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Southern South China Sea Dynamics: Sea Level Change from Coupled Model Intercomparison Project Phase 6 (CMIP6) in the 21st Century

Noah Irfan Azran [1], Hafeez Jeofry [1,2,*], Jing Xiang Chung [1,2], Liew Juneng [3], Syamir Alihan Showkat Ali [4], Alex Griffiths [5], Muhammad Zahir Ramli [6], Effi Helmy Ariffin [1,2], Mohd Fuad Miskon [6], Juliana Mohamed [6], Kamaruzzaman Yunus [6] and Mohd Fadzil Akhir [1]

1 Institute of Oceanography and Environment, Universiti Malaysia Terengganu, Kuala Nerus, Terengganu 21030, Malaysia
2 Faculty of Science and Marine Environment, Universiti Malaysia Terengganu, Kuala Nerus, Terengganu 21030, Malaysia
3 Department of Earth Sciences and Environment, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi 43600, Malaysia
4 Faculty of Mechanical Engineering and Technology, Universiti Malaysia Perlis, Perlis 02600, Malaysia
5 London Metallomics Facility, King's College London, London WCR 2LS, UK
6 Institute of Oceanography and Maritime Studies (INOCEM), Kulliyyah of Science, International Islamic University Malaysia, Kuantan 25200, Malaysia
* Correspondence: hafeez.jeofry@umt.edu.my

Abstract: Sea level rise will significantly impact coastal areas around the world. As a coastal country, Malaysia's rising sea levels are a significant concern because they would affect 70% of its population. The study of sea level rise is important in order to implement effective mitigation and adaptation strategies. This study investigates the performance of CMIP6 Global Climate Models (GCMs) in simulating sea level rise in the Malaysian seas using various statistical methods. The models' performances were evaluated by comparing historic CMIP6 GCM runs from 1993 to 2010 with sea level measurements from the satellite altimetry AVISO+ using the Taylor diagram. The SCS (SCSPM and SCSEM) had a higher sea level range and trend in both selected areas than the SM and SS. With 1.5 °C warmings, the multi-model ensemble means predicted that the SCS would rise by 16 mm near the Peninsular, with sea levels increasing by 0.908 m at a rate of 1.5 mm/year, and by 14.5 mm near East Malaysia, with sea levels increasing by 0.895 m at a rate of 1.1 mm/year. In contrast, 2.0 °C warmings project that SCSPM and SCSEM would cause sea levels to rise by 20.2 mm and 21.5 mm, respectively, at a rate of 0.6 mm/year and 0.7 mm/year. This information will provide an insight into Malaysian sea levels between now and the end of the twenty-first century, which will be beneficial for government agencies, academics, and relevant stakeholders.

Keywords: dynamic sea level; sea level rise; CMIP6; South China Sea; future projections; climate change

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1. Introduction

All components of the climate system have changed: the atmosphere and the ocean have warmed; the amount of snow and ice at polar latitudes has decreased; sea levels have risen; the ocean has acidified and its oxygen content has decreased; and atmospheric concentrations of greenhouse gases (GHGs) have increased [1]. Sea level rise is one of the most significant effects of climate change due to global warming, potentially affecting many coastal areas worldwide [2]. Climate-induced Sea level rise, for example, has been identified as a severe threat to low-lying coastal regions and communities worldwide since the concept of human-induced global warming was discovered in the 1980s [3–6]. Global sea levels have increased dramatically over the last 15 years, and the trend is expected to accelerate by the end of the twenty-first century [7]. Sea level rise does not occur globally but is influenced by various regional factors [8]. Regional sea level rise varies according to the rate of melting glaciers, atmospheric processes, isostatic adjustment, thermal expansion, and other localised processes [9]. Estimating the effects of sea-level rise on coastal regions and communities using global sea level projections is challenging [10]. The Malaysian coastline stretches 1972 km on the Peninsular and 2873 km on the East (i.e., Sarawak and Sabah) [11]. A total of 70% of Malaysia's total population lives around coastal zones [12] and is at risk from sea level rise. The concentration of people and assets along the coasts, including many large cities, has already rendered them "risky locations," vulnerable to various climatic and geophysical hazards such as storms and storm-induced flooding [13]. Sea level rise and other extreme climate events could harm coastal communities by inundating lowland coastal regions, causing coastal erosion, and causing infrastructure damage [14–16]. Unlike rare large-magnitude storms, which can alter the coastal area within hours, the effects of sea level rise are frequently slow, recurring, and cumulative [17]. Hence, the projected sea level rise would aid in developing mitigation and adaptation plans for coastal cities. Since coastal communities are likely to be impacted by sea level rise and affect built infrastructure systems [18], flood risks in specific coastal areas are frequently calculated by observing maximum sea levels from tide gauge data over decades or by numerical modelling [19].

Therefore, this study aims to analyse sea level rise in the southern South China Sea (SCS) based on a 1.5 °C and 2.0 °C rise in global temperature relative to pre-industrial levels until end-of-century sea levels using Coupled Model Intercomparison Project phase 6 (CMIP6) under the SSP3-7.0 scenario. The main purpose of the study is to evaluate the performance of CMIP6 models in simulating the dynamic sea level over the southern South China Sea, especially in the Malaysia region (0–8° N longitude and 98° E–120° E latitude). Numerous studies have evaluated global climate models (GCMs) in simulating the regional dynamic sea level, but these studies were limited to a specific region or time. Moreover, most of the studies focused on CMIP5 models, with a few regarding CMIP6 models. The shared socioeconomic pathways (SSPs) generate multiple radiative forcing pathways and associated warming up to the end of the twenty-first century using numerous assumptions. The SSPs represent a range of future greenhouse gas emission and land-use change scenarios based on various assumptions about economic growth, climate mitigation efforts, and global governance [20]. SSPs build on RCPs by allowing for systematic comparisons of societal choices and the subsequent variability of climate change; therefore, the modelling approach is based on the updated interpretation of our understanding in terms of how future changes will vary and likely occur. The CMIP6 GCMs and AVISO+ Satellite Altimetry are cropped down into the Malaysia regional area, which is the southern South China Sea. Fifteen GCMs' historical simulation are validated using the AVISO+ Satellite Altimetry, and well-performing models are then selected to produce a multi-model mean ensemble.

