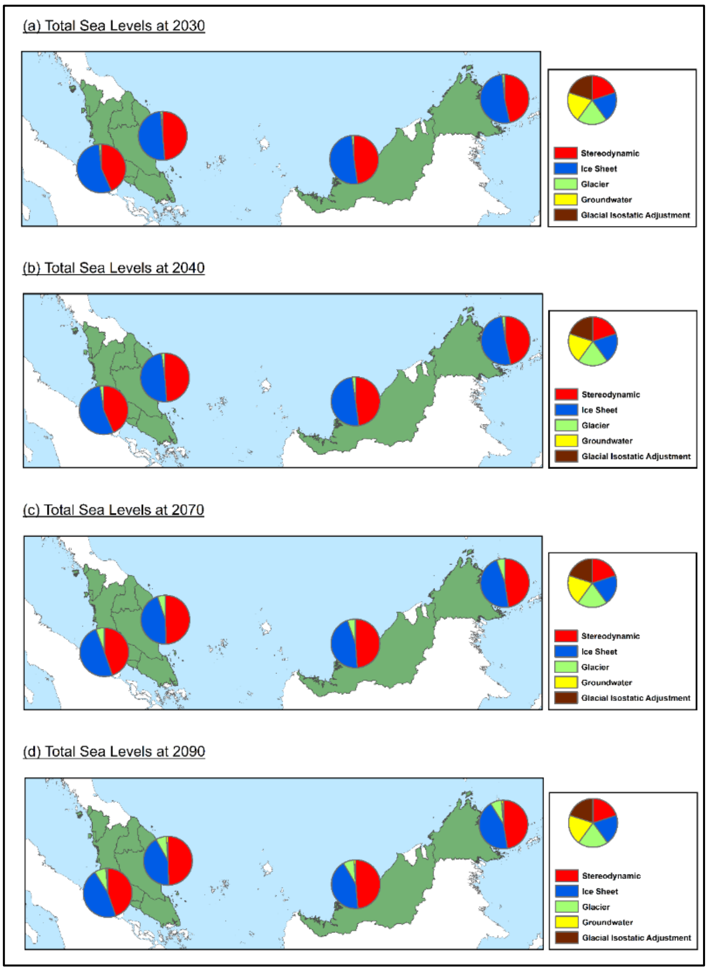

Figure 8: Contributions of sea level rise components in Malaysian seas, illustrating total sea levels for (a) 2030, (b) 2040, (c) 2070, and (d) 2090.

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Table 3: Percentage contributions of different components to total sea level (TSL) rise.

Year	Stero-dynamic	Ice Sheet	Glacier	Ground-water Discharge	Glacial Isostatic Adjustment
2020	46.9 %	52.5 %	0.9 %	0.1 %	-0.4 %
2030	46.8 %	52.1 %	1.6 %	0.2 %	-0.6 %
2040	47.0 %	51.2 %	2.4 %	0.3 %	-0.9 %
2050	47.1 %	49.9 %	3.7 %	0.4 %	-1.1 %
2060	47.8 %	48.5 %	4.5 %	0.6 %	-1.3 %
2070	48.0 %	47.2 %	5.5 %	0.8 %	-1.5 %
2080	48.2 %	45.9 %	6.6 %	1.0 %	-1.7 %
2090	48.5 %	44.7 %	7.5 %	1.2 %	-1.9 %
2100	49.1 %	43.0 %	8.6 %	1.4 %	-2.1 %

The total sea level (TSL) projection incorporates all significant contributors to sea level rise, as defined by the equation proposed based on IPCC AR6 recommendations by (Sung et al., 2021). This includes sterodynamic (i.e., halosteric and thermosteric) changes, contributions from ice sheets, glaciers, groundwater discharge, and GIA. Figure 8 illustrates the spatial distribution of each sea level rise component in the SM, SCS, and SS.

Table 3 provides the average percentage contribution of each sea level rise component projected by TSL. By 2030, under 1.5°C warming, sterodynamic and ice sheets are projected to contribute 46.8% and 52.1% respectively, while glaciers (1.6%), groundwater discharge (0.2%) and GIA (-0.6%) contribute minimally to total sea level rise. By 2040, with warming reaching 2.0°C, the contribution from ice sheets decreases to 51.2%, while sterodynamic, glaciers, and groundwater discharge increase to 47.0%, 2.4%, and 0.3% respectively. GIA shows a more pronounced sea level decrease (-0.9%) compared to 2030. By 2070, under 3.0°C warming, sterodynamic contributes 48.0% and ice sheets 47.2% to total sea level rise. Glaciers increase their contribution to 4.5%, and groundwater discharge to 0.8%, while GIA contributes -1.5% to sea level change. By 2090, with warming at 4.0°C, sterodynamic contributes 48.5% and ice sheets 44.7% to total sea level rise, with glaciers contributing 7.5% and groundwater discharge 1.2%. GIA shows a further increase in sea level decrease at -1.9% compared to 2070. By the end of the century, sterodynamic, glaciers, and groundwater discharge show increased contributions to total sea level rise (49.1%, 8.6%, and 1.4%, respectively), while ice sheets decrease to 43.0%. GIA contributes a higher sea level decrease (-2.1%) compared to its contribution in 2020.

