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Modelling Assessment of Sandy Beaches Erosion in Thailand

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ABSTRACT

This paper focuses on the spatial and temporal aspects of rising sea levels and sandy beach erosion in Thailand. The major scientific challenge tackled in this paper was to distinguish the relevance and contribution of sea level rise (including storms) to beach erosion. The Simulator of Climate Change Risks and Adaptation Initiatives (SimCLIM) and its' impact model (CoastCLIM) with two representative concentration pathway (RCP) scenarios (RCP2.6 and RCP8.5) was utilized to forecast changes in sea level and shoreline between the years 1940-2100. Input parameters underlying the modified Brunn Rule were applied (e.g., coastal and storm characteristics). Moreover, sand loss and forced people migration were estimated using fundamental equations. The sea level is predicted to rise by 147.90 cm and the coastline will be eroded around 517.09 m by 2100, compared to levels in 1995. This level of erosion could lead to a decrease of the coastal sandy area by about 2.69 km^2 and a population of 873 people, over the same period. In scientific terms, this paper quantifies the contribution and relevance of sea-level rise (SLR) to sandy beach erosion compared to other factors, including ad-hoc short-term impacts from stochastic storminess. The results also showed that 8.02 and 23.26 percent of erosion was attributed to storms and sea-level rise, respectively. Nevertheless, limited multi-century data of residual movement in Thailand could create uncertainties in distinguishing relative contributions. These results could be beneficial to national-scale data and the adaptation planning processes in Thailand.

1. INTRODUCTION

Sea-level rise (SLR) is one of the most significant problems of this century. Major factors that influence variations in sea levels are *global sea level* (thermal expansion and the melting of glaciers, ice caps and sheets), *local factors* (monsoonal winds and freshwater inflow) and *vertical land movement* (glacial isostatic adjustment (GIA), specific-area vertical land movement, and human-induced vertical land movement) (Church and Gregory, 2001; Niemnil and Trisirisatayawong, 2007; Snidvongs et al., 2008). The study of Church and Clark (2013) at the Intergovernmental Panel on Climate Change Fifth Assessment Report projected that global sea levels will rise by approximately 0.26-0.82 meters during the 2081-2100 period, compared to the 1986-2005 level. In addition, the rate will reach seven meters if the Greenland ice sheet is completely melted (United Nations Framework Convention on Climate Change, 2014). This is consistent with the study of Joyce and Robbins (1996), showing that when global temperatures increased by 0.5 degree Celsius, sea levels rose 0.9 millimeters per year. Similarly, the study of Cazenave and Llovel (2010) demonstrated that relative sea levels in the South China Sea increased by about 5-8 millimeters per year over the 1993-2008 period. For Thailand, the study of Trisirisatayawong et al. (2011), using global positioning system (GPS)-tide gauge data showed that absolute sea-level rise in the Gulf of Thailand was 3.0±1.5 to 5.0±1.3 millimeters per year and vertical land movement was 2.2±0.8 to 3.8±1.3 millimeters per year during the 1940-2004 period. The study of Snidvongs et al. (2008) also showed that the variability of southwest and northeast monsoons raised the sea level in the Krabi province by two millimeters per year. SLR would be expected to have a number of effects, particularly on coastal countries and island nations. The expected three main effects include coastal erosion, saltwater intrusion, and loss of accommodations, dry lands and wetlands (Church and Clark, 2013; United Nations Framework Convention on Climate Change, 2014).

Major causes of coastal erosion/accretion are physical parameters and human activities. Physical parameters comprise coastal geomorphology, wind, waves, tides, and vegetation. Moreover, human activities are those along the coast/river watersheds

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(building houses, dam constructions), and harbor development (building protective seawalls), including onshore and offshore activities (sand and coral mining) (Department of Marine and Coastal Resource, 2013a). Nevertheless, coasts will tend to erode (or accrete) depending on the combined effect of four factors: changes in mean sea level, changes in the frequency and magnitude of transient storm erosion events, extent of supply and loss of sediments from nearby sources and sinks and realignment of shorelines due to changes in wave direction (Smith, 2010). In the case of sea-level rise, there are uncertainties, as coastal erosion tends to be exacerbated when the rate of sea-level rise is faster than the global mean sea-level rise. The studies of Zhang et al. (2004) and Yates and Le Cozannet (2012) found that changes in sea level is one of the most important variables in explaining shoreline mobility, while accelerated coastal erosion rates are probably affected by higher rates of sea-level rise (for instance, accretion of Scandinavian coasts are influenced by glacial isostatic adjustment effects from the melting of the Fennoscandian ice sheet). In the case of Thailand, the Department of Mineral Resources (2003) found that there are five major causes of coastal erosion in Thailand; coastal development projects, dams and upland deterioration, climatic change during the off-season, improper land-use activities, and inefficient coastal utilization and local coastal protection structure (causing erosion in nearby areas). The study of Thampanya et al. (2006) found that the net erosion was approximately 1.3 to 1.7 meters per year along the southern Thailand coastline. This result is consistent with the study of Kraipanon (2010), who showed that coastal erosion problems occur both in the Gulf of Thailand and in the Andaman Sea. There are 18 critical/vulnerable areas where coastal erosion rates exceed five meters per year. The critical areas are 13 provinces located on the coast of the Gulf of Thailand (Chanthaburi, Rayong, Chachoengsao, Samut Prakarn, Bangkok, Samut Sakorn, Petchaburi, Prachuab Kiri Khan, Surat Thani, Nakorn Si Thammarat, Songkla, Pattani and Narathiwat) and in five provinces along the coast of the Andaman Sea (Ranong, Phuket, Krabi, Trang and Satun) (Kraipanon, 2010). Furthermore, the study of Snidvongs et al. (2008) estimated that sea levels in the Krabi province will increase by approximately 20 centimeters over the next 25 years, causing current shorelines to retreat by 10-35 meters.

