



Research Article



Combined climate impacts and vulnerability index on coastal ecosystems in prediction of future scenarios: extended sustainable indicator tool for adaptive strategy

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Abstract

This study presents the coastal vulnerability due to the forecasted climate change impact on the marine environment, including the sea level rise physical trait of risk impact. A combined methodology using Representative Concentration Pathways (RCPs), which corresponds to the greenhouse gas emissions scenarios, is used in this research; combined with Climate Change Vulnerability Index (CCVI) to rank the relative risk for each of the marine ecosystem zones in relation to the potential hazard exacerbated by climate change and sea-level rise. This method presents vulnerability in numerical data, which cannot be calculated directly based on their physical properties. From the results, it shows that the coastal areas of the study area of Marudu Bay would experience a warmer atmosphere both under RCP 4.5 and RCP 8.5 with an increment of 1.0 °C and 1.7 °C; meanwhile, the climate projection for total exhibits of increase in total precipitation by 2.6 mm/day and 1.6 mm/day under RCP 4.5 and RCP 8.5 at the regional measure. At the same time, the projection simulates an increase of sea level by 0.21 m and 0.27 m over the northern region of Marudu Bay under RCP 4.5 and RCP 8.5, respectively. In addition, 43.84 ha and 57.02 ha of land estimated would be potentially inundated by the mid-century year 2050 under RCP 4.5 and RCP 8.5. By the end of the century 2100, the sea level is projected to increase locally at about 0.32 m under RCP 4.5 and 0.38 m under RCP 8.5, consequently resulting in a total of 66.84 ha and 79.78 ha of additional inundation coverage. Therefore, the result from this study can be used when making effective adaptive strategies and conservation planning despite its inherent uncertainties.

Article Highlights

- Extension of methodology that integrates the climate variables (temperature, precipitation, and sea-level rise) with the changes of environment physical traits (CCVI) due to climate change impact were designed for coastal vulnerability assessment.
- The combined CCVI used ranked the relative risk by numerical vulnerability based on the physical properties for each of the marine coastal zone showing the potential hazard exacerbated by climate change and sea-level rise.
- Coastal areas of the Marudu Bay study area will experience a warmer atmosphere and increased total precipitation, and the sea level will rise under RCP 4.5 and RCP 8.5 at the regional measure. Thus, the study can be utilized as an extension to develop an effective adaptation strategy that is more targeted based and more focused type of the management plan.

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1 Introduction

Climate change impact and vulnerability assessment is an emerging concept that has been practiced over the recent decades to assess potential and observed climate change impacts, which is reflected in the fourth annual report of the Intergovernmental Panel of Climate Change Report [1]. As highlighted in the fifth annual report of the IPCC [2], the increment of global mean temperature since the pre-industrial era has shown historical trends of warming that vary spatially. The manifestation of climate change has also been recognized to associate with the increase in both frequency and intensity of climatic hazards and extreme climate events [3]. Natural resources that hinge on ecology and climatology can be highly vulnerable to climate change impact [4]. Warmer temperature contributes to ocean expansion [1], and the anticipation of global warming has led to sea-level rise. Due to its geographical setting, elevations and proximities to the ocean nexus, coastal areas are highly susceptible to climate change and sea-level impacts [5]. Despite the lack of geographic balance in data and literature on observed changes and geographically non-uniformity, different countries may suffer a varying degree of climate change impact and at different reaction time scales due to various natural feedbacks [3]. Hence, depending on their physical features, socio-economical characteristics, and anthropogenic setting, different marine and coastal areas will experience climate change effects and sea-level impact differently [6].

The primary marine vulnerability driving forces include the change of sea level, shift in precipitation pattern, increased ocean temperature, shift in the ocean circulation pattern, and increased atmospheric CO₂ [7]. These climate impacts interact in complex ways imposing additional stress on the marine areas. The major coastal hazards induced by climate change impacts may include increased frequency and intensity of coastal storm events, coastal erosion, inundation, and coastal erosion [8]. In the context of the coastal marine ecosystem, changes in sea-surface temperature have subsequently inflicted severe threats to marine biodiversity [9] and, therefore, are responsible for the unfortunate socio-economic impact on fisheries-dependent countries [10]. Significance implications of climate change to the marine environment are not just observed by the permanent inundation of low-lying areas and coastal erosion but also resulting in habitat loss, coastal displacement, and saltwater intrusion [11]. For these reasons, the ability of a marine and its ecosystem to provide environmental services and support humankind

and socio-economic development might be impaired [12]. Further warming results in more acidifying of the ocean, and diminishing coral reefs, decimating mangrove system and seagrasses [13], consequently affecting the dynamic marine ecosystem. With the projected changing of climate in the future, the physical and chemical characteristics of the coastal environment and the marine ecosystem will inadvertently be affected.

Available literature mentioned has demonstrated the potential threat of climate change against the various aspects of living. This may include food supply and securities, biodiversity, leisure and recreation services, tourism, climate mitigation, and natural hazard protection. The adversely complex climate change impacts have been reported to affect food security in Malaysia [14, 15]. For the past few decades, the mean surface temperature has increased from 0.6 to 1.2 °C and is projected to increase more than 2.3 °C by the end of the century [16, 17]. Climate change comparison between the two sub-regions of Malaysia (Peninsular and Borneo), carried out by Hallegatte et al. [18], has pointed out that the Malaysian Borneo region relatively experiences larger changes in mean temperature and receives more precipitation compared to the Malaysian Peninsular. Therefore, this research is essential concerning the case study, Marudu Bay, in order to obtain a clearer view of the sea level rise impacts of the extreme weather event on the local communities due to climate change in the Northern-Part of Malaysia Borneo in Sabah. This study has never been done before, especially in this region that is prone and is precisely located in the middle of the El-Niño-Southern Oscillation (ENSO) and covered by the western North Pacific Ocean and South China Sea cyclogenesis basin and path that brings the anomaly of the sea surface temperature. This often brings more coastal floodings due to intense heavy rainfall, strong wind, and rough seas reaching typhoon intensities, causing the sea level to rise in this region. This also includes the effect from the Orographic Effects of the typhoon cyclone topography and their synoptic circulation and interactions that bring the tropical typhoons/cyclones from neighboring countries such as the Philippine Sea. Such effects accelerated the sea level rise in this region, worsened the land submergence, beach erosion, and increased coastal storm flooding. Despite the fact that very limited research has only been conducted on this large floodplain inundation coverage of Marudu Bay although it frequently occurs flooding in this area. It is the largest bay in Malaysia, having larger tides than normal due to higher water tides produced by more water levels resonance of semi-diurnal

forcing. The bay also experiences mixed tidal forces from two (2) seas: the South China Sea on the western region and the Sulu Sea on the eastern side. As the mean water depth increases, the resonance frequency will change due to the climate change impact and crustal subsidence, increasing the wave propagation speed and creating iso-static reactions and adjustments.

The physical impacts of sea-level rise have been documented in several studies on a larger and global scale that is assumed as the average and represents the entire oceans [19–21]. Shoreline change, saltwater intrusion into groundwater, increase in frequency and intensity of flooding, erosion, and other extreme coastal hazards have been linked by previous studies [22–24] to the sea level rise impacts, with the risk of wiping out the low lying islands. To address these hazards, however, understanding the past pattern of sea-level change is necessary as the first step and the foundation of the entire vulnerability, especially to detect whether there are really changes in the mean sea level, subsequently for characterizing the present trend and estimating future scenarios. Further, projecting future climate change and impacts requires accurate estimates of past sea-level records and weather variability to increase the accuracy of estimating sea level as the higher priority. In this research, a novel method is developed by combining the status of sea-level rise vulnerability analysis with a visual technique approach at different spatial and temporal scales, including maps and 2D conceptual cross-sections and temporal series of vulnerability indexes due to climate change. Its relevance will help identify coastal areas that are at risk due to the coastal flooding from sea-level rise, where this method, unlike previous studies, does not require complex modelling that deals with lots of historical time-series analyses to capture the absolute trends of changes at the end. Focusing on the extreme value of episodic coastal flooding contributes to larger and more accurate confidence levels of estimates, especially in hydrological extremes in the context of changing climate. Compared to the previous research that mostly looks into the generalized climate change impact on the sea level rise forecasting by examining the global mean sea level averaged for entire oceans. However, in reality, the changes in sea level have a spatial distribution by regional distribution of their mean sea-level change. The regional distribution will be the difference attributed to the local differences in density structure and ocean currents, including the frequency of low-pressure systems. Furthermore, the actual changes in local mean sea level are combined by induced changes in ocean volume and local crustal and land movement, contributing to relative sea-level rise. As this sea-level rise relative to land changes is the external force affecting coastal zones, it is necessary to evaluate the impacts of sea-level rise by the relative/

regional sea-level rise. In this work, the climate variability links between the meteorological drivers and patterns based on weather-type approaches will be measured by a range of future climate projections with the sea level rise and vulnerability index using the extreme values. This would be one of the added value and extension of this study by classifying the regional weather setting that causes the specific sea level and extreme events at each episode and incident.

The low-lying coastal areas and deltas of Malaysian Borneo, particularly Marudu Bay, comprise small islands around it, broadly by human-induced changes, and the climate-induced changes can be rapid and modify the coastlines over a short period of time, outpacing the effects of forecasted sea-level rise. Therefore, an adaptation strategy must be undertaken in short to medium term by targeting local drivers of exposure and vulnerability. This study novelty aims to assemble the extensive model from climate change combined with the vulnerability index in a numerical characteristic. This is done by measuring the datasets and physical ground observations and assessment at the local or regional coastlines to provide a more accurate and targeted projection of the future sea level and coastal flooding. One of the main contributions of this study is to develop the simplifications of the methodology that may result in a minimal local error. However, comparisons with the actual recorded datasets, from known tide gauges and the targeted episodic coastal flooding, will reproduce extreme sea level findings with better and reasonable accuracy at a national scale, thus global, for both ambient and extreme conditions. In this context, an assessment of the present-day and future subject to episodic coastal floods due to sea-level rise with the increasing carbon emissions based on climate change model scenarios (RCP 4.5 and RCP 8.5, respectively) was conducted in the subject area. These findings on anthropogenic and regional environment/nature subsidence caused by human activities, as the important cause of relative sea-level rise change, in many low-lying coastal regions, were employed, implying the consideration of local processes in the critical projections in sea-level impacts at local scales. This due to sea-level rise is not globally uniform but varies regionally. Understanding the climate change vulnerability provides comprehensive information into substantial parts of the social-ecological system that have a high probability of changing in the future using climate projection. The Climate Change Vulnerability Index (CCVI) can be used as a tool to determine the scale of the climate issue, potential climate drivers (sea-level rise; temperature changes; precipitation; major climate impacts), and the priority mitigation measures to minimize the impact and maximize the resilience over coastal community and ecosystem. It also can be used to establish the relationship between

observed changes and observed impacts, thus allowing broader and more confident assessment. This paper aims to provide a framework when assessing the vulnerability of the Marine environment, such as the coastal area in Marudu Bay (gazette as protected marine park named Tun Mustapha Park) due to climate change, which can be used to mainstream climate change adaptation strategies. In the next Sect. 2, it presents the Methodology of the research for projecting coastal vulnerability to climate change impact in the future based on the CCVI analysis; Sect. 3 shows the obtained results and followed by the discussions, and finally, Sect. 4 explains and concludes the research key findings and contributions of the paper.