2. Materials and Methods

Since the early 1990s, satellite measurements have provided detailed measurements of Sea Surface Height (SSH) above geoid (zos) (m) [21]. Zos measures sea level pattern variations around the ocean geoid (defined as resting ocean state) at z = 0, with global mean thermosteric (thermal expansion) effects removed and only involving ocean dynamics [22], generating a dynamic sea level [21]. Many factors influence the static equilibrium of sea level, which refers to the sea level associated with the fluid dynamic state of the ocean and geophysical factors (such as ocean currents, density, the boundary of mass flux, buoyancy impact, earth's gravity, deformation, rotation, tectonic uplift, thermal subsidence, and shoreline morphology) [21,23–25]. AVISO (Archiving, Validation, and Interpretation of Satellite Oceanographic Data), retrieved from https://podaac-tools.jpl.nasa.gov/drive/files/allData/aviso/L4/dynamic_topo_1deg_1mo (accessed on 25 January 2022) provides satellite-derived SSH above geoid measurements from TOPEX/Poseidon, EN-

VISAT, JASON-1, and OSTM/JASON-2 altimetry. From October 1992 to December 2010, it provided merged and calibrated sea level data. On a 1° × 1° grid resolution, the data covers the area from 65° S to 65° N (near-global). The Earth System Grid Federation (ESGF) provided monthly averages for 15 CMIP6 models (Tables 1 and 2), and historical and projection data were obtained from the variable zos [26]. The model's performance was assessed by comparing CMIP6 GCM historical runs from 1993 to 2010 with sea level measurements from the AVISO satellite altimetry system. Based on the initial conditions used in model simulations, climate models can produce a variety of projections for sea level rise. The first ensemble member (referred to as "r1i1p1f1") from the CMIP6 models is based on their availability in the same ensemble. Each GCM in the CMIP6 contains a specific number of ensembles; each ensemble is distinguished by a variation label denoted by the indices r, i, p, and f; the designation identifies the realisation number, initialization technique indication, perturbed physics, and forcing index [25]. The SSP-3.70 Shared Socioeconomic Pathways (SSPs) scenario was used in model selection. The SSP3-7.0 path is rocky, with increasing population growth, resurgent nationalism, and regional conflicts that pose high mitigation and adaptation challenges [27]. The scenario represents the medium-to-high range of future forcing pathways [28] that led to the selection of the scenario, which would likely represent the current world situation. The models were then filtered based on their availability, as some may have historical simulations but no future projections and vice versa. Furthermore, the models were chosen based on their resolution grid, with selected models from the 100 km resolution grid and below. The models were validated to identify the best-performing models for sea level variability. For a comparison study between the models and observed data, each model was converted into a uniform grid size of 0.333° × 0.333° using bilinear interpolation. In addition, the smaller grid size aids in capturing zos data, particularly in a narrower area such as the Malacca Strait. The observed data for sea level were collected from AVISO products from 1993 to 2010, while the CMIP6 archive provides historical data for each model from 1850 to 2014, which were then cropped to match the observation data from 1993 to 2010 (Tables 1 and 2).

Table 1. Details of datasets used.

1. Dataset	2. Temporal Resolution	3. Spatial Resolution	4. Time Coverage
5. AVISO	6. Monthly	7. 1° × 1°	8. 1993–2010
9. CMIP6 Models	10. Monthly	11. Varies	12. Historical (1993–2010)

A Taylor diagram is employed to provide a graphical and statistical overview of correlation coefficients, root-mean-square deviation (RMSD), and standard deviation of the models [29]. The Taylor diagram is useful for examining multiple features of complex models or comparing the relative skill of various models. These were then used to select models to produce a multi-model mean ensemble for the future projection of sea levels in Malaysia. Four areas were chosen for the future projection of sea levels to represent all the seas in Malaysia (Figure 1 and Table 3). The four areas were chosen to evaluate the sea level change between 2015 and 2100 (which includes 1.5 °C and 2.0 °C warming) as sea levels do not rise uniformly across the Malaysian seas. These four areas would indicate the range of sea level rise at the start of the projection (2015) across the Malaysian seas. Malaysia's coastline is mostly made of easily eroded alluvium, with half of the coastline being sandy and the other half being muddy with a few rocky beaches. Sandy shores dominate the east coast of the Malaysian Peninsular, the west coast of East Malaysia, and some parts of Peninsular Malaysia. In contrast, the west coast of Peninsular Malaysia, as well as the north and east coasts of East Malaysia, are dominated by silt, mud, and clay [30,31]. The areas are the Strait of Malacca (SM), South China Sea—Peninsular Malaysia (SCSPM), South China Sea—East Malaysia (SCSEM), and Sulu Sea (SS). Each coordinate was determined, which is approximately ~30 km from the coast, and the sea level value was chosen based on the grid and its neighbouring grid (4 × 4 selected grid boxes), which were then averaged to produce the range of sea levels.

Table 2. Information on the Coupled Model Intercomparison Project Phase 6 (CMIP6) models.

Model	Coupled Model Name	Nominal Resolution	Grid Info
BCC-CSM2-MR	Beijing Climate Centre	100 km	360 × 232
CanESM5	Canadian Earth System Model version 5	100 km	360 × 291
CMCC-CM2-SR5	The Euro-Mediterranean Centre on Climate Change	100 km	362 × 292
CMCC-ESM2	The Euro-Mediterranean Centre on Climate Change	100 km	362 × 292
EC-Earth3	European Centre Earth Model version 3	100 km	362 × 292
EC-Earth3-AerChem	European Centre Earth Model version 3	100 km	362 × 292
EC-Earth3-Veg	European Centre Earth Model version 3	100 km	362 × 292
EC-Earth3-Veg-LR	European Centre Earth Model version 3	100 km	362 × 292
GFDL-ESM4	Geophysical Fluid Dynamics Laboratory	50 km	720 × 576
MIROC6	Model for Interdisciplinary Research on Climate version 6	100 km	360 × 256
MPI-ESM1-2-HR	Max Planck Institute Earth System Model	50 km	802 × 404
MRI-ESM2-0	The Meteorological Research Institute Earth System Model Version 2	100 km	360 × 363
NorESM2-LM	The Norwegian Earth System Model	100 km	360 × 385
NorESM2-MM	The Norwegian Earth System Model	100 km	360 × 385
TaiESM1	Taiwan Earth System Model	100 km	320 × 384