Sandy beaches are possibly affected by coastal erosion. The study of Dwarakish et al. (2009) in India ranked the relative erodibility of different landform types (which express the geomorphology variable) and showed that the lowest risk area (from coastal erosion) is rocky cliff coast, while the highest risk area is beach, coastal plain, and mud flat. Similarly, the study of Bird (2008) also showed that approximately 70 percent of the world’s sandy beaches have been identified as eroding. Moreover, Thampanya et al. (2006) showed that along southern Thai coastlines, sandy beach and sandy mud coasts are the most fragile areas, whilst mudflats are the least (less than 1 meter per year). Furthermore, its value in tourism and recreation will also be decreased. Thailand has approximately 320,000 square kilometers of maritime zones, 2,800 kilometers of shoreline (including the Gulf of Thailand and the Andaman Sea) and 23 coastal provinces (Aquatic Resources Research Institute, 2011). There are a number of renowned and attractive beaches located in the coastal provinces of Thailand, such as Sai Keaw beach in Rayong province, Patong beach in Phuket province, Pattaya beach in Chonburi province, SaiRee beach in Chumphon province, Railay beach in Krabi province, Khanom beach in Nakhon Si Thammarat province, and Chao Mai beach in Trang province. Consequently, if these valuable beaches are threatened and ruined by coastal erosion, it will absolutely affect tourism and the economic system of Thailand (National Research Council of Thailand, 2012).

Previous studies in Thailand focused mostly on erosion in coastal provinces (local scale) such as Surat Thani, Nakorn Si Thammarat, Krabi, and Phuket (Snidvongs et al., 2008; Saengsupavanich et al., 2009). However, few studies have been conducted on national-scale coastal erosion, and to the best of our knowledge there is no national estimation of sandy beach erosion caused by rising sea levels (Department of Mineral Resources, 2001; Department of Mineral Resources, 2002). Thus, this paper aimed to fill this information gap, using the coastal erosion model SimCLIM/CoastCLIM, as a tool for estimation. The main objectives of this study were: (1) to forecast the rate of sandy beach erosion, and (2) to estimate the impact of sand loss and forced people migration due to global/regional SLR at the Thai national level for the period 1940-2100. The results will contribute to national-scale data of sandy beach erosion, in terms of rate and potential impacts resulting from SLR for future Thai scenarios. Only three critical provinces were examined in this paper (Rayong, Nakhon Si Thammarat, and Trang). They represent the results for each coastline of Thailand: the eastern and western coast of the Gulf of Thailand, and the Andaman Sea coast respectively. In scientific terms, this paper attempted to quantify the contribution of SLR to sandy beach erosion in the three study areas, including ad-hoc short-term impacts from stochastic storminess. Moreover, questions were asked concerning the relevance of SLR to shoreline alteration, compared to other factors. Results were generated by the SimCLIM/CoastCLIM model.

The SimCLIM/CoastCLIM model was selected as the analytical tool due to its ability to simulate beach-scale erosion caused by SLR and by the storminess factors. There are other coastal impact models (e.g., Dynamic Interactive Vulnerability Assessment model; DIVA, Sea Level Affecting Marshes Model; SLAMM, Barataria-Terrebonne Ecological Landscape Spatial Simulation model; BTELSS, and inundation models), however SimCLIM/CoastCLIM with its open-framework allows users to generate and customize climate and SLR scenarios in terms of site-specific data including storm effects, local sea level trends, and shoreline lag-time response (CLIMsystems, 2013; Yin et al., 2013). The fundamental theory underlying the CoastCLIM program is the Bruun Rule and subsequent modifications to it. The Bruun Rule considers the relationship and relevance of sea level change and shoreline alteration. The modified Bruun Rule extends the consideration of coastline interaction to variations in storm surges with the shoreline response time. This allows more available and applicable ranges of analysis (Warrick, 1998; Rosati et al., 2013). Nevertheless, some limitations and uncertainties of the model and the Brunn Rule were encountered and these cannot be neglected. They included uncertainties in the general circulation model (GCM), and represented concentration pathway (RCP) projections on the local scale, the inability of alongshore sediment transport considerations, and the lack of ‘total/complete’ erosion analysis (Warrick, 1998; CLIMsystems, 2013; Hinkel et al., 2013).