2 Numerical model and methodology

2.1 The development of climate scenario

The climate projection was carried out using WRF (Weather Research Forecast) Model version 3.5.1 [11, 25], an atmospheric model designed for numerical weather prediction (NWP). We proposed the same climate simulation technique used in [18], carried out by two nested horizontal domains with 15 km × 15 km resolution covers the northern part of the Borneo region as our research domain and focuses more on a specific regional bases analysis. At 30 vertical layers with the top reaching 10 Mb (millibars) were used in the model and generated via Bias-corrected Community Earth System Model (CESM) version 1 as initial boundary conditions following the pressure level/surface [26]. As in support of the CESM coupled climate model, Intercomparison Phase 5 was utilized to produce the present day (2006–2015) dataset [27]. For this reason, CESM has a high ability in simulating observed temperature and rainfall globally [28]. The present-day (2006–2015) and future (2090–2100) climate change simulation scenarios were analyzed and presented based on the fifth report of IPCC [2] of Representative Concentration Pathways (RCPs) emission scenarios. The climate scenario of RCP 4.5 is defined as a low-to-moderate emission scenario in which greenhouse gasses (GHGs) are assumed to increase by 4.5 Wm⁻² in the future. On the contrary, RCP 8.5 corresponds to a high emission scenario with GHGs radiative forcing

that continues to rise to 8.5 Wm⁻² by 2100. The observation data obtained from Climate Research Unit Climatology (CRU Datasets) at the University of East Anglia was used to evaluate the model's performance. CRU dataset is a high-resolution (0.5° × 0.5°) gridded dataset. The observation data contained a complete set of monthly-mean surface climates and only covered land areas [29, 30].

2.2 Sea level scenario

The present-day sea-level dataset was retrieved from the Radar Altimeter Database System (RADS) (<http://rads.tudelft.nl/rads/rads.shtml>) and utilized to reconstruct sea-level projection due to changing climates. The RADS combined observations from various satellite altimetry data (TOPEX, JASON-1, ERS-1, ERS-2 and ENVISAT) to establish a harmonized and cross-validated sea-level database [31]. Over the years, significant progress has been made for global estimates of climate that are consistent with observations, given their limitations. The modest changes in mean sea level were attributed to natural climate feedbacks where a consequential relationship exists between climatic variables and sea level [29]. Therefore, the uses of climate variables in sea-level projections are less likely to be argued. Apart from zonal and meridional wind, sea-surface temperature and mean pressure level were used as climate variables and obtained from the ERA-Interim database with a spatial resolution of 0.7 km × 0.7 km and employing 37 levels of atmospheric from the period of 1979 until the present day. ERA-Interim provided a global reanalysis of recorded climate observation and was developed by the European Centre for Medium-Range Forecasts (ECMWF), which supplies a spatially, multivariate, and coherent record regarding the global atmospheric circulation aspect.

The Global Climate Models (GCMs) listed in Table 1 are employed to simulate the response of climate change interaction to the dynamic physical processes of the atmosphere, ocean cryosphere, and land surface and to provide projections of future sea-level states under selected climate scenarios (RCP 4.5 and RCP 8.5). The GCMs datasets were retrieved from Coupled Model Intercomparison Project Phase 5 (CMIP5) and retrieved from the Multi-Model Dataset Archive of the Programme of Climate

Table 1 Global Climate Models (GCMs) that were used in the sea level rise investigation

Model (version)	Model resolution	Time period
Commonwealth Scientific and Industrial Research Organization (CSIRO-Mk3.6.0)	1.875° × 1.875°	2006–2100
NASA Goddard Institute for Space Studies (GISS-E2-H)	1.875° × 1.875°	2006–2100
ESM of the Max-Planck-Institut für Meteorologie (MPI-ESM-MR)	1.875° × 1.875°	2006–2100
Japan Meteorological Research Institute (MRI-CGCM3)	1.875° × 1.875°	2006–2100

Model Diagnosis and Intercomparison (PCMDI) (<https://pcmdi.llnl.gov/projects/cmip5/>). Only the first simulation defined in the dataset is chosen for any cases in the simulation ensemble one another. In the case of multi-simulation ensembles with one another, the first simulation defined in the dataset was chosen.

Similarly, the climate variable mentioned was chosen for interpolation analysis with the observational data. Due to the coarse spatial scales (500 km × 500 km) resolved in the GCMs relative to the scale of exposure units in most impact assessment processes; the influence of sea-level variations cannot be properly presented. Therefore, an interpolation of the output of simulations with GCMs was employed for the estimation of climate-induced changes in the Northern Borneo region, including sea-level rise, with the application of statistical downscaling techniques, and so established a statistical relationship between the large-scale variables and local variables and then subsequently transferred the large-scale results produced by GCMs onto regional and local scales.

2.3 Dataset assimilation

Datasets from radar altimetry were matched with climate variables datasets, and the time range chosen was between 1993 and 2015. In order to investigate the dynamic relationship between climatic variables and sea-level changes, simple regression was applied, and sea level at any single station (SLA) was considered the predictions and predictors. The predictors and predictions evaluated and correlated using multi-paradigm numerical programming of MATLAB equipped Climate Analysis Toolbox. Meanwhile, we employed the Grid Analysis and Displays system (GrADS) to visualize output data. To study the possible spatial patterns of sea level variability and how it changes through time, the method of empirical orthogonal function (EOF) is applied by computing the eigenvectors to determine the anomaly covariance matrix. The time series for the Principle Components (PCs) of predictors and Coefficient value (CMP) of the predictors were utilized to conduct regression analysis to measure the coefficient matrix of the altimetry and PCs to establish the regression model to reconstruct sea-level change based on the coefficient value (Eq. 1).

$$Y_{(RSLA)} = C1P1 + C2P2 + \dots + CnPn \quad (1)$$

where $Y_{(RSLA)}$ = Reconstructed sea level anomaly (mm) at single station, C = Coefficient predictor value at single

station, P = Principle component predictor value at single station.

2.4 Sea level projection

The statistical relationship inception between observed climate variables and sea level allows a constructional model of functional climate change and sea level anomaly. Data grid from the four models listed in Table 1 incorporated onto 0.50 × 0.50 grid resolution corresponded with the specific duration of reanalysis of climate datasets. Based on Eq. (1), climate variables (predictors) information was used to develop Eq. (2). Time series are then extracted from each interpolated GCMs and assimilated into Eq. (2) to project the future sea level based on different scenarios.

$$SLF = C1G1 + C2G2 + \dots + CnGn \quad (2)$$

where SLF = Future projection for sea level (mm) at single station, Cn = Coefficient predictor value, Gn = Time series value of GCMs.

2.5 Inundation coverage

ArcGIS Map version 9.3 is used to project and present an inundation map due to sea-level and climate change scenarios. The inundation map was based on a reference base map and sea-level projection with geo-referenced imagery covering the study area to outline and digitize its shore and its surrounding physical feature. While for the elevation, we compared the data from google imagery and Shuttle Radar Topography Mission (SRTM) (<http://srtm.csi.cgiar.org>) before derived to the best fit of the island's terrain to produce contours of the study area. Based on sea-level projection, inundated areas for every epoch were calculated to analyze the coastal land loss for each zone to determine the highly prone area due to sea-level changes.

2.6 Coastal zoning

The selection of Marudu Bay as the research domain is due to the highest potential of the study area to be impacted by the sea level rise and climate changes based on its geographic dimensions, particularly on the location factor, the size of the area and physical environment where human beings co-exist based on biophysical and economical of interactions [32]. In order to facilitate the vulnerability assessment for a large area such as Marudu Bay, the regional coastal area was divided into 12 zones based on their three (3) Districts distribution around the bay which

Fig. 1 The 12 zones of Marudu Bay for the vulnerability assessment due to climate change



are Kota Marudu, Kudat, and Pitas, divided by the Local Government as shown in Fig. 1.

The twelve zone are Simpang Mangayau; Bak-Bak/Tajau Laut; Kudat Town/Kudat Bay; Limau Limauan/Parapat; Tagumal laut/Sebayan; Langkon/Tanah Merah; Kota Marudu/Tandek; Tanjung Batu/Kesagaan; Pinggan-Pinggan/Mempakad; Bengkoka/Pitas; Malubang; and Mangkubau. Marudu Bay is located in the most northern part of North Borneo, Sabah, Malaysia, and is the largest bay in Malaysia; where the opening of the bay mouth is about 34 km in width, and the bay's territorial water area is estimated to be around 900 km² while the digitized shoreline length measured about 246 km. The bay experiences mixed tidal forces from two (2) seas: the South China Sea on the western region and the Sulu Sea on the eastern side. The geomorphological features inside the bay are dynamically formed where sandy beaches dominate the foreshore of the bay mouth and muddy shores with escalating mangroves colonies in the inner part of the bay. The dominant hydrodynamic force acting on Marudu Bay is Northeast Monsoon (NEM), which

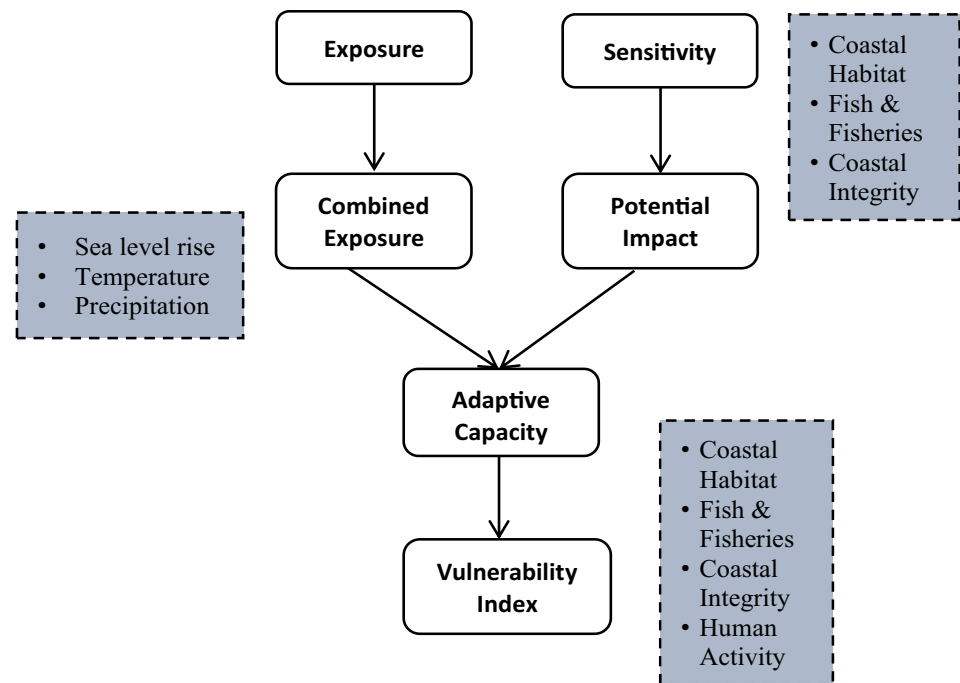
carries most rain from November until March every year. During the Southwest monsoon, it carries drier air flow through the bay [33].

2.7 Defining exposure, sensitivity and adaptive capacity

The coastal climate change vulnerability is measured by integrating its exposure, sensitiveness, and adaptive capacity to given climate change scenarios and the framework shown in Fig. 2.

We defined exposure as to how a system or community experienced climate change from a given scenario following [34]. The climate exposure factors in this study were surface temperature, precipitation, and sea-level rise and were gathered through climate models simulation. A guidebook of Vulnerability Assessment Tools for Coastal Ecosystem-A Coral Triangle Initiative (<http://www.coraltriangleinitiative.org/library/guide-vulnerability-assessment-tools-coastal-ecosystems>) referred in order to assess climate change vulnerability exposure

Fig. 2 Climate change vulnerability assessment framework



component. It was utilized to communicate with the local population or apply in areas with no population to investigate how climate change affects them. The tools provide a participatory assessment with a list of climate-related variables to evaluate either past or present status (Sensitivity) and a process that allows selected areas to respond successfully to associated climate impacts (Adaptive Capacity). The score was then weighted based on the climate threat level or climatic exposure.