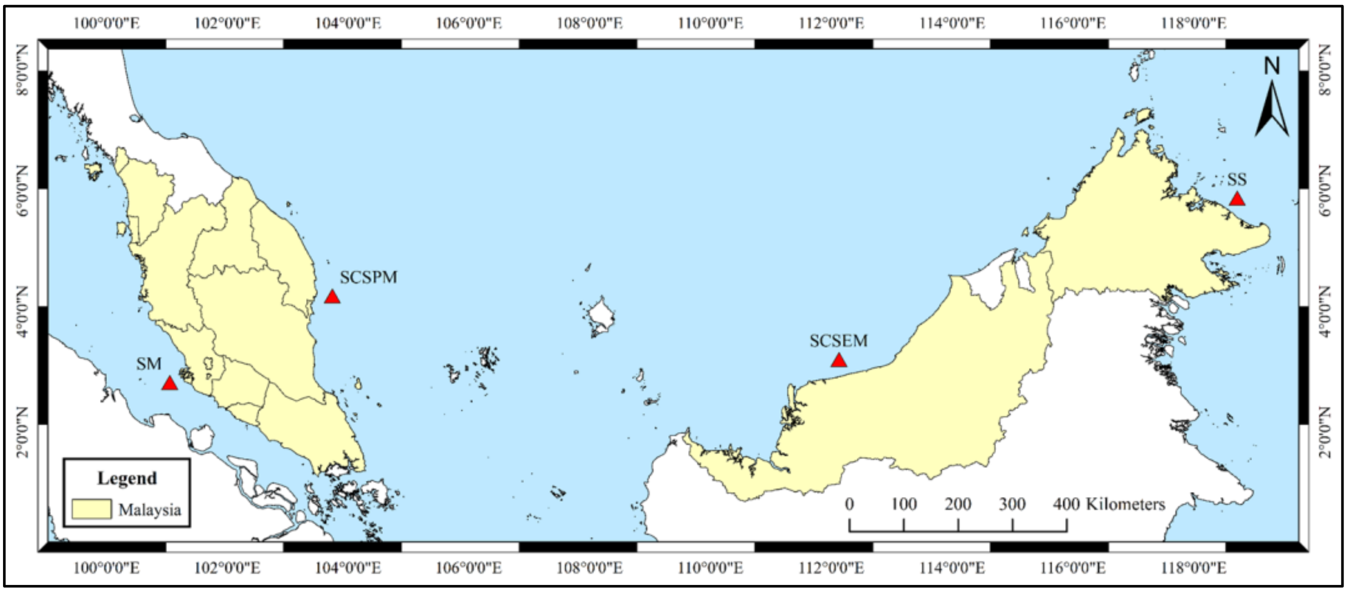

Figure 1. Map of study area and location selected for SSH observation.

Table 3. Coordinates of location selected for SSH observation.

Point	Location	Longitude	Latitude
SM	Malacca Strait	101°3′8.57″ E	2°49′38.36″ N
SCSPM	SCS—Peninsular	103°44′34.45″ E	4°15′34.30″ N
SCSEM	SCS—Sarawak	112°7′52.34″ E	3°12′31.81″ N
SS	Sulu Sea	118°43′30.36″ E	5°52′49.73″ N

3. Results

The results were separated into three different parts: the historical spatial analysis of sea levels around Malaysia; the selection of models based on spatial analysis; and sea level projections for Malaysian seas. The first two parts consist of assessing dynamic sea level from the CMIP6 historical simulation with satellite observation and selecting models based on the Taylor diagram (Figures 2–4). The sea level projection for Malaysian seas was made to project the future dynamic sea level from CMIP6 models based on the SSP3-7.0 scenario (Figure 5 and Table 4). The future projection consists of dynamic sea level projection timesteps (2015–2100).

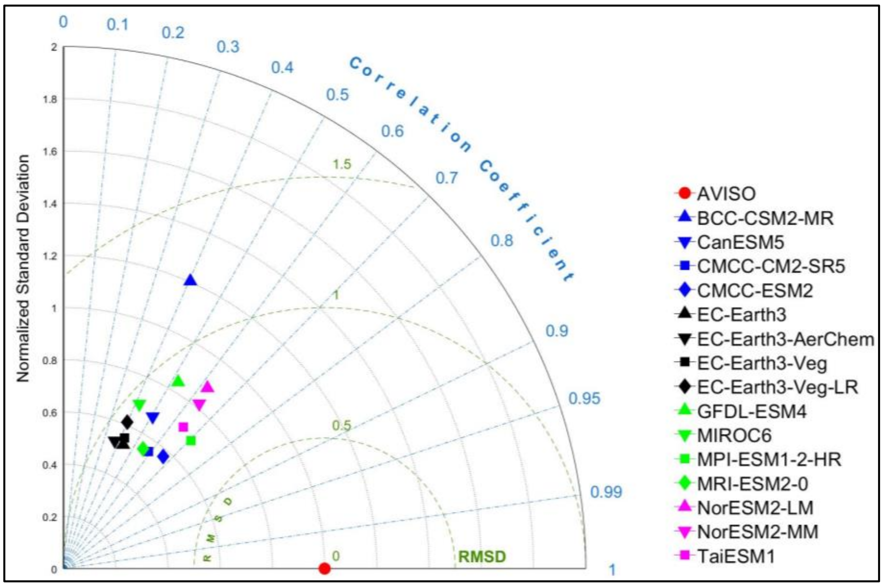

Figure 2. Taylor diagram of CMIP6 mean SSH above geoid (zos) compared with observation (AVISO).