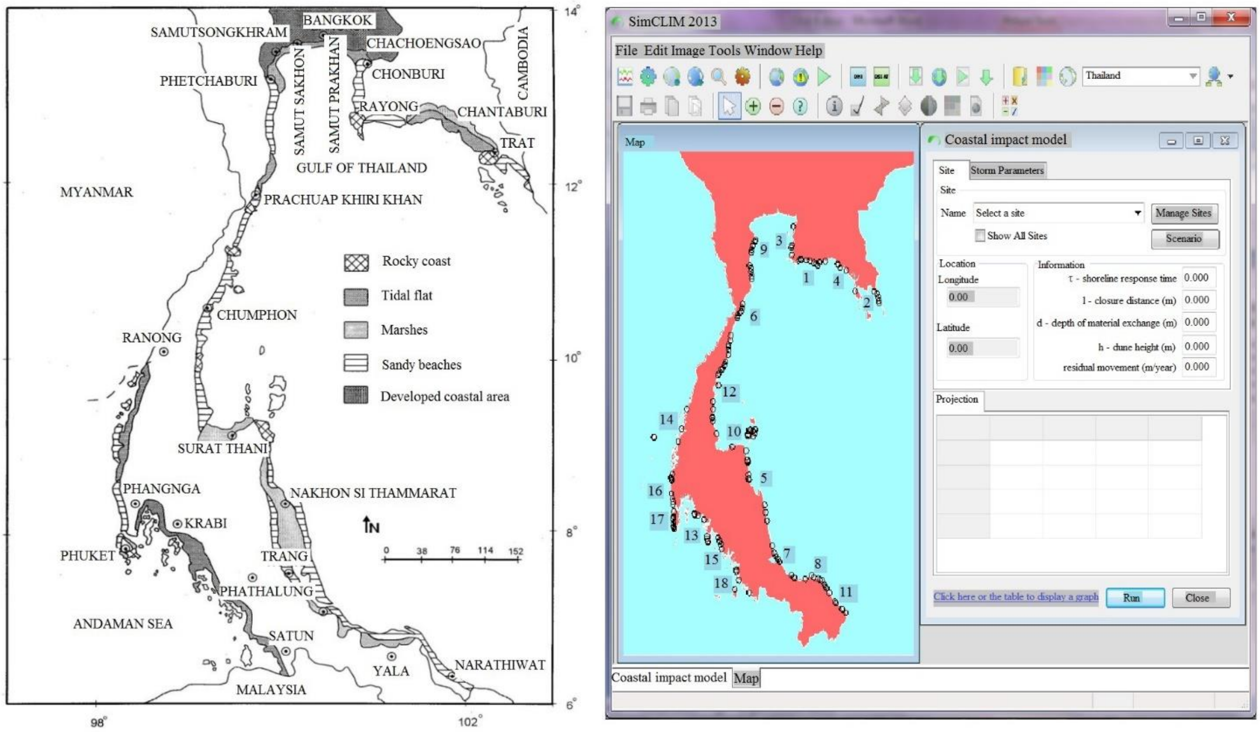
2. METHODOLOGY

2.1 Study area

This study was conducted in 2014. Thus, sandy beach location data from the Department of Marine and Coastal Resource (2013b) and the Department of Mineral Resources (2014) were collected for map comparison with the SimClim/CoastCLIM model at 1-kilometer resolution. 152 sandy beaches from 18 different provinces in Thailand were identified as the study area (Figure 1). More recent data (after 2014) could be collected for further researches, if it is possible. However, difficulties in frequency of beach alteration data collection including geographic information system (GIS)-data that is conducted every 5 years causes problems for the later one.

2.2 Modelling and calculation

This study utilized the coastal impact model (CoastCLIM) of the Simulator of Climate Change Risks and Adaptation Initiatives model (SimCLIM 2013 version 3.3) to forecast sandy beach erosion due to SLR. SimCLIM is a computer-based modeling system, developed by CLIMsystems Ltd. The model can assess and examine the biophysical and socioeconomic consequences of future climate change, sea-level rise, coastal erosion, coastal flooding, and extreme climatic events, including adaptation options. It also considers storm effects, local sea-level trends, and lag effects to provide time-dependent responses of the shoreline to sea-level rise at specific sites. The "open-framework" feature allows users to customize the model in application of a climate scenario generator (climate sensitivity, GHG scenarios or representative concentration pathways; RCPs and general circulation models; GCMs) and a sea-level rise generator (with/without vertical land movement) (CLIMsystems, 2013; Yin et al., 2013).



Name Select a site

☐ Show All Sites

Location

Longitude 0.00

Latitude 0.00

Information

τ - shoreline response time 0.000

l - closure distance (m) 0.000

d - depth of material exchange (m) 0.000

h - dune height (m) 0.000

residual movement (m/year) 0.000

Figure 1. Location of study area (Source: Central Database System and Data Standard for Marine and Coastal Resources and Status of coastal geo-environment in Thailand)

CoastCLIM performs based on the modified Bruun Rule that focuses on change of the equilibrium shoreline position of a beach-and-dune system due to variations in sea level. The equilibrium shoreline position will be re-adjusted or re-established landward and will be eroded when sea level rises, as shown in Equation (1). The Bruun Rule was modified by adding the time lag of the shoreline response and variation in the occurrence of severe stormy seasons, as shown in Equation (2). The modified Brunn Rule attempts to overcome its two main drawbacks; inability to estimate change of yearly actual shoreline position and lack of storm parameter consideration (Warrick, 1998).

$$C_{eq} = z\, l / (h + d) \tag{1}$$

$$dC/dt = (C_{eq} - C)/\ \tau + S \tag{2}$$

where C_{eq} is the equilibrium change in shoreline position, z is the rise in sea level, l is the closure distance; h is dune/bern height at the site, d is depth of material exchange at closure distance (l/(d+h) thus gives slope), t is time (year), C is the shoreline position relative to t=0, τ is the shoreline response time, and S is a stochastically generated storm erosion factor.

Shoreline response time refers to the responsiveness of the coastal system to SLR in a given year, and influences the annual change in the shoreline. Closure distance is the distance offshore at which the process of sediment exchange ceases and the sediment is lost. Depth of material exchange is the water depth at the closure distance. Dune height is the frontal dune/berm/beach height. Storm parameters represent random storm characteristics including storminess (frequency and intensity). These factors determine the erosion potential of the shoreline caused by storms in terms of mean and standard deviation of impacts (meters of erosion). Users can select and add values in storm surge cut mean (SSCM) and storm surge cut standard deviation (SSCSD) flexibly, as representative of the mean and standard deviation of erosion potential in any given year. For the SimCLIM/CoastCLIM model, actual storm erosion was assumed to be 10% of the value selected in the potential one. For analysis with CoastCLIM, all parameters mentioned in Equations (1) and (2) were used as input parameters, including another two parameters; residual movement and vertical land movement. Residual movement is the long-term variation in shoreline position (erosion and accretion), which influences trends of sediment supply and transport. Vertical land movement is the change in relative sea level that excludes climate-change-related components (e.g., land subsidence or uplift) (Warrick, 1998; CLIMsystems, 2013). Closure distance and depth of material exchange were obtained from observation data of the Aquatic Resources Research Institute. Dune height and residual movement were obtained from observation data of the Department of Mineral Resources. Vertical land movement data were collected from SLR with VLM for Cities data of CLIMsystems, and a study of Trisirisatayawong et al. (2011). The VLM values from CLIMsystems data were generated from direct observations of continuous Global Positioning Systems-GPS, (the SONEL program), and from trend analysis of tidal observations (the PSMSL program). Due to lack of observations and secondary data, the default/initial values of the model were applied to shoreline response time and storm parameters.