Meanwhile, sensitivity was defined as the characteristic of the community or system to experience harm under climate stressors and how it influences its likelihood. Given that there were different dimension aspects of sensitivity, we only focused on the sensitivity of environmental components in terms of its coastal habitat (CH), aquaculture and fisheries (AF), and coastal integrity (CI) and assessed based on Marine Environment and Resources Foundation. On the one hand, adaptive capacity was defined as the potential or the ability of a system to reproduce or to cope with the climate impacts and includes adjustments in resources behavior and technologies [1]. On the other hand, adaptive capacity was also a designed condition and effective adaptive implementation strategies to reduce the magnitude of climatic impacts and the effect on community livelihood [35]. Therefore, the common understanding of adaptive capacity comes through a vulnerability assessment, even if the vulnerability itself does not explicitly include the determinants. Since vulnerability assessment can be generic or specific to particular climate hazards, the adaptive capacity dimension in this study was treated as

a lack of adaptive capacity (LAC) and referred to parameters that hinder the recovery of a system after being affected by climatic exposures.

2.8 Field data collection

Data used in this study were categorized as (1) digitized features, (2) census information, and (3) modeled climate scenarios. Field surveys, interviews, meetings, consultations, and workshops with targeted stakeholders were carried out to obtain information regarding the study area's socio-economics, coastal profile, and relevant climate issues. Observations of the physical attributes of the area provided quick results regarding onsite issues and land use in the area.

2.9 Calculating climate vulnerability indices (CCVI)

Integrated Coastal Sensitivity, Exposure, and Adaptive Capacity to Climate Change Vulnerability Assessment Tool (ICSEA-C-Change) v 1.0 was used to determine the climate change vulnerability indices (CCVI). The tools were adopted from the Marine Environment and Resource Foundation, which measures the integrated vulnerability of coastal system according to climate change impacts and offer a comparison of known vulnerabilities across sites and coastal aspects, as much as provides crucial information in determining prioritization on an area needed to be given attention taken after [36]. Prior to coastal zoning,

a sub-index was developed to measure the sub-index of exposure, sensitivity, and adaptive capacity for each zone.

The indicator and scoring for each zone were based on the individual contribution of each climatic variable, adopted from other previous studies [13, 37].

$$CESI = [(IND + P + T) / 3] \tag{3}$$

where CESI: Composite Exposure Sub-Index, IND: Inundated area (ha), P: Precipitation changes (mm/day), T: Surface temperature changes (°C).

The Exposure Sub-Index (ESI) describes the changes in the physical condition of the environment due to changing climate and sea level. Based on individual scoring (Table 2) of exposure, the Composite Exposure Sub-Index (CESI) was calculated using Eq. (3). The CESI demonstrated how the complex climatic drivers interact and exert cumulative pressure on each zone. Whereas the Sensitivity Sub-Index (SSI) demonstrates the prominent state of nature of the environment by zones that respond to the cumulative factor of climate change exposure and are calculated based on the average sensitivity values. Variables assessed were the coastal habitat, fish and fisheries, and coastal integrity adopted from the MERF.

Adaptive Capacity Sub-Index (ACSI) was defined as the ability or potential of an ecological system by zones to respond successfully to climate variability. ACSI was also calculated based on the average of adaptive capacity values. Parameters assessed were coastal habitat, fish and fisheries, coastal integrity, and human activity. The composite exposure, sensitivity, and adaptive capacity categories for each zone were determined based on the scoring, as shown in Table 3.

$$CVI = (CESI + SSI + ACSI) / 3 \tag{4}$$

The CESI value indicates the status of an area having the lowest (or highest) exposure and its likelihood of being

affected by the changing climate. At the same time, the lowest (or highest) SSI scoring shows the significant notion of changes exacerbated by climate stressors. Whereas the lowest (or highest) ACSI score, diagnose the process that allows the coastal ecosystem in a zone to cope with climate-associated impacts. Correspondingly, the ACSI helps identify early local efforts that need to be carried out to promote the capabilities of adaptations of a zone. Based on the coastal sub-index scores, the Climate Change Vulnerability Index (CCVI) on the coastal ecosystem of Marudu Bay was calculated using Eq. 4. Individual zones' relative vulnerability indicates their susceptibility, affectability, and responsiveness to adapt to changing climate conditions [38]. Our method yields numerical data which cannot be directly equated with physical effects. However, it does highlight those regions with the most significant climate change and sea-level impacts taken after [39].

The calculated CCVI presented in our study was nearly similar to previous studies by [13]. This method allows the coastal environment variables (coastal habitat, fisheries, integrity, and human activity) to be related and integrated quantitatively to express the relative coastal vulnerability due to changing climate scenarios. The calculated values for CCVI for each zone were further evaluated to determine the level of vulnerability based on the vulnerability scoring, as shown in Table 3 [12]. A coastal region with less than 2.00 would be categorized as low climate change vulnerability; above 2.00 but less than 3.99 would be categorized as moderate, while anything equal and above 4.00 would be categorized as high climate vulnerability.

Table 2 Scoring of exposures based on inundated area and changes in precipitation temperature

Category Variables	Low (L)		Moderate (M)		High (H)
	1	2	3	4	5
Inundation (ha)	≤ 2.00	2.01–4.99	5.00–7.00	7.01–9.99	≥ 10.00
Precipitation (mm/day)	≤ ± 9.99	± 10.00 to 18.99	± 19.00 to 29.99	± 30.00 to 39.99	≥ ± 40.00
Temperature (°C)	≤ 0.49	0.50–0.99	1.00–1.49	1.50–1.99	≥ 2.00

Table 3 Scoring and rating for the Sub-Indexes

Category	Low (L)	Moderate (M)	High (H)
Composite Exposure Sub-Index (CESI)	≤ 1.99	2.00–3.99	4.00–5.00
Sensitivity Sub-Index (SSI)	≤ 1.99	2.00–3.99	4.00–5.00
Adaptive Capacity Sub-Index (ACSI)	≤ 1.99	2.00–3.99	4.00–5.00
Climate Change Vulnerability Index (CCVI)	≤ 1.99	2.00–3.99	4.00–5.00

Table 4 Comparison of the surface temperature and total precipitation in January and July under RCP 8.5 and RCP 4.5 as relative to observed (CRU dataset) for normalized mean bias (NMB), fractional bias (FB), normalized mean square error (NMSE) and factor of two (Fa2)

Variable	Surface temperature				Precipitation			
	RCP 4.5		RCP 8.5		RCP 4.5		RCP 8.5	
	Jan	Jul	Jan	Jul	Jan	Jul	Jan	Jul
Model	25.0	25.3	24.0	25.0	7.7	3.7	5.6	5.8
CRU	25.9	26.1	25.9	26.1	4.4	8.1	4.4	8.1
NNM	-3.0	-3.0	-7.3	-4.2	75	-54.3	27.2	-28.4
FB	-0.035	-0.031	-0.076	-0.043	0.57	-0.75	0.24	-0.33
NMSE	-0.0012	-0.001	-0.0058	0.0018	0.32	-0.64	0.058	-0.11
Fa2	0.97	0.97	0.92	0.95	1.7	0.46	1.2	0.72

3 Results and discussion

3.1 Model evaluation

The output of the WRF climate model was evaluated with CRU observational dataset, and for evaluation purposes, the month January and July (representing northeast and southwest monsoon) were selected for the present-day slice (2006–2015). Table 4 shows the statistical evaluation of WRF relative to the CRU observation dataset. During the summer monsoon (January), the WRF model underestimates the CRU observation of the dataset for surface temperature, where both RCP 4.5 and RCP 8.5 have a cold bias of -4.2 (1.1 °C) and -7.3% (1.9 °C) respectively. A similar observation was found during the winter monsoon (July) with a lower temperature bias of -3.0% and -4.2% for both RCPs (0.8 °C and 1.1 °C for RCP 4.5 and RCP 8.5, respectively). The fractional bias in both RCPs lower than 0.1 indicates a good simulation. For precipitation, the model overestimates the CRU observation dataset during January with a bias of 27.2% (1.2 mm/day) and 75% (3.3 mm/day) under RCP 8.5 and RCP 4.5, respectively. While during July, the model has underestimated with a bias of -54.3% (4.4 mm/day) and -28.4% (-3.1 mm/day) under both RCPs, respectively. The model was observed to perform better simulation under RCP 8.5, where the fractional bias was higher than 0.5 during January and July under RCP 4.5. There are large discrepancies in total

precipitation between the model and CRU observational dataset, especially during July. This discrepancy might cause by a poor representation of convective parameters and hydrological cycle [40].

3.2 Climate change projection scenarios: surface temperature

The projected surface temperatures during winter (January) and summer (July) monsoons for the present-day and future scenarios (2050 and 2100) under RCP 4.5 and RCP 8.5 are shown in Table 5.

Relative to the baseline scenario under RCP 4.5, at the middle of the century (2050), the mean surface temperatures were projected to increase to 26.0 °C during winter; and 27.1 °C during the summer monsoons respectively. Under RCP 8.5, the magnitudes of surface temperature changes were relatively more significant, with increases of 1.7 °C and 1.5 °C during the winter and summer monsoons, respectively. At the end of the century (2100), the mean surface temperatures for both RCP 4.5 and RCP 8.5 are projected to increase further with a larger margin under RCP 8.5, of about 2.9 °C and 3.1 °C during the winter and summer monsoons respectively. The spatial variations and surface temperature changes under climate scenarios RCP 8.5 and RCP 4.5 are shown in Fig. 3 and Fig. 4.

Table 5 Mean surface temperature (°C) under RCP 4.5 and RCP 8.5 scenario

Climate scenario	Time Slice			Changes (°C)	
	2010	2050	2100	2050–2010	2100–2010
RCP 4.5					
Winter monsoon (January)	25.2	26.0	26.1	0.8	0.9
Summer monsoon (July)	26.1	27.1	27.3	1.1	1.2
RCP 8.5					
Winter monsoon (January)	24.2	25.9	27.1	1.7	2.9
Summer monsoon (July)	25.8	27.3	28.9	1.5	3.1