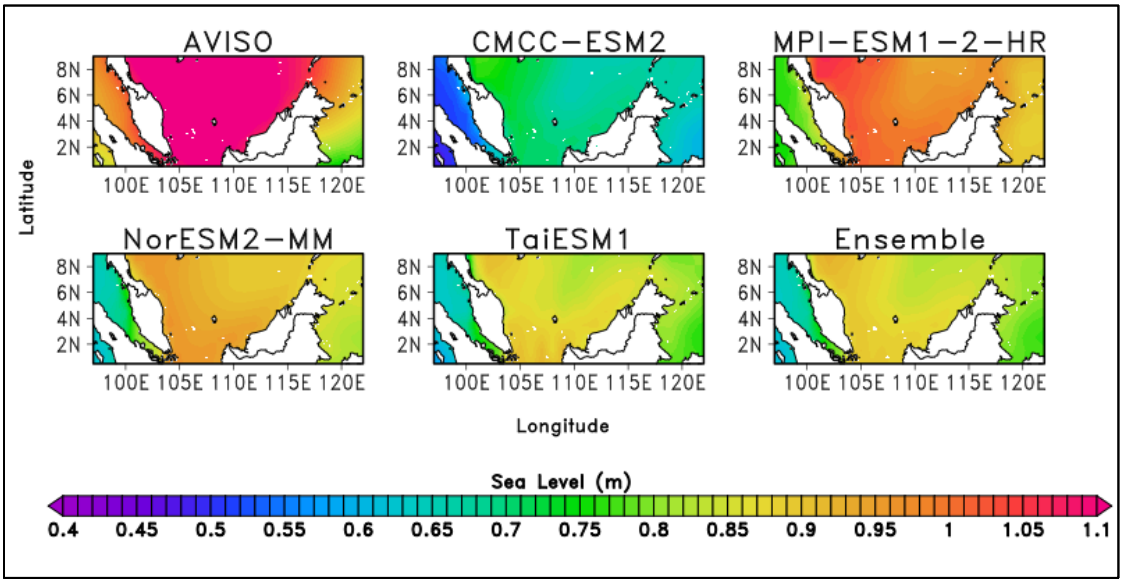

Figure 3. Spatial Distribution of well-performed CMIP6 models based on the Taylor diagram over the time mean 1993–2010.

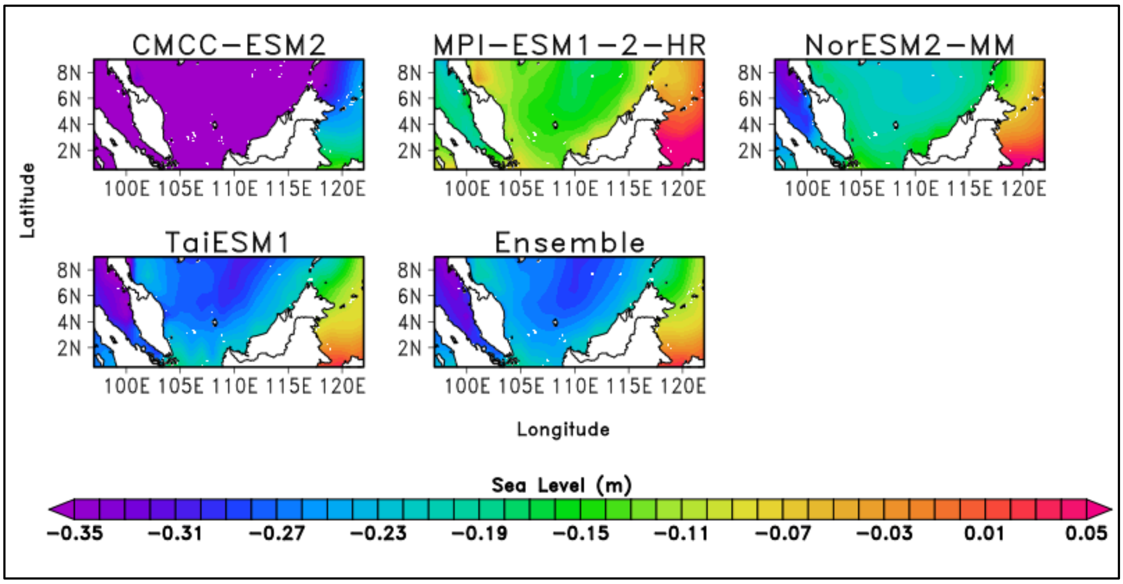

Figure 4. Spatial Distribution Bias of well-performed CMIP6 models based on the Taylor diagram over the time mean 1993–2010.