SLR and the change in the current shoreline (as sand beach erosion) between 1940-2100 were forecasted by SimCLIM/CoastCLiM in two scenarios; RCP2.6, RCP8.5 accompanied with high climate sensitivity, the median value of total 24 GCMs and the sea-level rise pattern (with vertical land movement). The output scenarios comprise vertical land movement (VLM). The representative Concentration Pathways (RCPs) are the 4 greenhouse gas concentration trajectories/scenarios adopted by the IPCC Fifth Assessment Report (AR5). RCP2.6, RCP4.5, RCP6.0 and RCP8.5 represent range of radiative forcing values in the year 2100 (2.6, 4.5, 6.0, and 8.5 W/m^2, respectively) (Moss et al., 2010; Van Vuuren et al., 2011; Rojeli et al., 2012).The comparison between RCPs, CO_2 Concentration and Model is demonstrated in Table 1. RCP2.6 and RCP8.5 stand for Best and Worst case scenarios for analysis in this paper. RCP2.6 (as the best-case scenario) represents the ‘peak and decline’ pathway of radiative forcing and GHG atmospheric concentration, which peak at approximately 3 W/m^2 and 475-490 ppm CO_2-eq in 2050, and decline to 2.6 W/m^2 in 2100. RCP8.5 (as the worst-case scenario) shows a ‘rising’ pathway of the two parameters, which leads to approximately 8.5 W/m^2 and 1,313-1,370 ppm CO_2-eq in 2100 (Intergovernmental Panel on Climate Change, 2014; International Institute for Applied Systems Analysis, 2015). These scenarios could be applied as extreme situations (in terms of high and low extreme future climates) for various climate-related analyses. Countries, including Thailand, can use the ‘extreme scenarios’ as input for climate modeling, atmospheric chemistry modeling, and thread and impact analysis for future climate-related planning (International Institute for Applied Systems Analysis, 2009).

Table 1. The representative concentration pathways (RCPs)

Description		CO_2 equivalent	Model
RCP8.5	Rising radiative forcing pathway leading to 8.5 W/m^2 in 2100.	1370	MESSAGE
RCP6.0	Stabilization without overshoot pathway to 6 W/m^2 at 2100.	850	AIM
RCP4.5	Stabilization without overshoot pathway to 4.5 W/m^2 2100.	650	GCAM
RCP2.6	Peak in radiative forcing at approximately 3 W/m^2 before 2100 and decline.	490	IMAGE

Source: Revised from Scenario process for AR5: Representative for concentration pathways (RCPs) (Intergovernmental Panel on Climate Change, 2014).

Nevertheless, SimCLIM/CoastCLiM was unable to estimate the socioeconomic impacts (sand loss and forced people migration). Thus, sand loss was calculated under the following equation (revised from Hinkel et al., 2013), while forced people migration was calculated in terms of area of sand loss, multiplied by average density per segment (Hinkel et al., 2013):

$$A_d = z \times R \times E_f \tag{3}$$

where A_d is sand lossz z is the segment length, R=erosion rate and E_f is Erosion factor. E_f stands for the factor used for estimating the proportion of z that is composed of sandy beaches and could be inferred for sand supply (Hinkel et al., 2013).

In this paper, only direct sand loss were estimated, indirect sand loss such as areas linked to tidal basins are not included. The required data for calculation under Equation (3) is the appropriate length of the beach which is expressed via z and E_f. In regards to the number of forced people migration, the populations are assumed to spread evenly over the beach area. This equation is proper for our analysis due to the data limitations (e.g., long-shore sediment transport) at national scale in Thailand. Moreover, Thailand's national agency (Department of Marine and Coastal Resource) also conducts the estimation similar to this equation (Department of Marine and Coastal Resource, 2013b; Hinkel et al., 2013; Alexandrakis and Poulos, 2014).

The segment length data were collected from observations and secondary data of the Department of Marine and Coastal Resource, Department of Mineral Resources and Provincial Governor's Office. The erosion factor of a sandy beach (assumed to be constant overtime) was taken as 1 according/refer to Vafeidis et al. (2004), Hinkel et al. (2013). The populations of the three study areas were obtained from the Bureau of Registration Administration, Department of Provincial Administration.

2.3 Model validation

In this paper, the root mean square error (RMSE) and the mean absolute error (MAE) were used together as statistical metrics for the model evaluation and validation process. The combination of these metrics could provide a more complete picture for the assessment of model prediction errors. While RMSE is appropriate to describe a normal distribution of errors, MAE is suitable for uniformly distributed ones. However, both metrics are beneficial when used for model performance measurement in the areas of meteorology, climate, and environmental data analysis (Chen et al., 2012; Akpinar et al., 2013; Chai and Draxler, 2014). Another advantage of RMSE is that RMSEs avoid the use of absolute value, which is highly undesirable in various mathematical calculations. MAE also has advantage as a more natural measure of average error, and is unambiguous. The two combined measures together evaluate and validate results/values of model estimation/prediction comparison to the "real-world" values. Evidence-base/observation data, especially from reliable organizations, are crucially needed for the comparison/process (Willmott and Matsuura, 2005; Chai and Draxler, 2014). The RMSE and MAE were calculated by using the following equations:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} e_i^2} \quad (4)$$

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n} e_i \quad (5)$$

where e_i is model estimation error of n samples (e_i, i=1,2,…,n) and is equal to the difference between the observed value (o_i) and the estimated or predicted value (p_i). Moreover, sensitivity analysis was introduced to assess the uncertainty and variation of the two main input parameters (SLR and storms) that may influence the results.