4. Discussion

4.1 Strengths and Limitations of CMIP6 models for projecting Malaysian Sea Levels

The term 'sea level change' denotes variations in mean sea level over time due to climate dynamics, while 'sea level' refers to the height of the sea surface relative to a specified vertical datum [30]. From 1901 to 2018, the global mean sea level rose by 0.2 meters (IPCC, 2021). In Malaysia, relative sea level trends vary regionally, with rates of 4.22 mm/year on the west coast of Peninsular Malaysia, 3.53 mm/year on the east coast of Peninsular Malaysia, and 3.40 mm/year in Sabah and Sarawak (Adebisi and Balogun, 2021). Climate models, including regional climate models (RCMs), are pivotal tools for elucidating climate change patterns and projecting future scenarios (Cai et al., 2021). RCMs offer finer spatial resolution compared to global climate models (GCMs), thereby enhancing the simulation of detailed physical processes (Bellprat et al., 2012; Giorgi, F., 2019). Despite advancements, CMIP6 models contain uncertainties that stem from grid resolution, numerical schemes, and parameterizations. Most global climate models operate at ~1° horizontal resolutions, which limits their ability to capture regional oceanic intricacies such as those in the SCS and the Strait of Malacca. Consequently, CMIP6 oceanic components incorporate parameterizations to account for mesoscale process impacts on transport parameters (van et al., 2020). Sea level changes in Malaysian waters are influenced by global and regional climate drivers, as well as local tectonic factors. These variations occur across different regions and seas.

Despite the parameterization and coupling methods used in CMIP6 models, spatial resolution plays a critical role in accurately capturing sea levels, particularly in smaller regions such as Malaysia. CMIP6 models were originally developed as General Circulation Models (GCMs) and cropped to the Malaysian region. However, due to their native grid resolution (as outlined in Tables 3.3 and 3.5), none of the models were able to fully capture all the seas within the Malaysian region, especially the Strait of Malacca. The Malacca Strait is a shallow, narrow body of water, with an average depth of 25 meters. It is wider and deeper in the northern section, with an average depth of 66 meters, but narrows and shallows in the south, reaching a depth of approximately 20 meters (Sakmani et al., 2013). Consequently, models with a spatial resolution of 1° (~111.1 km) produce limited or no data for such a region. These limitations are addressed through spatial interpolation, which is important for spatial mapping with scattered data obtained from multiple sources (Ghosh et al., 2020). However, while spatial interpolation helps mitigate data gaps, it is important to note that the choice of interpolation technique may introduce additional uncertainties, potentially affecting the accuracy of the interpolated results. Moreover, the accuracy of spatial interpolation may also be affected in small and narrow seas, such as the SM and the SS, due to the relatively coarse spatial resolution of the data.

Nonetheless, CMIP6 models offer distinct advantages over RCMs by providing a comprehensive framework for simulating the global climate system and capturing interactions among the atmosphere, oceans, land surface, and sea ice (Eyring et al., 2016). These models incorporate a broader spectrum of variables influencing sea level rise, including glacier and ice sheet melting, thermal expansion of seawater, and changes in oceanic circulation patterns. As a result, they offer a more accurate representation of large-scale climate and oceanic processes, which RCMs may overlook. However, if these variables were incorporated into RCMs, they could enhance the accuracy of regional climate projections by better capturing localized climate dynamics and their interactions with larger-scale processes.

In addition, the coordinated multi-model experiments of CMIP6 enhance the robustness and reliability of climate projections through ensemble averaging and intercomparison, systematically addressing uncertainties and biases (Tebaldi et al., 2021). CMIP6 models also support global-scale climate impact assessments, aiding international policymaking with accessible, standardized datasets (O'Neill et al., 2016). In this study, CMIP6 projections indicate that while sea levels will continue to rise in the future, the rate of increase may be slower than previously estimated due to feedback mechanisms embedded within the models. The IPCC report emphasizes that rising global temperatures are predominantly driven by anthropogenic activities such as fossil fuel combustion, with resulting impacts on sea level rise. The complex relationship between global temperatures and sea level dynamics remains a topic of ongoing research.