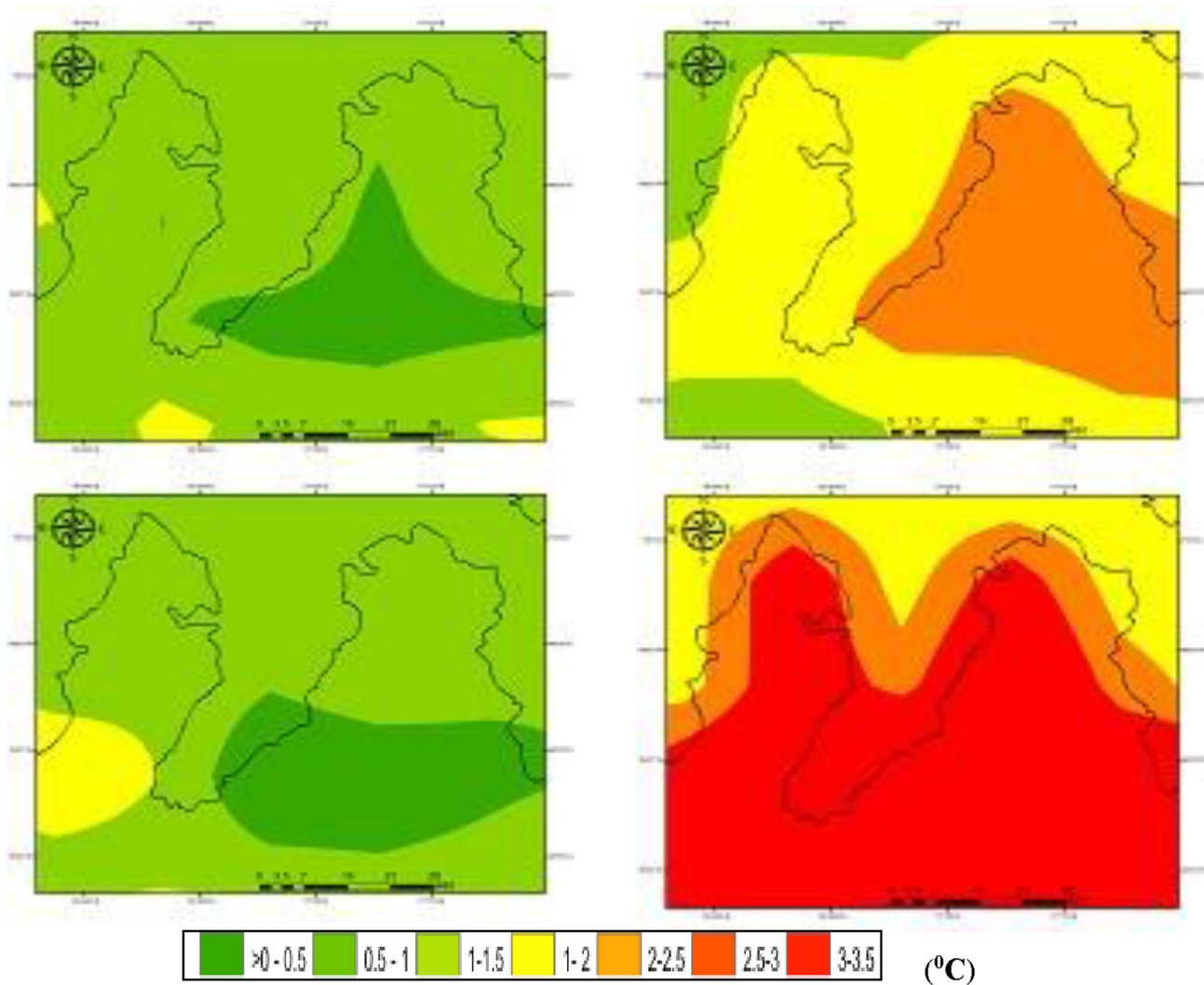


Fig. 3 Spatial changes of seasonal temperature (°C) changes for 2050 (left panel) and 2100 (right panel) to baseline (2010) during the winter (top panel) and summer (bottom panel) under RCP 4.5

3.3 Climate change projection scenarios: total precipitation

Relative to the baseline scenario under RCP 4.5, by the mid-century, the mean total precipitation is projected to increase to 19.66 mm/day during the winter and 14.17 mm/day during the summer seasons, which are increases of 11.04 mm/day and 2.73 mm/day respectively (Table 6).

At the end of the century, relative to the baseline, the northern region of Sabah would be experiencing a small increase of about 2.73 mm/day during the winter monsoon and an inappreciable decrease of -0.03 mm/

day during the summer monsoon. For the RCP 8.5 scenario, the total precipitation for the mid-century of winter and summer monsoons was 17.89 mm/day and 47.97 mm/day. Relative to the present-day period, winter monsoon mean total precipitation was slightly increased by 1.06 mm/day, but a larger magnitude was projected for the summer monsoon of about 31.65 mm/day. Meanwhile, in 2100, the total precipitation slightly increased by 6.13 mm/day during the winter monsoon and decreased by 7.75 mm/day during the summer monsoon. The spatial variations and total precipitation changes under climate scenarios RCP 4.5 and RCP 8.5 are shown in Figs. 5 and 6.

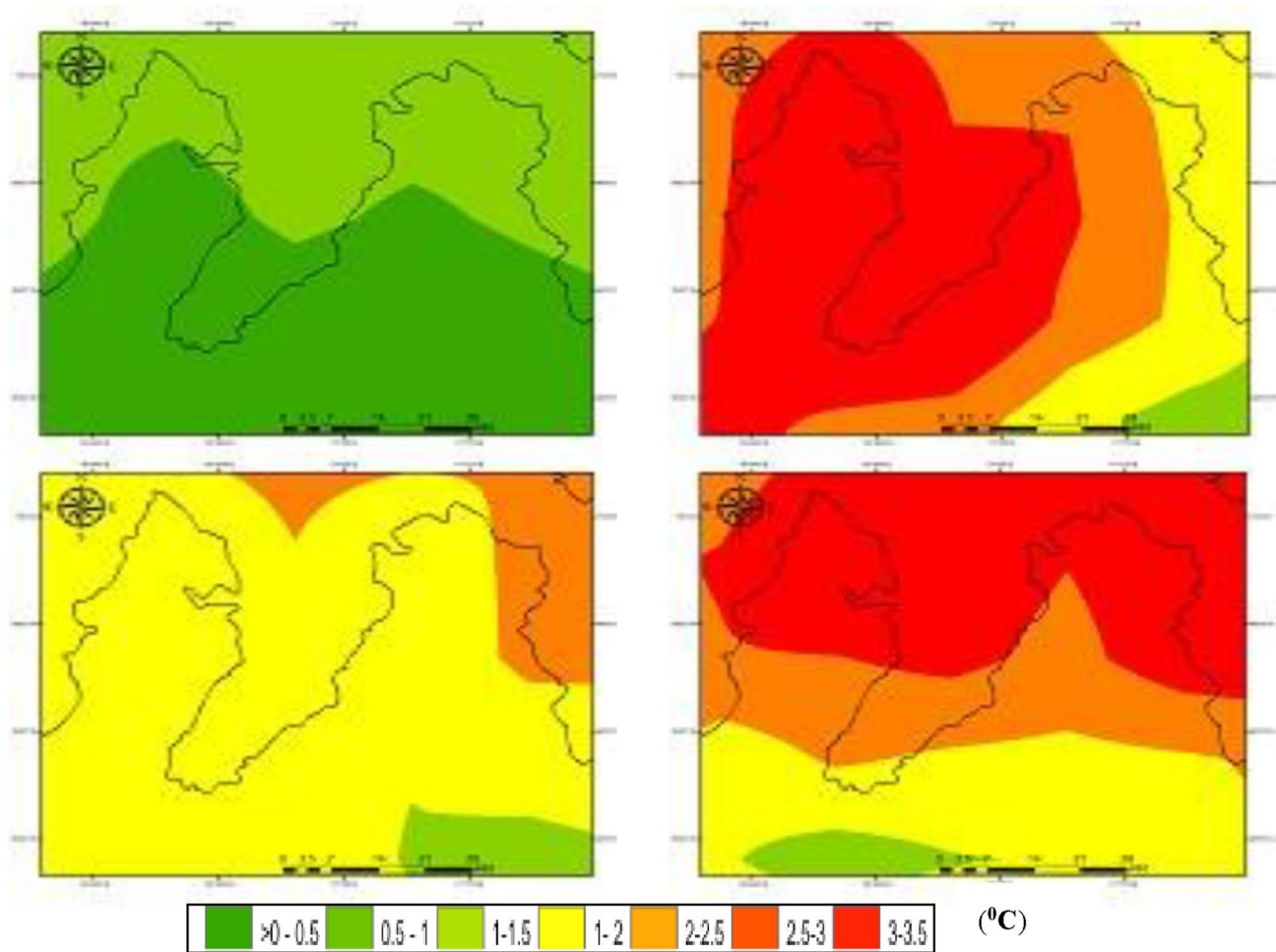


Fig. 4 Spatial changes of seasonal temperature (°C) changes for 2050 (left panel) and 2100 (right panel) to baseline (2010) during the winter (top panel) and summer (bottom panel) under RCP 8.5

Table 6 Mean total precipitation (mm/day) under RCP 4.5 and RCP 8.5 scenarios

Climate scenario	Time Slice			Changes (°C)	
	2010	2050	2100	2050–2010	2100–2010
RCP 4.5					
Winter monsoon (January)	8.62	19.66	11.32	11.04	2.7
Summer monsoon (July)	11.43	14.17	11.40	2.73	−0.03
RCP 8.5					
Winter monsoon (January)	16.83	17.89	22.96	1.06	6.13
Summer monsoon (July)	16.32	47.95	24.07	31.63	7.75

3.4 Sea level and inundation coverage

Under RCP 8.5, the sea level is projected to increase by about 273 mm (0.27 m) and 382 mm (0.38 m) by 2050 and 2100. Meanwhile, under RCP 4.5, the coastal area is expected to experience an increase in sea level of about

213 mm (0.21 m), as shown in Table 7. At the end of the century (2100), the sea level was projected to increase by 321 mm (0.32 m). Zone 7 shown will have the highest inundation of land due to sea-level rise during the middle of the century and at the end of the century, under the RCP 8.5 and RCP 4.5 scenarios. Under RCP 4.5, as much as 43.84 ha and 66.84 ha of total land loss due to

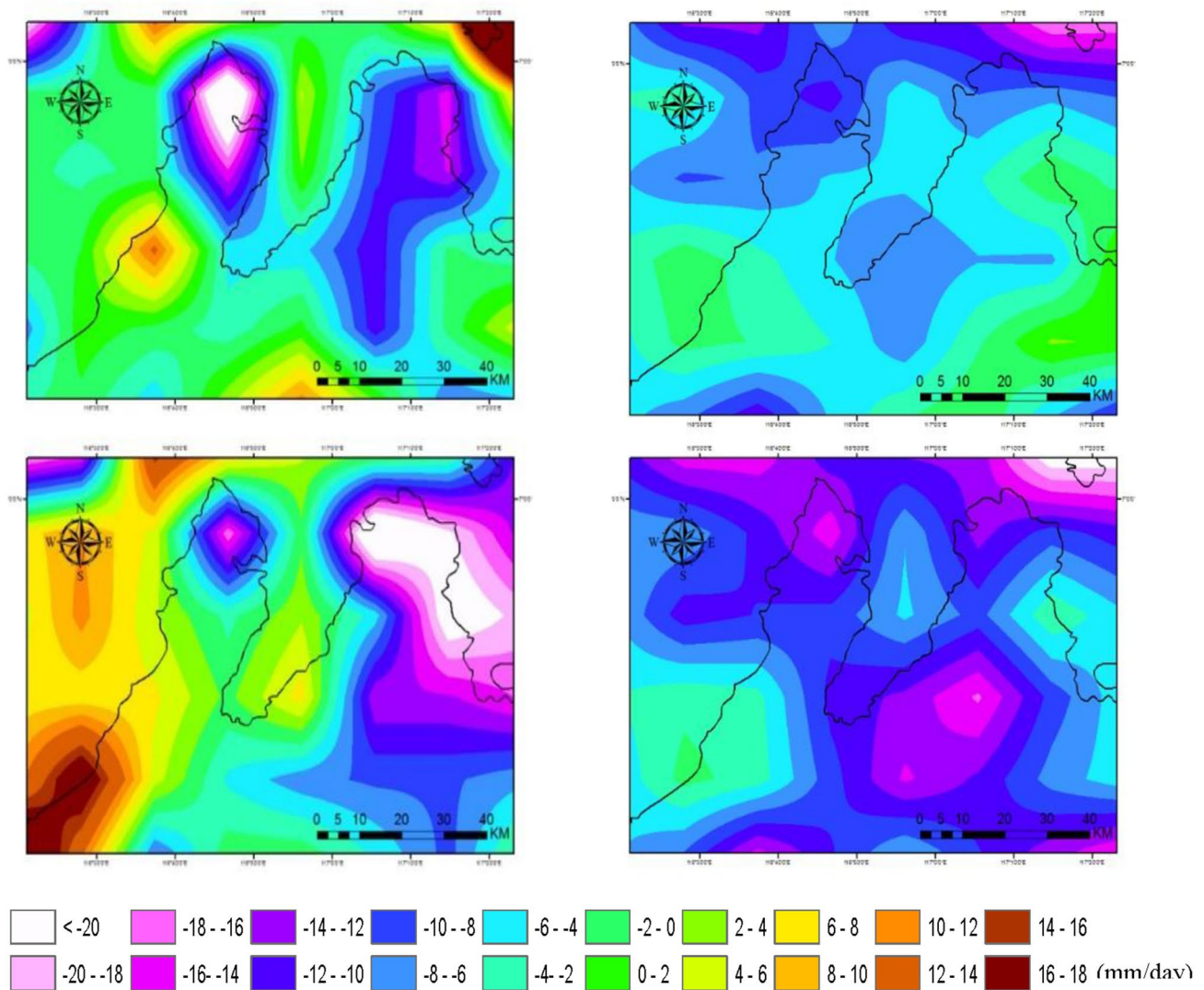


Fig. 5 Spatial changes of seasonal mean total precipitation (mm/day) change for 2050 (left panel) and 2100 (right panel) relative to baseline (2010) during the winter (top panel) and summer (bottom panel) under RCP 4.5

inundation are simulated by 2050 and 2100. Meanwhile, under the RCP 8.5 scenario, 57.02 ha and 79.78 ha of land were predicted to be submerged by seawater at the mid- and end-of-the-century, respectively. Figure 7 shows the zonal comparison of inundated areas due to sea-level rise under both climate scenarios.