3. RESULTS AND DISCUSSION

3.1 Historical trends

In this paper, the results were separated into two time spans; historical trends (1940-1995) and future projections (1995-2100). The results in the historical trend were applied to validate/calibrate the model for future projections. In this period, estimated values of relative sea-level change and the retreat of coastline were 0.17 centimeters per year and 2.28 meters per year, respectively. Sand loss and forced people migration values were about 0.01 square kilometers per year and 2 people per year, respectively. During the validation process, the two main outputs of the SimCLIM/CoastCLIM model (relative sea-level change and retreat of coastline) were applied with evidence-base/observation data from various organizations and studies; Sojisuporn et al. (2013), Saramul and Ezer, (2014) including data of the Marine Department and the National Oceanic and Atmospheric Administration (2014). RMSE and MAE represent the difference between actual observed values and estimated values, as well as describing the accuracy of the model's predictions. In this study, RMSE and MAE of relative sea-level change are 0.24 to 0.83 and 0.24 to 0.48 centimeters per year, respectively, whist the values of retreat of coastline are 0.29 to 1.86 and 0.29 to 1.57 meters per year, respectively (Table 2). In the ideal case, these two values should be closer to 'zero', which shows a higher accuracy for the model's predictions. Thus, the accuracy of SimCLIm/CoastCLIM prediction is quite satisfactory and reliable in comparison to the high accuracy level (0.5-2.0 of the referred unit) mentioned in Marghany (2013); Murdukhayeva et al. (2013). The errors of the model estimations are quite acceptable, as mentioned previously (particularly at national and coastal scales). However, at the provincial/local scale, there are rather high errors in the estimation, especially in the estimation of retreat of coastline (1.86 and 1.57 meters per year for RMSE and MAE values, respectively). Thus, the results should be interpreted and applied carefully by considering these errors.

Table 2. RMSE and MAE values of the SimCLIM/CoastCLIM model

Scales	Relative sea-level change (cm/year)		Retreat of coastline (m/year)	
	RMSE	MAE	RMSE	MAE
National scale	0.24	0.24	0.29	0.29
Coastal scale	0.34	0.33	0.74	0.56
Provincial/local scale	0.83	0.48	1.86	1.57

3.2 Future projection

In regard to future projections, results during the 1995-2100 period (106 years) of the four main parameters (relative sea-level change, retreat of coastline, sand loss, and forced people migration) were exhibited as follows:

Estimated relative sea-level change (compared to 1995 levels) of all 18 provinces was estimated to have an increased tendency (about 17.50-147.90 centimeters of the rise) over the 1995-2100 period (Figure 2). At high climate sensitivity, the values will reach 107.40 and 147.90 centimeters for RCP2.6 and RCP8.5 scenarios in 2100, respectively. On the eastern coast of the Gulf of Thailand, Chonburi has the highest rate of SLR, while Rayong has the lowest. On the western coast of the Gulf of Thailand, Prachuap Khiri Khan has the highest rate of SLR, while Phetchaburi has the lowest. On the coast of the Andaman Sea, Ranong has the highest rate of SLR, while Phuket has the lowest.

The estimated retreat of coastline of all 18 provinces was estimated to have a similar tendency as relative sea-level change (about 41.64 to 517.09 meters) (Figure 3). At high climate sensitivity, the values will reach 463.69 and 517.09 meters for RCP2.6 and RCP8.5 scenarios in 2100, respectively. On the eastern coast of the Gulf of Thailand, Chanthaburi has the highest change, while Trat has the lowest. On the western coast of the Gulf of Thailand, Narathiwat has the highest change, while Songkhla has the lowest. On the coast of the Andaman Sea, Satun has the highest change, while Krabi has the lowest.

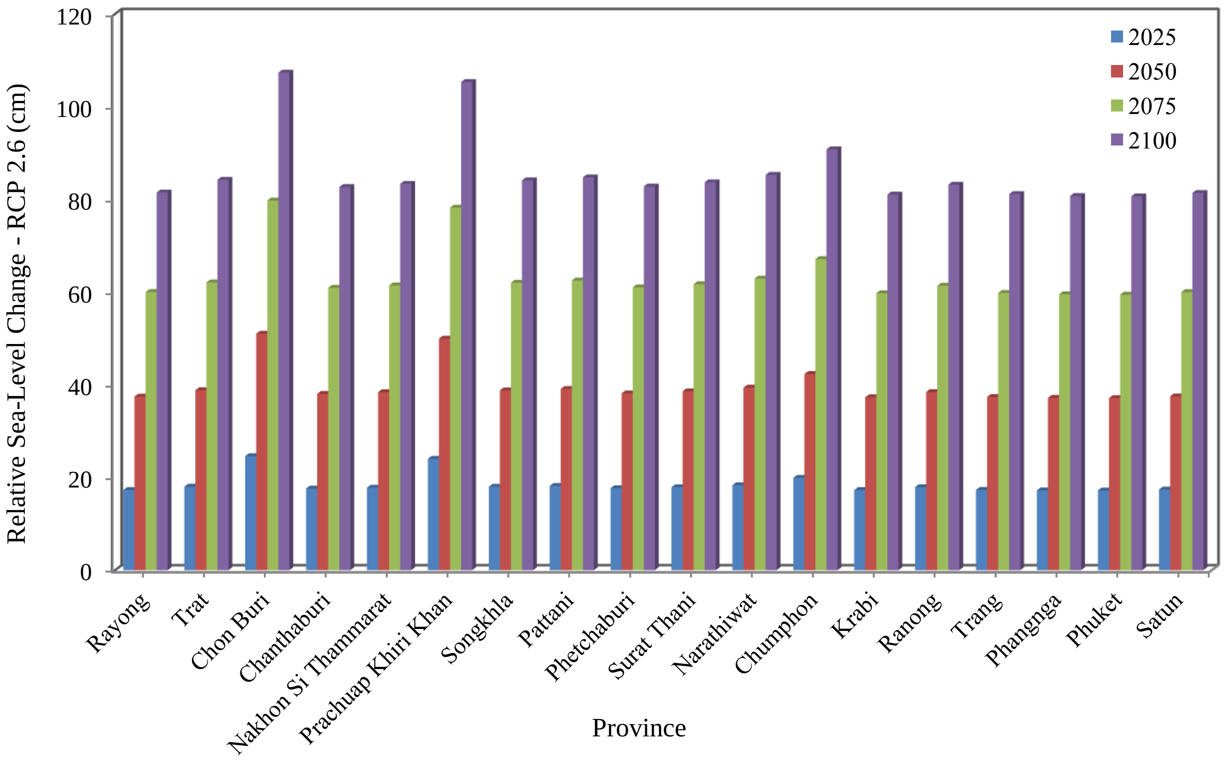
The possible socioeconomic impacts from sandy beach erosion are sand loss and forced people migration. The level of erosion mentioned previously could lead to a decrease of the coastal sandy area and population of about 0.10 to 2.69 square kilometers and 6 to 873 people over the 1995-2100 period (compared to the 1995 level), respectively, as shown in Figure 4 and Figure 5.