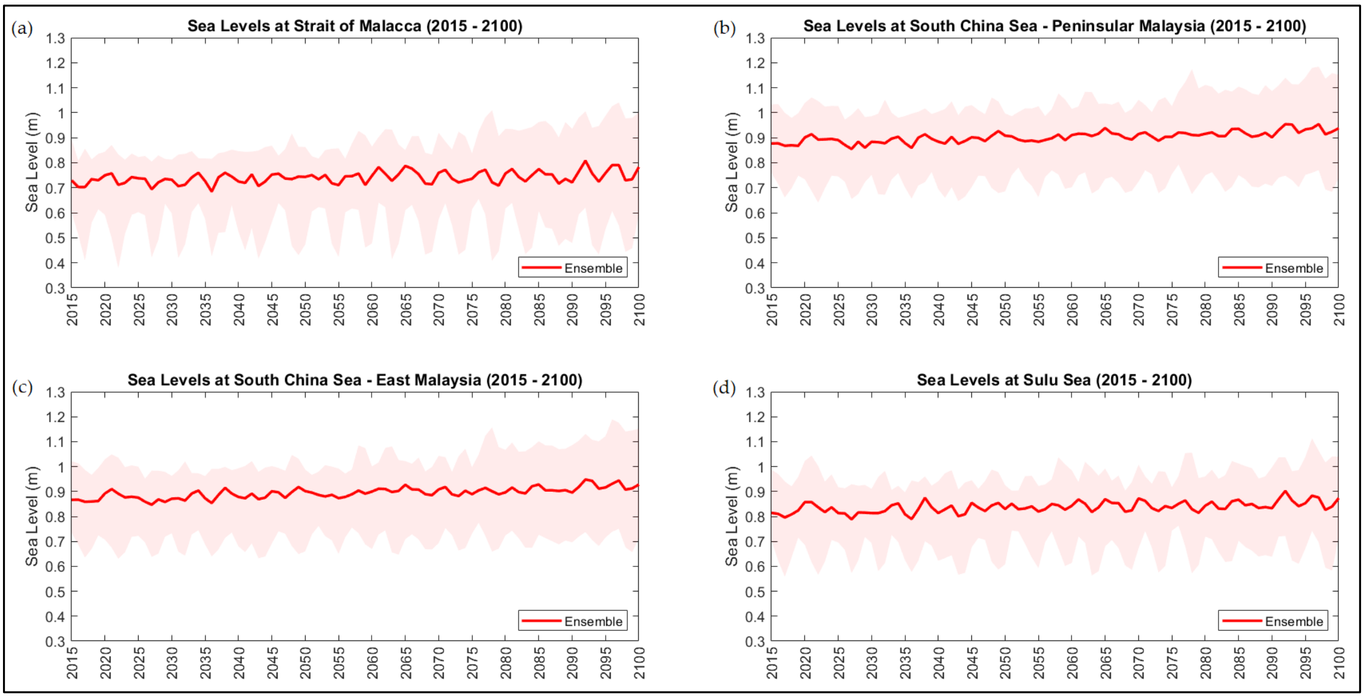

Figure 5. Sea Surface Height (SSH) Projection 2015–2100 with maximum and minimum ranges (shaded area). (**a**) Sea Levels at the Strait of Malacca; (**b**) Sea Levels at SCS—Peninsular Malaysia; (**c**) Sea Levels at SCS—East Malaysia; (**d**) Sea Levels at Sulu Sea.

Table 4. Multi-model mean ensemble projected sea level, sea level change, and trend from start year (2015).

Warming	Year	Strait of Malacca			SCS—Peninsular Malaysia			SCS—East Malaysia			Sulu Sea		
		Sea Level (m)	Sea Level Change (mm)	Trend (mm/Year)	Sea Level (m)	Sea Level Change (mm)	Trend (mm/Year)	Sea Level (m)	Sea Level Change (mm)	Trend (mm/Year)	Sea Level (m)	Sea Level Change (mm)	Trend (mm/Year)
1.5 °C	2028	0.752	4.5	1.0	0.908	16.0	1.5	0.895	14.5	1.1	0.838	9.2	0.6
2.0 °C	2043	0.757	10.0	0.5	0.912	20.2	0.6	0.903	21.5	0.7	0.844	15.4	0.5
	2080	0.783	36.3	0.6	0.950	57.7	0.8	0.934	53.2	0.7	0.869	40.1	0.6
	2100	0.806	58.8	0.8	0.975	83.1	1.0	0.963	81.7	0.9	0.894	65.2	0.8

3.1. Historical Spatial Analysis of Sea Levels around Malaysia

Figure 2 depicts the Taylor diagram, which compares the simulated zos from CMIP6 with satellite-derived data (AVISO) from 1993 to 2010. The Taylor diagram selected the models CMCC-ESM2, MPI-ESM1-2-HR, NorESM2-MM, and TaiESM1 based on their standard deviation, correlation coefficient, and RMSD spatially to the AVISO satellite data. Models exhibiting the highest correlation coefficient and the lowest RMSD and standard deviation were classified as the best models [10]. The RMSD indicated the models' variation from the observation. Most models had a RMSD score between 0.5 and 1, meaning that many models were close to the observations, the only exception being the BCC-CSM2-MR model, which had a higher RMSD score of >1. Since the correlation coefficient value ranged between 0.2 and 0.7, values greater than 0.6 were chosen as the value to assess model performance. Lastly, the standard deviation revealed that most models were scattered around or below one, except for the model BCC-CSM2-MR, which has a higher standard deviation of approximately 1.2.

Figure 3 shows the monthly average zos data simulated by selected models, which were cropped down from the GCM, and the AVISO observation plotted from the time mean from 1993 to 2010. According to AVISO data, the Malaysian seas have an average SSH of 0.7 to 1.15 metres. The observational sea levels in the SCS are almost evenly distributed spatially, with a value of 1.1 metres. The value falls as it approaches the Sulu Sea region, eventually reaching 0.95 metres. The Malacca Strait changes as it narrows, with sea levels rising from 0.7 metres to 1.05 metres. The models, MPI-ESM1-2-HR and NorESM2-MM, underestimate sea levels the least, with spatial variability ranging from 0.9 to 1.05 metres and increasing inshore to the East Coast of Malaysia Peninsular. Meanwhile, CMCC-ESM2 and TaiESM1 underestimate sea levels even further, with sea levels ranging from 0.7 to 0.9 metres. The CMCC-ESM2 model underestimates sea levels even more, with the models displaying a blue shade in the area, indicating it is less than 0.6 metres. Alternatively, the observation showed that sea levels range between 0.85 and 1.05 metres, while the multi-model mean ensemble stays in the middle between 0.75 metres and 0.95 metres.

Compared with the AVISO values in Figure 4, selected model outputs (CMCC-CM2-SR5, CMCC-ESM2, MPI-ESM1-2-HR, NorESM2-MM, TaiESM1, and the multi-model mean ensemble) were found to have a bias ranging from −0.35 to 0.05 m. This demonstrated that all the models understated the zos values. The models MPI-ESM1-2-HR and NorESM2-MM showed that as sea levels approached the east coast of Peninsular Malaysia, the bias range increased steadily from −0.2 to −0.05 m. CMCC-ESM2 showed minor sea level variations, with the sea level bias indicating a shaded blue colour on most seas. In contrast, the TaiESM1 and multi-model mean ensemble show that going down the SCS, the bias range drops from −0.2 metres to −0.15 m. These biases arise from the models' ability to replicate the ocean processes to simulate the dynamic sea level variance [32].