4.2 Total Sea Level projection (TSL) for Southeast Asia

From a pool of 15 models, CMCC-ESM2, MPI-ESM1-2-HR, and MPI-ESM1-2-LR are selected based on their performance, assessed using Taylor diagrams. These models are chosen to generate ensemble mean projections of future sea levels in Malaysian waters. In SCS, CMIP5 models project a minimum sea level rise of 25.8 cm (2.72 mm/year) under RCP2.6 and a maximum rise of 84.5 cm (8.89 mm/year) under RCP8.5 by the end of the century (Zuo et al., 2021). Under anthropogenic forcing scenarios such as SSP3-7.0, long-term sea level projections rely on global coupled climate models to simulate oceanic responses to varying radiative forcings (Lyu et al., 2020).

Table 2 presents the sea level projection capabilities of the ensemble mean models. Projections indicate higher sea levels in SCS and the southern SCS compared to SS and SM, reflecting their greater exposure to open ocean dynamics. Spatial and temporal sea level variations are primarily driven by climate change, wind patterns, and shifts in ocean circulation (Mohan and Vethamony, 2018). Situated between the western Pacific and Indian Oceans, the SCS exhibits significant interannual and decadal sea level variability influenced by major climate modes such as the El Niño–Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the Indian Ocean Dipole (IOD) (Soumya et al., 2015). Additionally, sea level variability in this region is modulated by both local and remote forcing mechanisms, including volume transport through key straits and variations in depth-integrated temperature and salinity (Mohan and Vethamony, 2018). Under the SSP3-7.0 scenario, the ensemble mean projections (Table 2) indicate that sea level rise is most pronounced in the SCS's Pacific-facing regions, particularly in the SCSPM and SCSEM subregions. This pattern underscores the dominant influence of open-sea exposure relative to the more enclosed SM and SS regions. Long-term sea level fluctuations in the SCS are governed by large-scale climate variability, wind-driven changes, and ocean circulation dynamics. The interplay between local and basin-scale processes, such as throughflow transport and thermohaline structure variations, further complicates sea level trends in the northeastern Indian Ocean and the SCS (Mohan and Vethamony, 2018).

The ensemble mean models project consistent sea level trends across all regions through 2080, with estimated rates of 0.6 mm/year for the SM, 0.8 mm/year for the SCSPM, 0.7 mm/year for the SCSEM, and 0.6 mm/year for SS. These projections align with previous CMIP5 simulations for the SCS, which indicate a slight positive linear trend under Representative Concentration Pathway (RCP) scenarios, with rates ranging from 0.63 mm/year to 1.04 mm/year for the period 2006–2100, although some simulations also suggest localized negative trends within the same timeframe (Huang and Qiao, 2015).

By 2100, the ensemble mean models project an acceleration in sea level rise, with annual rates reaching 0.8 mm/year for SM, 1.0 mm/year for SCSPM, 0.9 mm/year for SCSEM, and 0.8 mm/year for SS. These estimates are generally consistent with CMIP5 projections under RCP8.5, which suggest sea level rises of 0.68 to 0.74 meters across Malaysian waters by the end of the century (Mohamed Rashidi et al., 2021). However, the ensemble mean projections exhibit slightly lower rates in certain regions, potentially due to differences in model resolution, regional forcing factors, or the incorporation of additional observational constraints. While both modelling approaches indicate an overall rising trend, the ensemble mean models provide refined regional-scale insights, whereas CMIP5 outputs primarily capture broader-scale trends influenced by large-scale climate dynamics.

4.3 Sea Level Change from CMIP6 Key Contributors in TSL

The projected decline in the ice sheet contribution to TSL over time, despite rising global temperatures, is likely driven by dynamic ice sheet responses, including enhanced ice discharge, structural instabilities, and increased surface meltwater percolation. Initially, ice loss from Greenland and Antarctica is substantial due to intensified surface melting and calving (McInnes and Zhang, 2024).However, over longer timescales, negative feedback mechanisms, such as increased basal water pressure temporarily stabilizing ice streams, may moderate mass loss rates (Wang et al., 2023). Conversely, mass loss from glaciers and ice caps is expected to accelerate, as smaller ice bodies, which respond more sensitively to warming, undergo rapid retreat and contribute disproportionately to sea level rise (Mimura, 2013). The sterodynamic contribution, encompassing both thermosteric (heat-driven expansion) and halosteric (salinity-driven) effects, is projected to increase due to sustained ocean warming and shifting circulation patterns (Govorčin et al., 2025). Additionally, while groundwater discharge currently plays a minor role in TSL, its contribution is expected to grow due to anthropogenic factors, including excessive groundwater extraction and land-use changes that reduce terrestrial water retention (Naish et al., 2024).