Regarding sand loss, at high climate sensitivity, the values will reach 2.35 and 2.69 square kilometers for RCP2.6 and RCP8.5 scenarios in 2100, respectively. On the eastern coast of the Gulf of Thailand, Chanthaburi has the highest change, while Trat has the lowest. On the western coast of the Gulf of Thailand, Phetchaburi has the highest change, while Songkhla has the lowest. On the coast of the Andaman Sea, Trang has the highest change, while Krabi has the lowest.

Regarding forced people migration, at high climate sensitivity, the values will reach 591 and 873 people for RCP2.6 and RCP8.5 scenarios in 2100, respectively. On the eastern coast of the Gulf of Thailand, Rayong has the highest change, while Trat has the lowest. On the western coast of the Gulf of Thailand, Pattani has the highest change, while Surat Thani has the lowest. On the coast of the Andaman Sea, Phuket has the highest change, while Krabi has the lowest.

Considering the model’s results, they could lead to the conclusion that the province with higher relative sea-level change does not always have the higher retreat of coastline, as observed in the Chonburi and Narathiwat provinces. In the SimCLIM/CoastCLIM model, other factors (e.g., storm parameters and residual movement) can affect the rate of retreat of coastline in each province/area.

(a)



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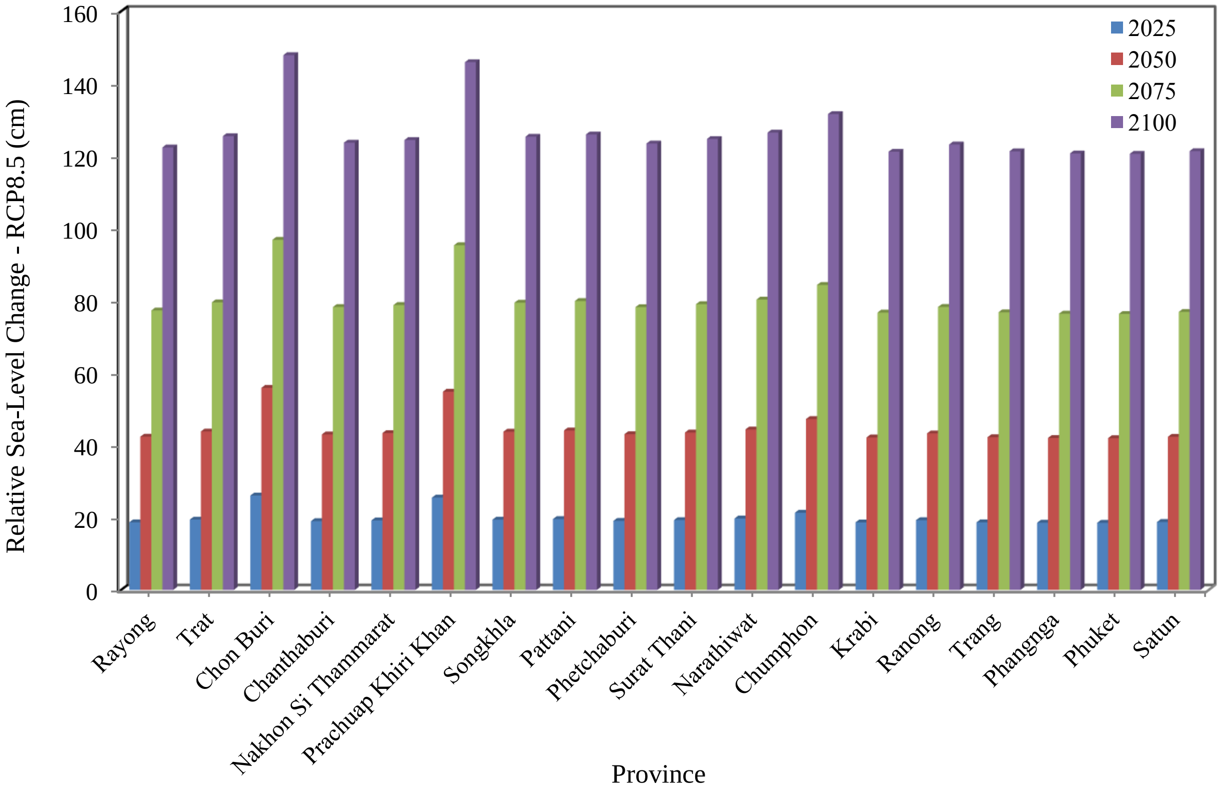
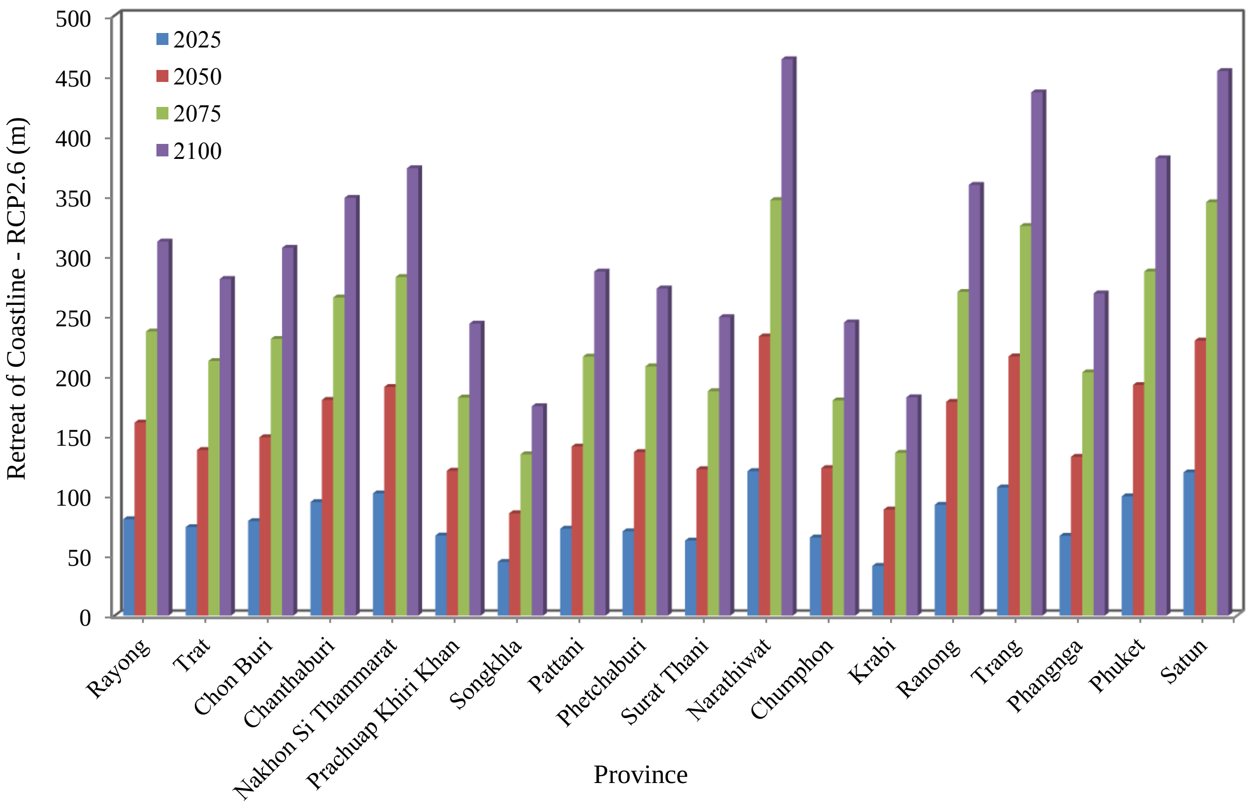