3.2. Selection of Models Based on Spatial Analysis

Four of the best-performing models were chosen based on historical spatial analysis (Figure 3): CMCC-ESM2, MPI-ESM1-2-HR, NorESM2-MM, and TaiESM1, and they produce an ensemble mean to project future sea levels in the Malaysian seas. A total of four models were used to produce the multi-model mean ensemble. In keeping the intercomparison manageable, model ensemble means were focused rather than using only individual models [33]. All the figures for the individual models are provided in the Supplementary Material. The CMCC-ESM2 uses the European community model, Nucleus for European Modelling of the Ocean (NEMO) (v3.6), to simulate general ocean circulation, which also solves the transport of oceanic tracers [34]. NEMO is a versatile instrument for studying the ocean and its interactions with other components of the Earth's climate system at several spatial and temporal dimensions. The NEMO physical engine solves the traditional primal equations of ocean circulation using the Boussinesq, hydrostatic, and incompressibility approximations. The three velocity components, the SSH, potential seawater temperature, and salinity, are the prognostic factors in which the engine includes a variety of numerical schemes for solving key physical processes such as advection, diffusion, vertical dynamics, seawater equations of state, lateral and bottom boundaries, and air-sea interactions [35].

The MPI-ESM1.2 is the most recent version of the Max Planck Institute Earth System Model. It serves as the baseline for the Coupled Model Intercomparison Project Phase 6 and current seasonal and decadal climate predictions, with the MPI-ESM1.2-HR representing the higher-resolution version compared with its lower-resolution version, the MPI-ESM1.2-LR [36]. The land-surface scheme JSBACH is included in the atmospheric submodels of MPI-ESM1.2 and ECHAM6.3. In contrast, the ocean and sea ice submodels are merged in the Max Planck Institute Ocean Model (MPIOM), whereas ECHAM6.3 and MPIOM are coupled via the Ocean-Atmosphere-Sea-Ice coupler version 3 (OASIS3-mct) [37].

The NorESM2-MM model is the medium-resolution version, while the NorESM2-LM model is the low-resolution version; both models primarily share the same surface ocean biases. However, the MM version is slightly closer to the observations [38]. Due to its higher resolution, NorESM2-MM would have been better than NorESM2-LM at capturing the sea levels in Malaysia. This pertains primarily to the water levels in the Strait of Malacca, a narrow strait that encompasses the western coast of Peninsular Malaysia. While the land and sea-ice components are primarily the same as in CESM2, NorESM2 has completely different coupled models. For the ocean (Bergen Layered Ocean Model, or BLOM), ocean biogeochemistry (isopycnic coordinate Hamburg Ocean Carbon Cycle, or iHAMOCC), and atmosphere (the Community Atmosphere Model, Version 6-Norwegia, or CAM6-Nor, which includes various modules, i.e., aerosol life cycle, aerosol–radiation–cloud interactions, changes related to the moist energy formulation, deep convection scheme, and angular momentum conservation), and the turbulent air-sea flux computations are adjusted, accurate temporal averaging of the solar zenith angle is applied in the albedo estimate [38].

The addition of different coupled models affects the dynamic processes of the ocean and the air-sea interaction, which in turn influences the dynamic sea level of the NorESM2-MM model. Although the Atlantic Ocean's SSH is too low, the NorESM global mean SSH is comparable with observations. Although the atmospheric time of oceanic water vapour is consistent with observations, the model overestimates oceanic evaporation by about 4% and the flux of water vapour from the ocean to land by about 8% [39]. The model simulates the Madden–Julia Oscillation (MJO), El Nino Southern Oscillation (ENSO), and northern and southern annular modes. During the simulation period, the model has a robust Atlantic Meridional Overturning Circulation (AMOC), which contributes to the efficient transport of heat into the deep oceans and reduces the heat available for increasing the surface temperature and melting ice and snow, with exceptions near sizeable deep water formation zones, such as the Arctic's Atlantic sector and Northwest Europe, where warm water in the upper ocean converges [40].

Meanwhile, the TaiESM1 was developed with modifications to the Community Earth System Model Version 1.2.2 (CESM1.2.2) (cumulus convection scheme and cloud fraction scheme, replacement of the aerosol scheme with a new one, and implementation of a unique scheme for three-dimensional surface absorption of shortwave radiation that resolves the effects of complex terrains on the surface radiation budget) [41]. The inclusion of surface absorption could capture the radiation forcings of Malaysian seas, as the equator receives more sunlight. Unlike other model evaluations, TaiESM1 focuses on climatic variations, such as precipitation extremes, synoptic eddy activity, intraseasonal fluctuation, monsoon evolution, and interannual and multidecadal atmospheric variations and oceanic teleconnection patterns [41].

To begin with, the BCC-CSM2-MR has a weak oceanic overturning circulation model bias. However, the bias in CMIP6 has been reduced, and the BCC-CSM2-MR major updates emphasise atmospheric processes (e.g., modification of the deep convection parameterisation, new cloud fraction scheme, indirect effects of aerosols through clouds and precipitation, and gravity wave drag generated by deep convection) [42]. The BCC-CSM2-MR identifies temporal variation on an inter-decadal time scale [43]. Most CMIP6 models can realistically capture the eastward propagation of MJO; however, the simulation of MJO magnitude in CMIP6 remains a complex problem. It has been demonstrated that while CMIP6 models exhibit sufficient spectral power or total variance within intraseasonal timescales compared with observations, they tend to underestimate the variability contributed by the MJO model [44–46]. Better simulations of coupled ocean-atmosphere dynamics are required for climate models, as the models still exhibit flaws and underestimations in their projections.

3.3. Sea Level Projection for Malaysian Seas

The models were made into a multi-model ensemble from the four well-performed models. Figure 5 depicts the sea level trends in Malaysian seas. Four areas: SM, SCSPM, SCSEM, and SS, were selected to observe the future projections of sea levels across the Malaysian seas. Table 4 shows the projected sea level range, change, and trend. Based on SSP3-7.0, sea level trends were calculated from the beginning of the projection year (2015) to a warming of 1.5 °C and 2.0 °C in 2028 and 2043, respectively [47]. Meanwhile, the projected sea level rise reaches the end of the twenty-first century in 2080 and 2100.

Upon reaching 2028 or 1.5 °C warming, the sea levels in Malaysia (SM, SCSPM, SCSEM, and SS) would be in the range of 0.752 m, 0.908 m, 0.895 m, and 0.838 m, respectively. From this, SM, SCSPM, SCSEM, and SS would experience a sea level change of 4.5 mm, 16.0 mm, 1.1 mm, and 0.6 mm before 2015, respectively. The trend of sea level change varies according to location, as SM would experience a rise of 1.0 mm/year, SCSPM of 1.5 mm/year, SCSEM of 1.1 mm/year, and SS of 0.6 mm/year.