3.5 Climate change vulnerability index (CCVI): RCP 4.5

Under RCP 4.5, Zone 8 has the lowest vulnerability index for both monsoon seasons for the middle and end of the century. Low vulnerability ratings are derived from low exposure and relative medium sensitivity values (Table 8). For Zones 1 and 2, both zones have also shown lower vulnerability ratings, but not during the summer monsoon of

the century, where a projection of higher climate exposure with increments of 16% and 60%, respectively. The most vulnerable zone due to climate change with the highest vulnerability index was Zone 7, with Climate Change Vulnerability Indexes (CCVI) of 3.57 and 3.68 during the winter and summer monsoons in the mid-century and a CCVI of 3.79 at the end of the century. Zone 7 is one of the low-lying areas, and tidal forces largely influence the coastal dynamic.

Low-lying areas are generally vulnerable to climate change and sea-level rise [6], thus making this area susceptible to coastal flooding and coastal erosion [41] and permanent inundation [2]. It has also been observed that the CCVI in both monsoon seasons increased in the range of 3.30% and 12.94% during the winter monsoon. During the summer monsoon as shown in Fig. 8, it is also projected

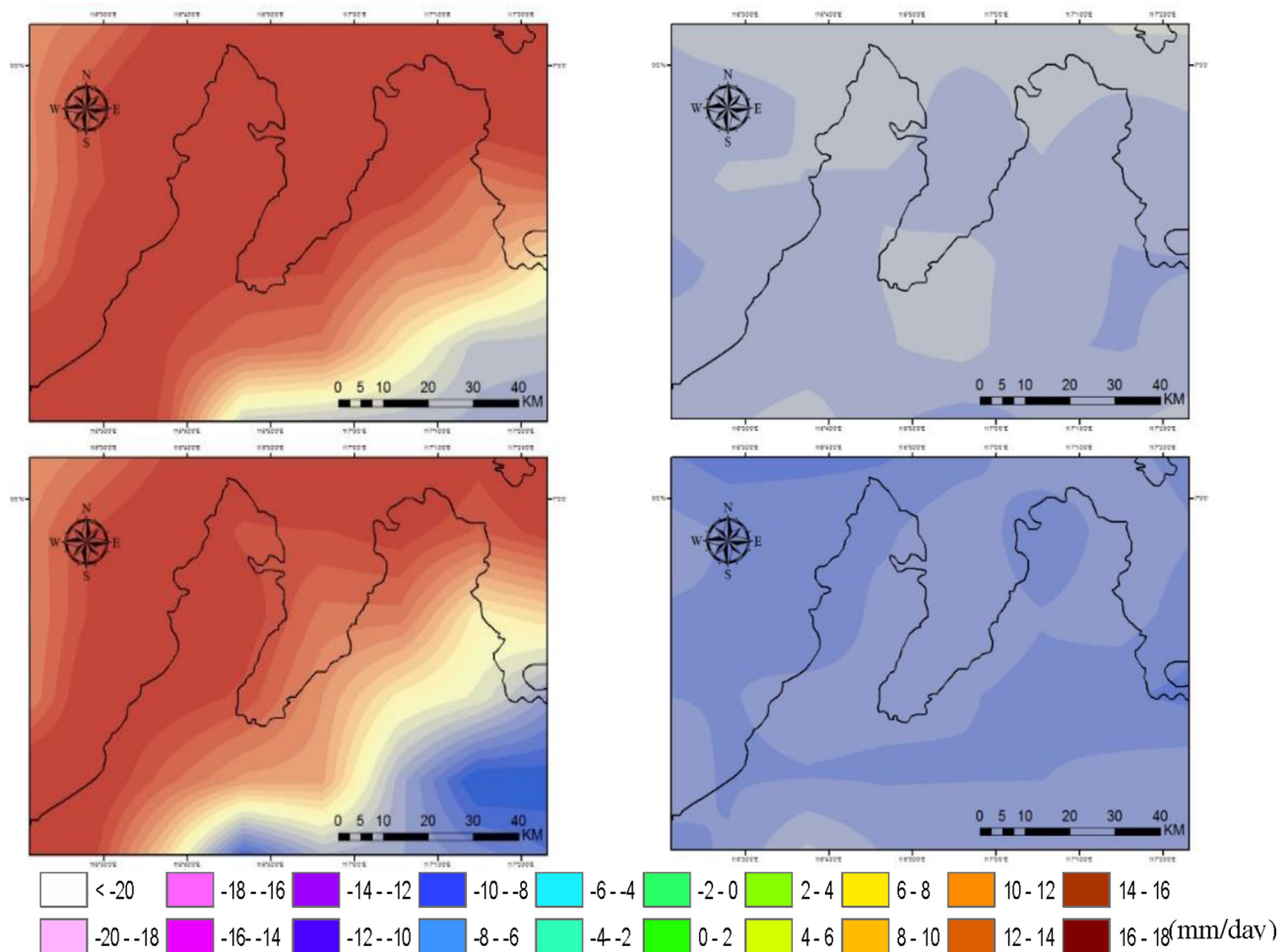


Fig. 6 Spatial changes of seasonal mean total precipitation (mm/day) change for 2050 (left panel) and 2100 (right panel) relative to baseline (2010) during the winter (top panel) and summer (bottom panel) under RCP 8.5

to increase from 3.3% to 12.94% during the summer from mid-century to the end of the century in most zones.

These increments are associated with the increases in surface temperature and precipitation changes of 0.5–1.5 °C and 1 mm/day to 17 mm/day, respectively. Low adaptive capacity, which hinders system recovery, amplifies the more prominent climate anomalies and results in a higher vulnerability rating by the end of this century. For relative comparison of the two monsoons changes, the CCVI at Zones 2, 3, 6, and 7 increased by 3.2% (for winter monsoon) to 3.8% (summer monsoon) due to the increase in surface temperature by 0.2–0.4 °C during the mid-century. Higher vulnerability rating margins ranging from 3.26 to 11.96% were observed at the end of the century. The changes in the vulnerability index are driven by a significant change in surface temperature (0.7–1.1 °C) and total precipitation (2 mm/day to 12 mm/day) in both monsoon seasons.

3.6 Climate change vulnerability index (CCVI): RCP 8.5

In the mid-century, a notable shift of vulnerability from low to moderate values is observed in Zones 1, 2, and 8, particularly during the summer monsoon, with CCVI increments of 10.62%, 14.8%, and 12.83% (Table 8 and Fig. 9).

The climate change vulnerabilities in all coastal zones were observed to increase from winter to summer monsoons ranging from 3.32 to 14.8% mid-century and 3.22–10.65% by the end of the century. During the summer period, the coastal areas in Zones 3, 6, and 7 are observed to experience high levels of CCVI at the end of the century. This is due to the increase in surface temperature and huge precipitation fluctuations and is subject to a larger margin of land loss exacerbated by rising sea levels.

Table 7 The projected sea level rises and inundated areas for each zone at Marudu Bay

Climate scenarios	RCP 4.5		RCP 8.5	
	2050	2100	2050	2100
Sea level rise (mm)	0.21	0.32	0.27	0.38
Zone 1	1.20	1.80	1.54	2.16
Zone 2	0.30	1.39	1.18	1.65
Zone 3	5.75	8.64	7.37	10.31
Zone 4	3.34	5.02	4.28	5.99
Zone 5	0.54	0.81	0.69	0.96
Zone 6	4.18	6.29	5.37	7.51
Inundation coverage (ha)				
Zone 7	11.80	17.73	15.12	21.16
Zone 8	1.66	2.49	2.12	2.97
Zone 9	3.11	4.68	4.00	5.59
Zone 10	7.37	11.08	9.45	13.23
Zone 11	2.99	4.50	3.84	5.37
Zone 12	1.60	2.41	2.06	2.88
Total	43.84	66.84	57.02	79.78

Comparison observations between mid-century and end-of-century vulnerability assessments for both monsoon seasons showed an increasing vulnerability trend ranging from 2.90 to 10.68% during the winter monsoon in most zones. In contrast, others were remained unchanged or showed insignificant marginal changes, particularly in

Zones 2, 5, 7, and 8. These lateral increments were paralleled with the climate projection with increasing temperature changes between 0.4 and 1.3 °C (winter monsoon) and 0.1 °C and 0.5 °C (summer monsoon). Meanwhile, the total precipitation was expected to increase by 2 mm/day during the winter monsoon from the mid-century to the end of the century in most zones, whereas other zones showed reductions between 3 and 10 mm/day. During the summer monsoon at the end of the century, the total precipitation decreased drastically by 2–50 mm/day, thus causing the potential of a long dry season (drought) and a temporal shift of precipitation.

This research not only involves the climate change exposure to the sea level rise based on the surface temperature and precipitation for the climate models simulation, but also employs it to measure the vulnerability of the local community's well-being by integrating its exposure, sensitivity, and adaptive capacity at a given climate change scenarios, which is the main concerns and main contributions in this study. Unlike any other studies by New et al.; Mitchell and Jones; [29, 30] on climate change impact analysis on the sea level rise, this work involved the integration of methodology to reconstruct the sea level rise and inundations events for future projection based on the historical and present database retrieved from radar altimeter. Then, we combine the observational data in the field with the vulnerability risk observed on-site, which has been done for the first time, foremost, in this case study