Figure 2. Relative sea-level change in 2025, 2050, 2075, 2100 (comparison to 1995) at high climate sensitivity under RCP2.6 (a) and RCP8.5 (b)

(a)



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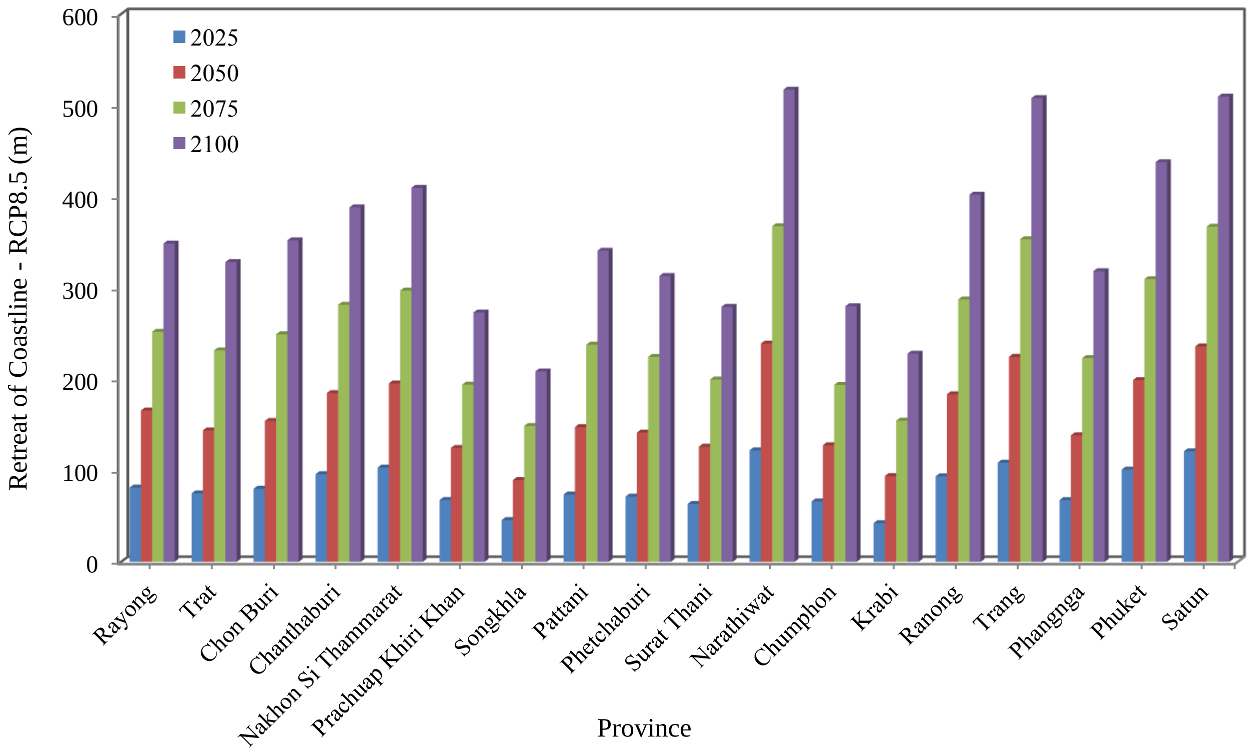
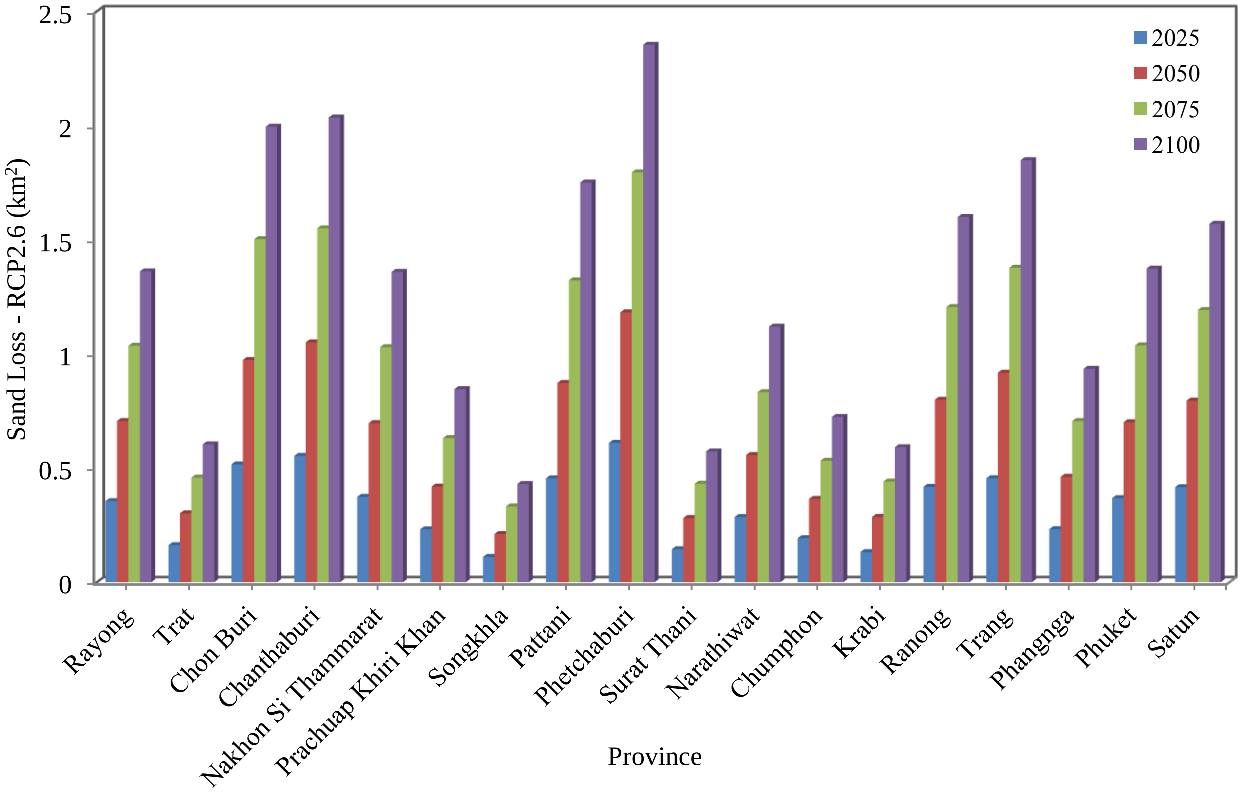