Next, if we reach 2043 or 2.0 °C warming, SM, SCSPM, SCSEM, and SS would have a sea level range of 0.757 m, 0.912 m, 0.903 m, and 0.844 m, respectively. The sea levels would experience a higher change compared with 1.5 °C warming, as SM, SCSPM, SCSEM, and SS would experience a difference of 10 mm, 20.2 mm, 21.5 mm, and 15.4 mm, respectively. The sea level trend would be almost the same throughout all areas, as SM and SS would experience a rising trend of 0.5 mm/year while SCSPM and SCSEM would rise at a rate of 0.6 mm/year and 0.7 mm/year, respectively.

By 2080, the sea levels at SM, SCSPM, SCSEM, and SS would be in the range of 0.783 m, 0.950 m, 0.934 m, and 0.869 m, respectively. The sea levels will have a higher change as SM, SCSPM, SCSEM, and SS will experience a difference of 36.3 mm, 57.7 mm, 53.2 mm, and 40.1 mm, respectively. The trend will be a slight increase or none compared with 2.0 °C warming, with SM and SS showing a 0.6 mm/year rising trend and SCSPM and SCSEM showing a 0.8 mm/year and 0.7 mm/year rising trend, respectively.

Reaching the end of the century in 2100, the sea levels in Malaysia (SM, SCSPM, SCSEM, and SS) would be in a range of 0.806 m, 0.975 m, 0.963 m, and 0.894 m, respectively. The sea levels at 2100 would exceed sea level change in 2028 (1.5 °C warming), 2043 (2.0 °C warming), and 2080. SM would see an increase of 58.8 mm, SCSPM of 83.1 mm, SCSEM of 81.7 mm, and SS of 65.2 mm. The sea level trend of SM, SCSPM, SCSEM, and SS would be 0.8 mm/year, 1.0 mm/year, 0.9 mm/year, and 0.8 mm/year, respectively.

Overall, the sea levels in the SCS (SCSPM and SCSEM) would be relatively higher than those in SM and SS. Most of the sea levels in the SCS will be higher than 0.9 m compared with the SM and SS. All areas would experience an increase in sea level as the year went on, but it is in 2100 that the SCS, SCSPM, and SCSEM would have the highest change of 83.1 mm and 81. 7 mm, respectively, while SM would have a total change of 58.8 mm and SS would have a total change of 65.2 mm. This shows that sea levels in Malaysia will rise differently depending on their location by the end of 2100.

4. Discussion

Between 1901 and 2018, the global mean sea level rose by 0.2 m [48]. Alternatively, Malaysia would have a relative sea level trend of 4.22 mm/year on Peninsular Malaysia's west coast, 3.53 mm/year on Peninsular Malaysia's east coast, and 3.40 mm/year on Sabah and Sarawak [49]. Climate models have been regarded as one of the primary tools for understanding climate change patterns and mechanisms to project future climate change [50]. Therefore, this study examined 15 models that simulated SSH above the geoid in Malaysian seas, and well-performing models were chosen to represent the region's future climate. RCMs have the potential to bridge the gap between global climate models and impact assessments. Meanwhile, RCMs could simulate the climate system more accurately than GCMs at a finer scale because they resolved some physical processes in greater detail [51,52]. Despite model validation, the CMIP6 model has several uncertainties due to its grid resolution, numerical schemes, and parameterisations. Most of the current global climate models have horizontal resolutions of around 1°, which causes issues with regional ocean details, such as the SCS and the Strait of Malacca. Due to their low spatial resolution, the ocean component of CMIP6 models includes a parameterisation of the influence of mesoscale processes on transport parameters [53]. The sea levels vary depending on location; Malaysian waters can be divided into regions and seas, resulting in various settings. Sea level change refers to the change in mean sea level over time caused by global climate and local tectonic processes.