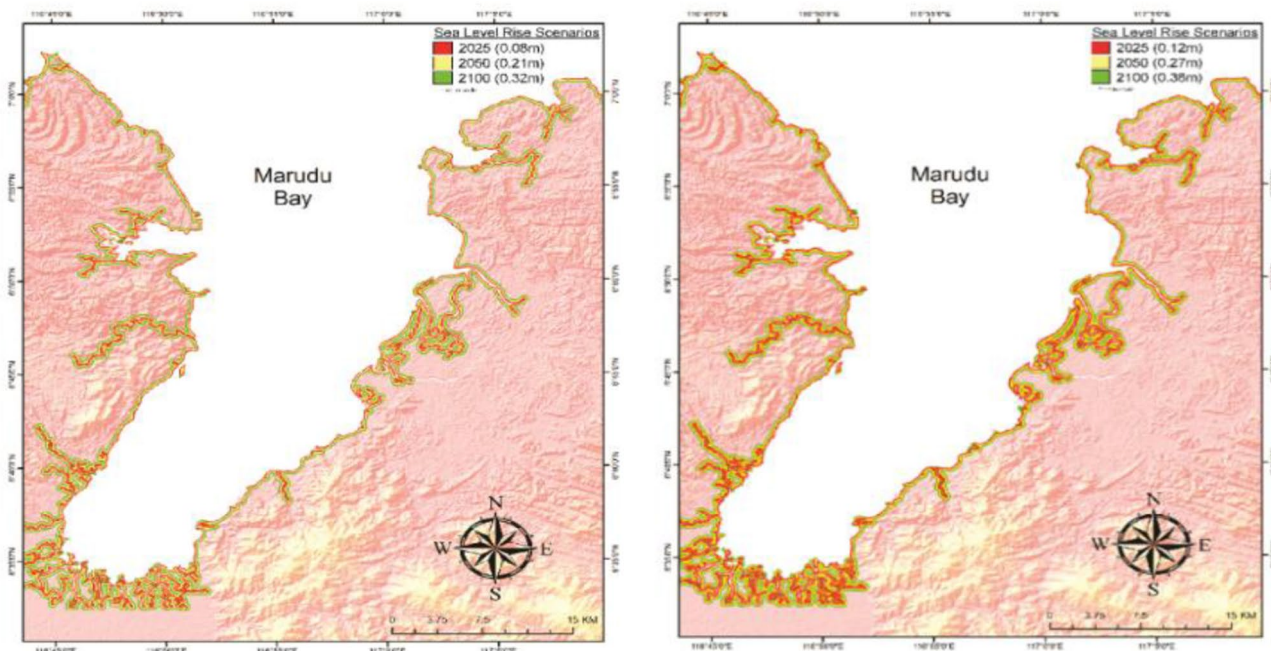


Fig. 7 Projected sea-level rise under (a) RCP 4.5 and (b) RCP 8.5 climate scenarios during the winter monsoon (January) and summer monsoon (July)

Table 8 Climate Change Vulnerability Index (CCVI) for each zone under climate projection of RCP 4.5 and RCP 8.5 for the years 2050 and 2100

Zone	Year	Monsoons	Coastal Vulnerability Index Scoring				RCP4.5				RCP 8.5			
			CESI	SSI	ACSI	CCVI	CESI	SSI	ACSI	CCVI	CESI	SSI	ACSI	CCVI
1	2050	Winter (Jan)	1.67	3.10	3.50	2.76	2.67	3.10	3.50	3.09	2.67	3.10	3.50	3.09
		Summer (July)	1.67	3.10	3.50	2.76	3.67	3.10	3.50	3.42	3.67	3.10	3.50	3.42
	2100	Winter (Jan)	1.67	3.10	3.50	2.76	3.67	3.10	3.50	3.42	3.67	3.10	3.50	3.42
		Summer (July)	2.67	3.10	3.50	3.09	4.00	3.10	3.50	3.53	4.00	3.10	3.50	3.53
2	2050	Winter (Jan)	2.00	3.10	3.70	2.93	2.33	3.10	3.70	3.04	2.33	3.10	3.70	3.04
		Summer (July)	1.67	3.10	3.70	2.82	3.67	3.10	3.70	3.49	3.67	3.10	3.70	3.49
	2100	Winter (Jan)	2.00	3.10	3.70	2.93	3.00	3.10	3.70	3.27	3.00	3.10	3.70	3.27
		Summer (July)	2.33	3.10	3.70	3.04	3.67	3.10	3.70	3.49	3.67	3.10	3.70	3.49
3	2050	Winter (Jan)	2.67	3.10	4.00	3.26	3.67	3.10	4.00	3.59	3.67	3.10	4.00	3.59
		Summer (July)	3.00	3.10	4.00	3.37	4.67	3.10	4.00	3.92	4.67	3.10	4.00	3.92
	2100	Winter (Jan)	3.00	3.10	4.00	3.37	4.33	3.10	4.00	3.81	4.33	3.10	4.00	3.81
		Summer (July)	3.33	3.10	4.00	3.48	5.00	3.10	4.00	4.03	5.00	3.10	4.00	4.03
4	2050	Winter (Jan)	2.33	3.40	3.80	3.18	3.00	3.40	3.80	3.40	3.00	3.40	3.80	3.40
		Summer (July)	2.33	3.40	3.80	3.18	4.00	3.40	3.80	3.73	4.00	3.40	3.80	3.73
	2100	Winter (Jan)	2.67	3.40	3.80	3.29	3.67	3.40	3.80	3.62	3.67	3.40	3.80	3.62
		Summer (July)	3.33	3.40	3.80	3.51	4.33	3.40	3.80	3.84	4.33	3.40	3.80	3.84
5	2050	Winter (Jan)	1.67	3.40	4.10	3.06	2.33	3.40	4.10	3.28	2.33	3.40	4.10	3.28
		Summer (July)	1.67	3.40	4.10	3.06	3.67	3.40	4.10	3.72	3.67	3.40	4.10	3.72
	2100	Winter (Jan)	2.00	3.40	4.10	3.17	3.00	3.40	4.10	3.50	3.00	3.40	4.10	3.50
		Summer (July)	2.33	3.40	4.10	3.28	3.67	3.40	4.10	3.72	3.67	3.40	4.10	3.72
6	2050	Winter (Jan)	2.00	3.50	3.90	3.13	3.00	3.50	3.90	3.47	3.00	3.50	3.90	3.47
		Summer (July)	2.33	3.50	3.90	3.24	4.33	3.50	3.90	3.91	4.33	3.50	3.90	3.91
	2100	Winter (Jan)	2.67	3.50	3.90	3.36	3.67	3.50	3.90	3.69	3.67	3.50	3.90	3.69
		Summer (July)	3.00	3.50	3.90	3.47	4.67	3.50	3.90	4.02	4.67	3.50	3.90	4.02
7	2050	Winter (Jan)	3.00	3.50	4.20	3.57	3.67	3.50	4.20	3.79	3.67	3.50	4.20	3.79
		Summer (July)	3.33	3.50	4.20	3.68	5.00	3.50	4.20	4.23	5.00	3.50	4.20	4.23
	2100	Winter (Jan)	3.67	3.50	4.20	3.79	4.00	3.50	4.20	3.90	4.00	3.50	4.20	3.90
		Summer (July)	3.67	3.50	4.20	3.79	5.00	3.50	4.20	4.23	5.00	3.50	4.20	4.23
8	2050	Winter (Jan)	1.67	3.20	3.10	2.66	2.67	3.20	3.10	2.99	2.67	3.20	3.10	2.99
		Summer (July)	1.67	3.20	3.10	2.66	4.00	3.20	3.10	3.43	4.00	3.20	3.10	3.43
	2100	Winter (Jan)	2.67	3.20	3.10	2.99	3.00	3.20	3.10	3.10	3.00	3.20	3.10	3.10
		Summer (July)	2.67	3.20	3.10	2.99	4.00	3.20	3.10	3.43	4.00	3.20	3.10	3.43
9	2050	Winter (Jan)	2.00	3.20	3.20	2.80	3.00	3.20	3.20	3.13	3.00	3.20	3.20	3.13
		Summer (July)	2.00	3.20	3.20	2.80	4.00	3.20	3.20	3.47	4.00	3.20	3.20	3.47
	2100	Winter (Jan)	2.67	3.20	3.20	3.02	3.33	3.20	3.20	3.24	3.33	3.20	3.20	3.24
		Summer (July)	2.67	3.20	3.20	3.02	4.33	3.20	3.20	3.58	4.33	3.20	3.20	3.58
10	2050	Winter (Jan)	2.67	3.20	3.40	3.09	4.00	3.20	3.40	3.53	4.00	3.20	3.40	3.53
		Summer (July)	2.67	3.20	3.40	3.09	4.67	3.20	3.40	3.76	4.67	3.20	3.40	3.76
	2100	Winter (Jan)	3.67	3.20	3.40	3.42	4.33	3.20	3.40	3.64	4.33	3.20	3.40	3.64
		Summer (July)	3.67	3.20	3.40	3.42	5.00	3.20	3.40	3.87	5.00	3.20	3.40	3.87
11	2050	Winter (Jan)	2.00	3.10	3.50	2.87	3.33	3.10	3.50	3.31	3.33	3.10	3.50	3.31
		Summer (July)	2.00	3.10	3.50	2.87	4.00	3.10	3.50	3.53	4.00	3.10	3.50	3.53
	2100	Winter (Jan)	3.00	3.10	3.50	3.20	3.67	3.10	3.50	3.42	3.67	3.10	3.50	3.42
		Summer (July)	3.00	3.10	3.50	3.20	4.33	3.10	3.50	3.64	4.33	3.10	3.50	3.64
12	2050	Winter (Jan)	1.67	3.10	3.50	2.76	3.33	3.10	3.50	3.31	3.33	3.10	3.50	3.31
		Summer (July)	1.67	3.10	3.50	2.76	3.67	3.10	3.50	3.42	3.67	3.10	3.50	3.42
	2100	Winter (Jan)	2.67	3.10	3.50	3.09	3.67	3.10	3.50	3.42	3.67	3.10	3.50	3.42
		Summer (July)	3.00	3.10	3.50	3.20	4.00	3.10	3.50	3.53	4.00	3.10	3.50	3.53

Vulnerability Index (CCVI) with higher ranking (> 4.00)

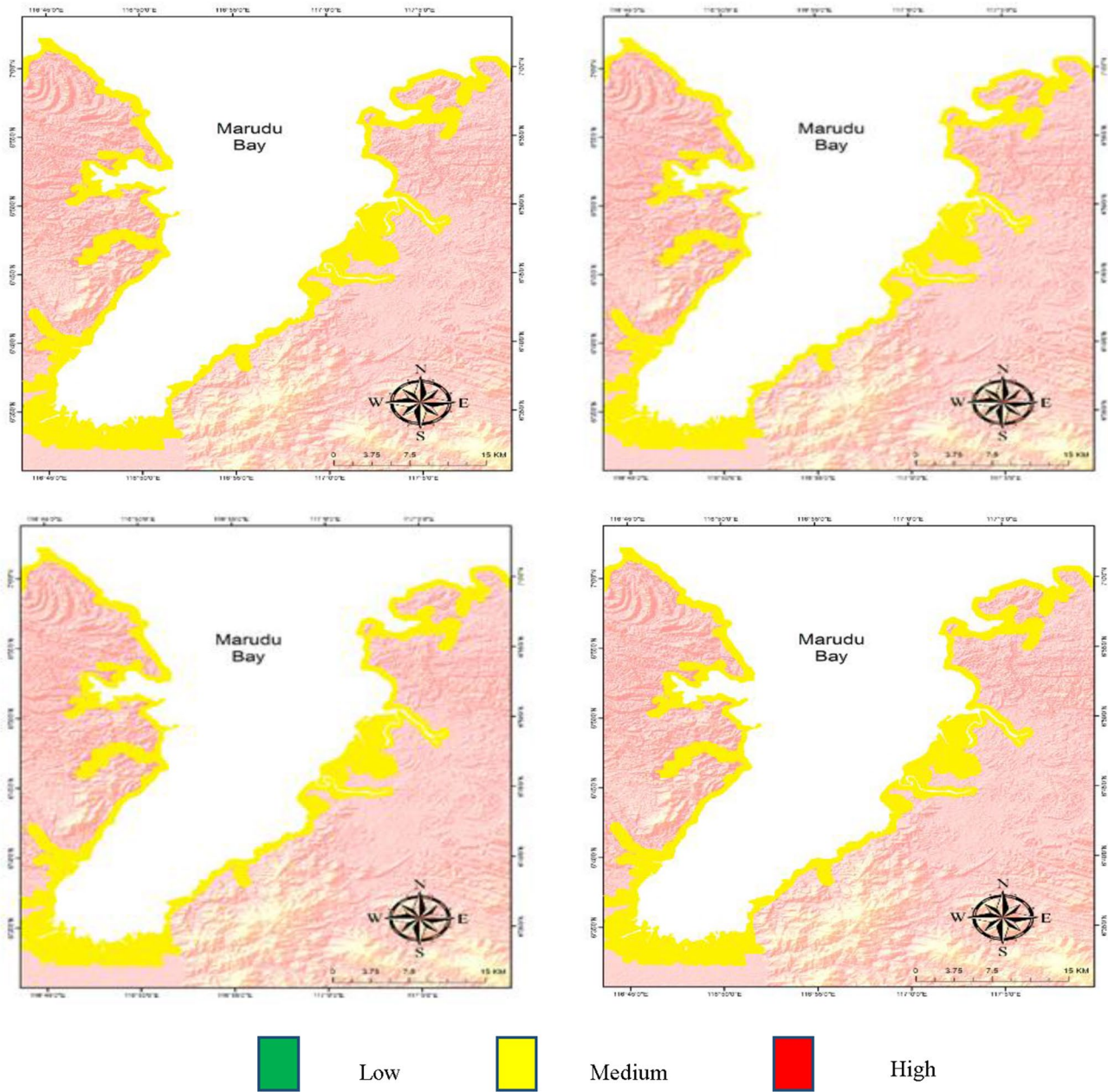


Fig. 8 CCVI for coastal Marudu bay at 2050 (left panel) and 2100 (right panel) during winter monsoon (top panel) and summer monsoon (bottom panel) under RCP 4.5 climate change scenario