Several studies support these findings, particularly those based on the IPCC AR6 framework. report a similar trajectory in sea level rise components, which highlights the increasing dominance of sterodynamic effects and the declining relative contribution of ice sheets beyond the mid-century (McInnes and Zhang, 2024). Similarly, indicate that sterodynamic changes and glacier melt will become the primary drivers of sea level rise, while ice sheet contributions may stabilize or slightly decline, depending on future emission scenarios (Slangen et al., 2023). Regional analyses further demonstrate spatial variability in sterodynamic contributions, with pronounced impacts projected in tropical and subtropical regions, including Southeast Asia by (Jin et al., 2024).

The negative contribution of GIA to sea level rise is well-documented in the literature (Kopp et al., 2010). GIA represents a delayed response to ice mass loss following the Last Glacial Maximum, leading to land uplift in previously glaciated regions such as Scandinavia and parts of Canada, while inducing relative subsidence in forebulge regions, including parts of Southeast Asia (Weeks et al., 2023). This process results in a localized reduction in relative sea level, partially offsetting the effects of rising ocean waters in these areas. The increasing magnitude of GIA's negative contribution over time reflects ongoing crustal adjustments as ice mass loss continues to redistribute Earth's mass balance (Thiéblemont et al., 2019).

5. Conclusion

This study investigates projected sea level changes in Malaysian waters using CMIP6 models within the SSP3-7.0 framework throughout the 21st century. The analysis focuses on sea-level changes in Southeast Asia, specifically SCS, which includes SCSPM, SCSEM, SM, and SS. Various key contributors to sea level rise are examined, including thermal expansion, ice sheet and glacier melting, groundwater discharge, and glacial isostatic adjustment. CMIP6 models are tailored to the study region and validated against observational data to identify high-performing models. Based on this validation, three models (CMCC-ESM2, MPI-ESM1-2-HR, and MPI-ESM1-2-LR) are selected and combined to derive an ensemble mean for future sea level projections.

The ensemble mean is utilized to forecast sea level trends across Malaysian seas, encompassing SM, SCSPM, SCSEM, and SS. Sea level changes exhibit spatial variability across these regions, as detailed in Table 2. Notably, the SCS (SCSPM and SCSEM) shows more pronounced variability compared to SM and SS. By 2030, the ensemble mean projects a sea level rise of 16 mm in the SCS, with Peninsular Malaysia experiencing levels reaching 0.908 m and a trend of 1.5 mm/year, while East Malaysia shows a rise of 14.5 mm, with levels reaching 0.895 m and a trend of 1.1 mm/year. By 2040, SCSPM and SCSEM are projected to rise by 20.2 mm and 21.5 mm, with trends of 0.6 mm/year and 0.7 mm/year, respectively. This represents an increase of sea level to 1.749 m and 1.719 m for SCSPM and SCSEM respectively. By 2070, sea levels for SM, SCSPM, SCSEM, and SS range between 1.713 m and 1.888 m, corresponding to significant increases of 162.2 mm, 182.5 mm, 189.8 mm, and 173.9 mm, respectively. By 2080, projections indicate increases of 57.7 mm and 53.2 mm for SCSPM and SCSEM, with rate of 0.8 mm/year and 0.7 mm/year. By the end of the century, the ensemble mean forecasts a rise of 83.1 mm and 81.7 mm for SCSPM and SCSEM, with trends of 1.0 mm/year and 0.9 mm/year, respectively. SS is also expected to experience significant changes, with a projected rise of 65.2 mm and a trend of 0.8 mm/year by 2100. In contrast, SM shows a more modest projection of 58.8 mm and a rate of 0.8 mm/year by the end of the century. The sea level projections by 2100 ranges between 1.875 m and 2.073 m, which shows a clear trend of rising sea levels.

TSL changes throughout the 21st century reveal a shifting balance in the contributions of different components to sea level rise. While ice sheets dominate the contributions in the early decades, their relative significance diminishes towards the end of the century, with sterodynamic changes becoming more prominent under increasing warming scenarios. By 2030, ice sheets (52.1%) and sterodynamic (46.8%) are the main contributors, while glaciers (1.6%) and groundwater discharge (0.2%) play minor roles, and GIA contributes a negative change of -0.6%. However, by 2100, sterodynamic processes contribute nearly half of the total sea level rise, highlighting their growing influence under continued warming. Glacier melt and groundwater discharge also exhibit a gradual increase in their contributions, although their overall impact remains minor compared to sterodynamic and ice sheet contributions. Meanwhile, GIA consistently offsets sea level rise, but its influence on sea level variability remains negligible in the long term. The study emphasizes the growing influence of oceanic thermal expansion and salinity-driven changes as primary drivers of future sea level rise in the SCS.

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