Sea Level Projection for Malaysian Seas

Out of the 15 models, CMCC-ESM2, MPI-ESM1-2-HR, NorESM2-MM, and TaiESM1 were selected based on the Taylor diagram. The four models were chosen to produce a multi-model mean ensemble to project future sea levels in Malaysian seas. The zos variable represents dynamic sea-level changes caused by ocean dynamics that are not used in projecting global mean sea-level changes. There are three main reasons for global mean sea level rise: thermosteric change, barystatic change, and halosteric change [21]. In the SCS, CMIP5 models predict a minimum SLR of 25.8 cm (2.72 mm/year), 32.6 cm (3.43 mm/year), 44.7 cm (4.7 mm/year), and a maximum SLR of 57.1 cm (6.01 mm/year), 65.6 cm (6.91 mm/year), and 84.5 cm (8.89 mm/year) in RCP2.6, RCP4.5, and RCP8.5, respectively [54]. Under anthropogenic forcing, long-term dynamic sea level projections rely on global coupled climate models to mimic ocean dynamical responses to changing radiative forcing [14]. Under the relative forcing of scenario SSP3-7.0, Table 4 shows the projection capabilities of the multi-model mean ensemble. The sea levels are higher in SCSPM and SCSEM. This is due to the SCS's open-sea location compared with the SM and SS. Sea level reflects spatially and temporally changing physical and dynamic processes. Longer-term sea level variability is caused by changing climate, wind variability, and changes in ocean circulation [55]. Because the SCS is located between the western Pacific and Indian Oceans, it is heavily influenced by inter-annual and decadal sea level variability caused by the El Nino Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and Indian Ocean Dipole (IOD) in the Pacific Ocean [56]. Sea level variability in the north-eastern Indian Ocean and the SCS is complicated by local and remote forcing, volume transport through various straits, and depth-integrated temperature and salinity variations [55]. The multi-model mean ensemble showed nearly the same sea level trend across all seas reaching 2080, with 0.6 mm/year on the SM, 0.8 mm/year on the SCSPM, 0.7 mm/year on the SCSEM, and 0.6 mm/year on the SS. Sea level projections in SCS based on CMIP5 models simulated positive but very weak linear trends (i.e., 0.64 mm/year for RCP2.6, 0.63 mm/year for RCP4.5, and 1.04 mm/year for RCP8.5 between 2006 and 2100), while a negative trend was also projected in the twenty-first century [57]. Reaching 2100 revealed an increase in sea level trends, with SM rising at 0.8 mm/year, SCSPM at 1.0 mm/year, SCSEM rising at 0.9 mm/year, and SS rising at 0.8 mm/year. The CMIP5 RCP8.5 projection of sea level rise in Malaysia to the year 2100 indicates that the sea level along the Strait of Malacca would have risen between 0.68 and 0.70 metres, the SCS—Peninsular Malaysia between 0.70 and 0.71 metres, the SCS—East Malaysia between 0.71 and 0.74 metres, and the Sulu Sea at 0.73 metres [30]. A one-meter rise in sea level can result in the loss of 180,00 hectares of agricultural land, 15–20% of mangrove forests along the coastline, and the relocation of shore-based power stations [12]. A study of the settlements on Pulau Ketam in Selangor found that a 0.53 m rise in sea level would affect almost all existing village settlements [30,58]. Inundation modelling at the Kedah River mouth shows that a 0.5 m rise in sea level would inundate 20% of adjacent agriculture and all coastal mangrove forests [59]. A study by [58] stated that low-lying areas along the Klang and Langat rivers, which are currently flood-prone, are the main areas that could potentially be impacted by sea level rise in the year 2100. Overall, the multi-model mean ensemble shows that sea level projections rise when the temperature increases to 1.5 °C, while the projection shows a higher rise upon reaching 2.0 °C. This is due to the time range, with 2.0 °C warming expected around 2043 and 1.5 °C warming expected around 2028 [47]. The rise in global temperature will continue yearly in the twenty-first century, reaching the end of the century when the sea level trends in 2080 and 2100 are computed. According to the 2015 National Coastal Erosion Study, 1348 kilometres of shoreline, or 15% of the total shoreline, are currently experiencing erosion problems that can be classified as critical, significant, or acceptable. Coastal erosion may be caused by a lack of foresight in the development and placement of infrastructure or facilities. The continued placement of infrastructure in susceptible coastal areas may exacerbate the problem of coastal erosion unless developers take into account the causes and effects of erosion [60]. As sea levels rise, the coastline will be impacted by higher waves and tide levels, which influences the design of coastal structures because increased sea levels and wave forces will affect the effectiveness and stability of these structures [61]. Multiple coastal protection measures were implemented along the Malaysian coastline, which included management strategy options such as "move seaward", "hold the line", "managed realignment", "limited intervention", "adaptation", and "do nothing". These shoreline protection methods introduced methods such as coastal hard structures, beach nourishment, mangrove replanting, relocation, and coastal reclamation [30].

5. Conclusions

This study observed changes in SSH above the geoid, particularly in Malaysian seas, upon reaching 1.5 °C and 2.0 °C warming projections from climate models. The GCMs were cropped down to the study area (Figure 1) and compared with satellite altimeter data in determining well-performed models. Four models were identified after going through validation processes: CMCC-ESM2, MPI-ESM1-2-HR, NorESM2-MM, and TaiESM1, which were combined to produce a multi-model ensemble mean to project future sea levels.

The multi-model mean ensemble was then used to show projections of sea level changes across Malaysian seas. These four areas represent the Malaysian Sea settings, including the Strait of Malacca, the SCS (Peninsular and East), and the Sulu Sea. All seas do not rise uniformly and vary depending on location. This factor also applies to the future sea level projection, as shown in Table 4. The SCS (SCSPM and SCSEM) had a higher sea level range and trend in both selected areas than the SM and SS. At 1.5 °C warmings, the multi-model mean ensemble predicted that the SCS would rise by 16 mm, with sea levels ranging at 0.908 m and a trend of 1.5 mm/year on the Peninsular, and a 14.5 mm rise, with sea levels ranging at 0.895 m and a trend of 1.1 mm/year on East Malaysia.

While 2.0 °C warmings project that SCSPM and SCSEM would rise 20.2 mm and 21.5 mm, respectively, with a trend of 0.6 mm/year and 0.7 mm/year. Upon reaching 2080, the sea level projection shows that the SCSPM and SCSEM would rise 57.7 mm and 53.2 mm, respectively, with a trend of 0.8 mm/year and 0.7 mm/year. By the end of the 21st century, the multi-model mean ensemble projected SCSPM and SCSEM would have risen to 83.1 mm and 81.7 mm, respectively, with a trend of 1.0 mm/year and 0.9 mm/year. The SS also shows a promising change in sea levels, as sea level projections show that the SS will experience a total of 65.2 mm of rise with a 0.8 mm/year rising trend by the end of 2100. The SM Sea level projection, however, shows that it would experience a 58.8 mm rise with a trend of 80.8 mm/year by the end of 2100, which is considered lower compared with other areas. Although the data shows that the sea level changes without considering all the other components, the sea level rises annually based on the multi-model mean ensemble. Therefore, it can be concluded that sea level rise can disrupt Malaysian infrastructure, affecting the socioeconomic environment. Although sea levels vary depending on location in Malaysia, these data would aid in providing insight into Malaysian sea levels and how they can be overcome to protect the infrastructures that lie along Malaysia's coastal areas. The projected rise in sea level can be used for the adoption of adaptation measures in coastal areas, which are required to reduce the potential impacts of sea level rise, particularly in coastal zones [62]. In the long term, the rise in global sea level will affect the coastline as the coast is adjusted to new conditions, increasing erosion, inundation, and saltwater intrusion into groundwater. Numerous areas in Malaysia, especially coastal areas, are at risk of being eroded, flooded, and inundated due to sea level rise; an increase in sea levels by 1 metre would lead to the loss of development areas around Malaysia [12]. The sea level projection data will be useful for the government bodies or stakeholders in mapping and identifying possible inundation zones and areas at risk of high erosion rates both regionally and globally. National development plans will need to address the issue of sea level rise in adapting and mitigating the coastal area for future developments.

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