area Marudu-Bay. This is believed to contribute for better assessment, especially when involved in the community’s well-being for their risk acceptability. Compared to other works such as Watanabe et al.; Räisänen and Ra [42, 43] mostly looked into the alterations and modification of the methodology for improvement and extension of the tools that were focused on reducing the number of uncertainties as mentioned in the previous work by Deque

et al.; Dobler et al. [44, 45]. For example, Räisänen and Ra; Pulido-Velazquez et al. [43, 46] have incorporated the delta change approach to modify the historical data series feeding into the RCM simulations to obtain the future projections with better accuracy.

In this context of this research, the climate simulation of the future sea-level rise conditions, due to GCMs that have broader and larger coarse spatial scales, we

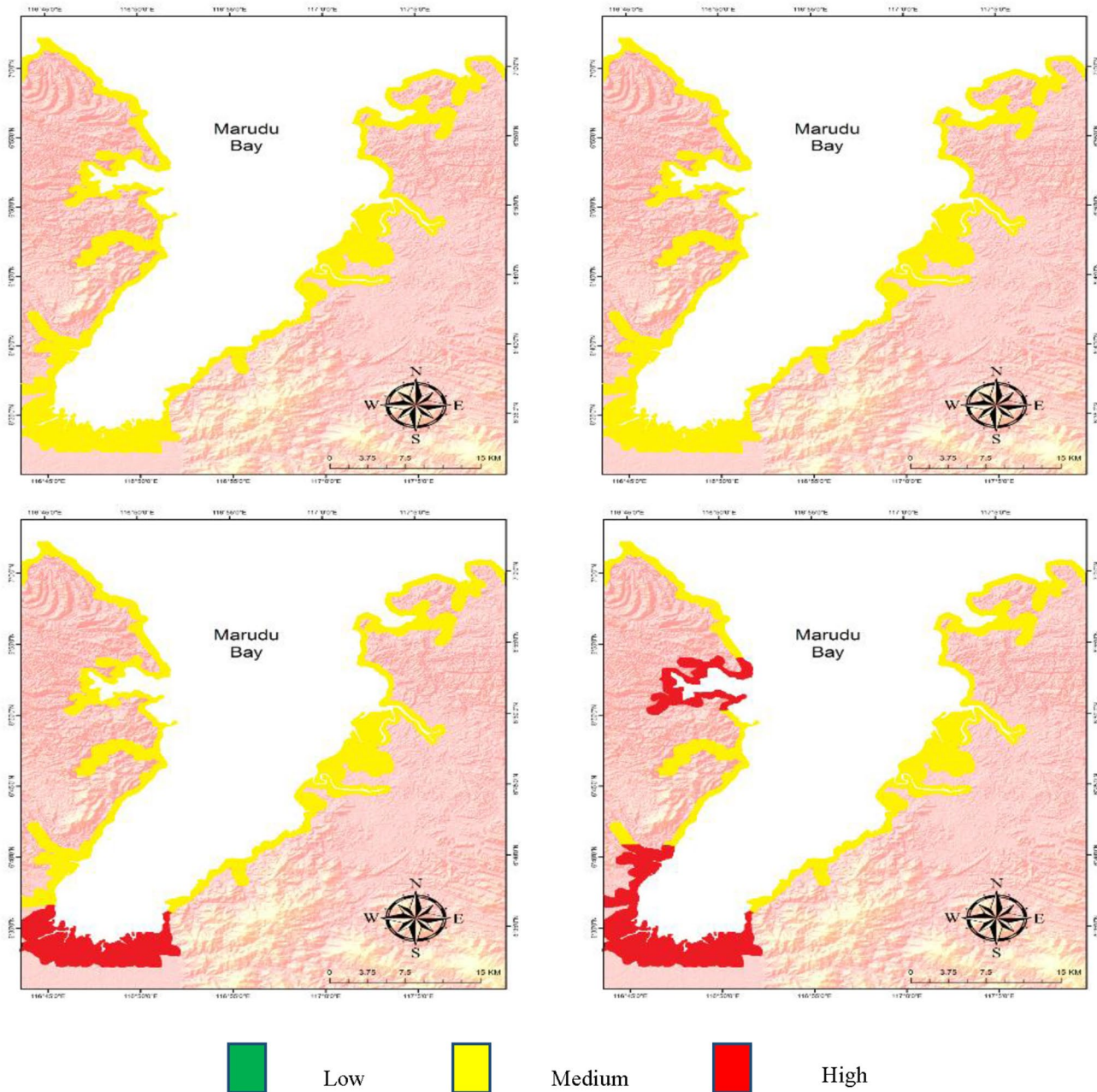


Fig. 9 CCVI for coastal Marudu bay at 2050 (left panel) and 2100 (right panel) during winter monsoon (top panel) and summer monsoon (bottom panel) under RCP 8.5 climate change scenario

had improved the methodology by applying statistical downscaling techniques, combined with the radar altimetry for verifications. This is to establish the statistical relationship between the larger-scale variables with the local variables. This was conducted to make sure a more accurate interpolation of the output simulations will be obtained to estimate the climate-induced changes in the Northern Borneo region downscaled. A regression model analysis was applied in this study to detect the sea-level rise at a specific/individual single station (SLA) to obtain

the predictions and predictors. This phase will help for the next step in extracting and determining the selected events that have sea level anomalies at that period for the future projection of sea level at the specific station (SLF). This phase of the research was conducted by using MATLAB climate analysis toolbox and GrADS to visualize the output of the data. From this point, it can re-produce the type of regional mapping result, which is spatially more localized output constructed. Subsequently, the output will only be transferred to the downscaling process, from

the larger-scale results transferred onto regional/ local scales, for a specific event in the area to detect any of the sea level anomaly and its variability. In this study, the data grid has been narrowed from 500×500 resolution down-scaled now to 0.50×0.50 grid, which only corresponded to the specific period of sea level anomaly extracted and reanalyzed from each interpolated GCMs time series output of the climate datasets.

In here, we not only looking at the sea level rise projections based on the climate change scenarios, unlike previous work from Pulido-Velazquez et al.; Hurrell et al. [24, 25], but also emphasize on the vulnerability assessment. Where the novel contribution in this research is an extension approach not only employs corrective datasets with the statistical technique by using regression analysis, but also integrates the participatory of the local community (with local population compared with no population). Looking at how climate change affects them, in terms of their sensitivity from past to present events, and how the communities of the selected case studies areas respond to the associate climate impacts (Adaptive Capacity). This work, foremost, has produced for the first time a numerical reference for Marudu-Bay, that will portray the status of the sea level impact based by scoring. In which it was constructed from the vulnerability index (CCVI) that was weighted based on the climate threat level and exposure. This progressive methodology approach can also be used and employed for other case study types. Apart from that, in this work, the inundation coverage map due to sea-level rise and climate change scenarios was investigated based on the reference base map projection and then compared with the geo-referenced imagery that covers the study area and to digitize the impacted shoreline and surrounding physical features. The land loss for each coastal zone was analyzed based on the calculated epoch values to determine the inundated areas and highly prone to sea-level changes. The elevation changes were detected by comparing the best fit of the island terrain using the Shuttle Radar Topography Mission (SRTM) for the contour changes of the study area. This phase of the study entirely, especially by the inundation information combined with the vulnerability assessment, will provide important understanding based on the community's adaptive response, on how they cope with the climate-associated impacts [1], thus determining the main factors or drivers that cause the specific, particularly on the climate impacts or hazards.

The adaptive capacity in this study was treated based on the lack of adaptive capacity (LAC) for the recovery of a system after being affected by climatic exposures. This will give the individual zone's relative vulnerability by the numerical data produced from the equated physical effects, indicating their susceptibility, affectability,

and responsiveness to adapt to the changing conditions [38]. Based on the previous studies done by Mucke 2012; Shepard et al. [13, 37], the index scoring was based on the individual contribution of each specific zone and each climate variable by cumulative pressure and exposure to the communities. Then the Sub-Index Exposure (ESI) is based on the Sensitivity Sun-Index (SSI) and Adaptive Capacity (ACSI) that will describe the changes in the physical condition of the environment due to the changing climate and sea level. All parameters are assessed through the changes in their coastal habitat, fish and fisheries, coastal integrity, and human activity by interview, survey, and field observation. This methodology practice is adopted from the Marine and Environment Resources Foundation [47]. In addition, in this work, field data collections and surveys, including interviews and meetings with targeted stakeholders, were also carried out to obtain the actual ground information to verify the significant impact regarding the study area's socio-economics, coastal profile, and relevant weather issues. The observations field study is an essential and powerful tool for detecting the changing physical attributes that affected the study areas regarding the issues that may occur and only can be seen and detected on the site and land use issues with a quick result. In this study, the index and scoring of exposures are based on the inundated areas due to the changes in precipitation and surface temperature. A similar study by [13] has also used the quantitative approach by using the calculated CCVI that combines with the sea-level change, which also shows results with higher coastal vulnerability relatively based on the constructed climate scenarios. Our results show the same sea-level rise that will likely increase in many of the coastal zone's areas in Marudu-Bay, as the same results obtained by Shepard et al. [13]. There was recorded no inundation before their study, however, from the projection analysis, the overall probable sea level will rise estimated at 0.5 m by 2080 with vastly increased numbers of people by 47% increment and property loss at 73% increase due to storm surge impacts recorded in southern shores of Long Island, New York.

3.7 Assumptions and limitations

In this work, we demonstrate a novel method combining the hazard exposure and community vulnerability to spatially characterize the risk by index (CCVI) approach for both present and future sea-level conditions using climate scenario projections. The produced maps of hazard exposure and community vulnerability provide a clear and useful reference for the visual representation of the spatial distribution of the components at risk that can be helpful for developing the targeted hazard mitigation and climate change adaptation strategies. The definition of

future scenarios used in this work is using the latest IPCC scenarios 5th Assessment Report (AR5) [48]. The usage and application of the climate models/ variables in sea-level projections are most likely to be argued, especially when dealing with climate change for analyses that take decades of a minimum of 10 years of impacts studies that can only be seen and observed by simulations. The only standard method established and approved by United Nations (UN) level is using the Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathway (RCPs) that have been applied widely [49–51], which have been said and commented by many researchers [52–54] for its reliability and plausible to represent of the uncertain future that enables the researchers to explore the future of climate change based on the function of greenhouse gases (GHGs) emission from the evolution of the human activities and their implications for the climate. Nevertheless, other researchers have improvised the approach of constructing the future climate change scenario, using the combination of statistical approaches in their climate scenarios simulation to improve and reduce the uncertainty range of the climate model projections. Such work by Collados-Lara et al. [54] works with water resources systems and hydrology as the subject applications. It has improved by correcting the obtained output from the Regional Climate Models (RCMs), including RCPs simulations using bias correction from the statistical distribution of data such as Qmap; [55] 24 and CMhyd; [56] and delta change [42, 43] before extracting and propagate them for other application to generate local series. The control time series employed by this type of approach is believed can be different from the actual event as it deals with a lot of historical databases within the climate change duration, which is for at least a decade/century of analysis; and then compare with the observed time series based on the considered baseline period. This could contribute to lots of missing data and produce higher uncertainty due to the many datasets involved. Their work by Colladoe et al. [54] emphasizes generating scenarios by individual or specific projections of global warming that have not been included in RCPs and RCMs tools. It also contributes to a new potential alternative; when want to identify the certain period of RCM to be used for specific local warming to generate the projections, thus produce the local climate change scenarios from the climatic model; in their case study towards water resources systems impacts.

In this work, we have also conducted the statistical correction techniques using the regression approach by comparing the control data series with the historical information to obtain the corrected simulation and local projections for our subject area, Marudu-Bay. However, this type of approach using the correction techniques; to generate the projection of the potential sea-level rise for local

scenarios; can be overwhelming and complicated things, where it involves lots of complexity of work, extensive of long-term analysis, a lump of databases, trivial tasks, time consumed for accuracy, thus costly, and can be an obstacle if it is dealing with a missing or incomplete datasets for the analysis. In RCPs, the main purpose is to provide the trajectories as in "climate modeling community", that underlying the integrated assessment model output for land-use change, atmospheric emissions of greenhouse gases (GHGs), and aerosols concentration data, harmonized across models and scenarios in order to generate new climate projections [57]. In recent years, many climates modeling communities commented and requested on the additional approach to deal with the uncertainty of the projection's climate model, especially when dealing with the type of future scenarios either by global or regional warming; local or specific climate scenarios or future horizons [54]. Nevertheless, it has to be remembered that the main purpose of the RCPs scenarios produced by the IPCC is not to predict the future nor probability associated with the different scenarios but to take into account the uncertainty linked to future human activities and to inform the decisions of government and more widely to the societies [58]. The Representative Concentration Pathways (RCPs), is a new set of greenhouse gases (GHGs) concentrations trajectories introduced in 1992 and 2000 for the 2nd generation, which is named based on the radiative forcing at the end of the twenty-first century (by the year 2100; and with extension to 2300 for the RCPs period). The RCPs scenarios can be seen as more precise trajectories than the previous. It explores different scenarios based on the evolution of emissions and is representative of multiple concentrations of GHGs and aerosols of existing scenarios as the inputs to the climate model's trajectories. Although it has been said not to be as accurate, but at least there is an effort to project the future of the sea level rise using RCPs for safety measures that can be taken to protect the coastal communities for their future and sustainability, thus to manage the storm surges risk at utmost priority.

To add to this, although with the uncertainty analysis it might not be as accurate to forecast the sea level rise, but with the RCPs analysis, as mentioned, at least there is an effort or stepping stone as a first step that could be continued for the next step, and this effort will be the foundation and basis of the following future measurement tools. Hence, although the plausible high-end of the sea-level rise scenarios using the conventional IPCC AR5 climate models' application has been widely discussed for their sensitivity studies and continuously reviewed, nevertheless IPCC scenarios are still considered given the essential needs of the sea level rise and climate change impact assessment, especially for the need of the communities' adaptation and well-being for the long-term planning

and decision making. Although it can be seen to give a low probability of accuracy but at least at the higher consequences, it will provide important and the essential information for the changes in sea level that could be detected and the subsequent changes; for a strategic and more targeted coastal storm surges management and planning. Furthermore, from many plausible arguments [42, 43] rising due to the application of RCPs as the future horizon instead of the potential levels of global/regional warming, as our scientific understanding to argue that no acceleration in sea level rise would not occur even with the increase of GHGs continues at an accelerated pace, would mean it is rejecting the established scientific foundations of the chemical and physical interactions and processes relating to GHGs to global warming and to ice melt and ocean thermal expansion. The kind of analysis using statistical extrapolations [44, 45] of current rates as a replacement for the scenarios from IPCC meaning it does not include in the physical grounds of the GHGs as combined and multiple effects of the bigger picture existence in climate change formulation and implication. Future scenarios, if only based on the global or regional warming but not taken into account the greenhouse gas emissions, has to be remembered, by mitigating the GHGs emission itself only will definitely reduce the future global and regional warming, hence the sea level rise [58]. Therefore, the process of sea-level scenario development in many cases may not require a high precision of sensitivity assessment, as its already proven scientifically. The main purpose of the entire research is for getting the sea level, whether there is a change occurring or not, and if it does, how much it increases or if any inundated event exists or not. Moreover, it is also important to remember that as impact assessment for sea-level rise is commonly based on the elevation changes, and there is no requirement for a sea-level scenario if its already inundated with 0.01 m accuracy and when the topographical data generally has a vertical precision of 0.3 m at best as mentioned in the previous study by Brock and Purkis [59]. Simple sea level rise projections based on RCPs can allow preliminary impact assessments, especially to the impacted areas, which can inform general adaptation requirements. It has to be noted as well that the first assessment is rarely the last and more research on sea level needs to be conducted in the study areas so future scenarios can be improved. Sea level rise scenarios should evolve with the impact and adaptation assessment based on the first scoping done of the problem and identify the issues to a more detailed understanding of impacts and ultimately to adaptation measures. Therefore, here in this paper, it emphasizes that adaptation assessment to sea-level change is best-considered practice as a process rather than expecting a single assessment to address all issues to a conclusion. The choice of sea-level scenarios

will vary with the focus and objective of the assessment being carried out by Nicholls [58], either to know the consistency in the magnitude of impacts across the scenarios or the probability of the sea level rise occurrence.

Limitations and assumptions in this research, it does not account for complicated sea processes and their systems in detail, such as wave breaking, ocean dynamics, and crustal deformation effects, nor does the model account for rotational and gravitational effects based on the ocean mass, associated with the thermal expansion of seawater due to the decay of glaciers/ice caps/sheets, and changes to land and water storage by the artificial reservoir and groundwater extraction. It also does not predict significant isostatic adjustment and other impacts such as saltwater intrusion. However, it emphasizes the contemporary contribution to the climate change impacts of the shoreline changes. It is also more suited for comparing sites under seemingly-like conditions that ensemble the predictions that can also be employed to achieve and emphasize the relative in climate change vulnerability index (CCVI). The process-based modeling approach in this study also is for regional sea-level projections sums the contribution of sea-level components contributed from the weather drivers such as temperature and precipitation; combined with the GHGs emissions and climate scenarios that causing the sea-level changes, and not involved other factors that is assumed constant. Nonetheless, from this work, it presented as a new tool for a potential future climate change simulation for sea-level rise by only taking into account the attributes of temperature and precipitation as the inputs of the weather scenarios, but nevertheless still integrates with the 2-main and important meteorological drivers in the case study. This research not only considers the statistical approaches as in regression analysis, standard deviation, and asymmetry coefficient, but more on the intensity, magnitude and duration of the historical data obtained which is by detecting the extreme values. In spite of that, the main advantage of the tool employed here is its applicability to any case study and series of data (RCMs, RCPs, and simulation period; requires only historical data and RCMs simulations to generate the potential future scenarios; able to generated individual local projections that ensembles). The tool introduced here allows the determination of the future simulation period based on a specific increment in mean temperature, for example, due to local warming scenario, and propagates the impact that might reduce the precipitation. Understanding sea-level scenarios are expected to progressively develop as part of an iterative process of impact and adaptation assessment. At the same time, the understanding of sea-level rise will improve, and this knowledge should be incorporated with an improvement of new and advanced approaches and

reviewed methodology as the guidance for support of the future sea-level rise analyses.

4 Conclusions

Climate change projection has demonstrated that the coastal area would experience a warmer atmosphere both under RCP 4.5 and RCP 8.5. Relative to the baseline scenario of RCP 4.5, the mean land-surface temperatures in mid-century are projected to increase to 26.0 °C during winter and 27.1 °C during the summer period. Which thereby is an increase of 0.8 °C and 1.0 °C, respectively. Comparatively, a larger increase in the mean land-surface temperature is projected under RCP 8.5 with an increment of 1.7 °C and 1.5 °C during the winter and summer seasons. Whereas, by the end of the century, the mean land-surface temperatures of both RCP 4.5 and RCP 8.5 are projected to increase further with a larger margin under RCP 8.5 with an increment of 2.9 °C and 3.1 °C during winter and summer seasons, respectively. Meanwhile, the climate projection for total precipitation relative to the baseline period that manifested under RCP 4.5 at 2050 exhibits an increase of total precipitation by 11.04 mm/day and 2.73 mm/day during winter and summer monsoons. In spite of that, the northern Borneo region would be experiencing a slight increase of precipitation of about 2.7 mm/day during the winter period at the end of the century and an inappreciable decrease of about 0.03 mm/day during the summer season, respectively. As for the RCP 8.5 climate change scenario, total precipitation is simulated to increase by 1.6 mm/day during the winter period but to increase substantially during the summer period with an increment of 31.65 mm/day at the middle of the century. By the end of the century, the total precipitations are projected to further increase by 6.13 mm/day during the winter monsoon but decrease by 7.75 mm/day during the summer monsoon. The global climate projection simulates an increase of sea level by 0.21 m and 0.27 m over the northern region under RCP 4.5 and RCP 8.5, respectively. Correspondingly, a total of 43.84 ha and 57.02 ha of land estimated would be potentially inundated at the mid-century under RCP 4.5 and RCP 8.5 accordingly. By the end of the century, the sea level is projected to increase about 0.32 m under RCP 4.5 and 0.38 m under RCP 8.5, consequently resulting in 66.84 ha and 79.78 ha of additional inundation coverage. Zone 7 would have the highest inundated coverage due to sea-level rise in both climate scenarios arising from the gentle slope and proximity to the ocean.

This study presents a framework for assessing marine vulnerability to climate change impact that brings together the climate variables (e.g., surface temperature, total precipitation, and sea level) and the marine physical

traits information. Changing climate scenarios presented in this study estimate the future of marine vulnerability to climate change impact manifested from the future greenhouse emissions as the climate change drivers. Despite the limitations of using an indicator-based analysis to generate CCVI, this climate change impact on marine vulnerability approach provides a broader perspective on vulnerability study by providing the fundamentals for projecting marine and coastal vulnerability to climate change in the future. Based on the CCVI at the end of century, coastal areas in Zone 3, 6, and 7 have been identified as highly vulnerable under RCP 8.5. These zones could be considered hotspot areas due to sea-level rise and climatic changes. Applying the integrated vulnerability assessment method to the Marudu Bay area led to a ranking of the relative risk for each coastal zone in relation to the potential hazard exacerbated by climate change and sea-level rise. This method presents vulnerability in numerical data, which cannot be calculated directly based on their physical properties, and the result highlights the zones where the climate changes impacted and sea-level rise may be the greatest. Therefore, the result of this study can be used to make effective adaptive strategy and conservation planning despite its inherent uncertainties.

Lastly, given the large uncertainties in future conditions, there is some risk that sea-level rise under or overestimated for a selected adaptation measure may be exceeded. Hence, ongoing monitoring of the actual sea-level rise, combined with the interpretation of the field observation, is essential as an extension to the scenario development so that additional measures can be implemented in a timely manner if required. Twenty-first-century sea level rise adaptation has been widely analyzed. However, it must be remembered that sea-level rise is expected to continue long after 2100, even if GHGs concentrations are stabilized. Therefore, further research should look beyond the 2100-time horizon.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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