Figure 3. Retreat of coastline in 2025, 2050, 2075, 2100 (comparison to 1995) at high climate sensitivity under RCP2.6 (a) and RCP8.5 (b)

(a)



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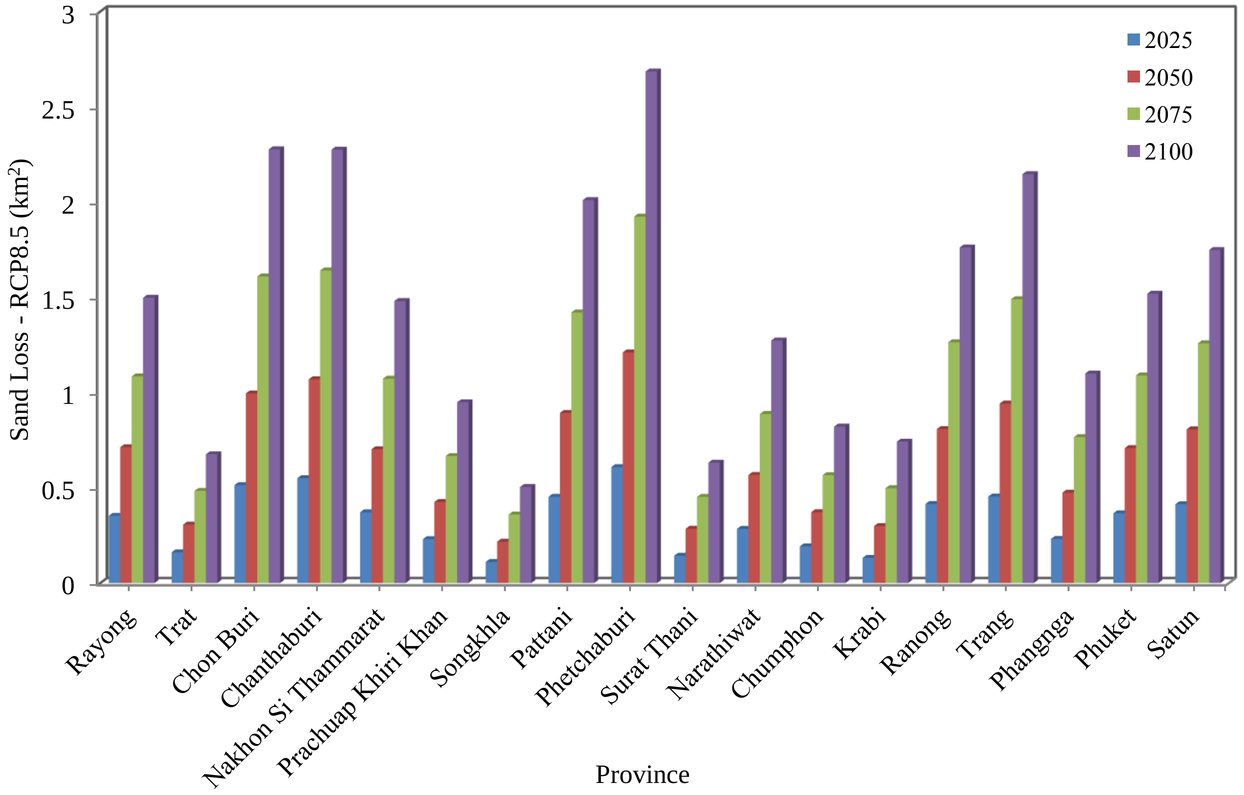
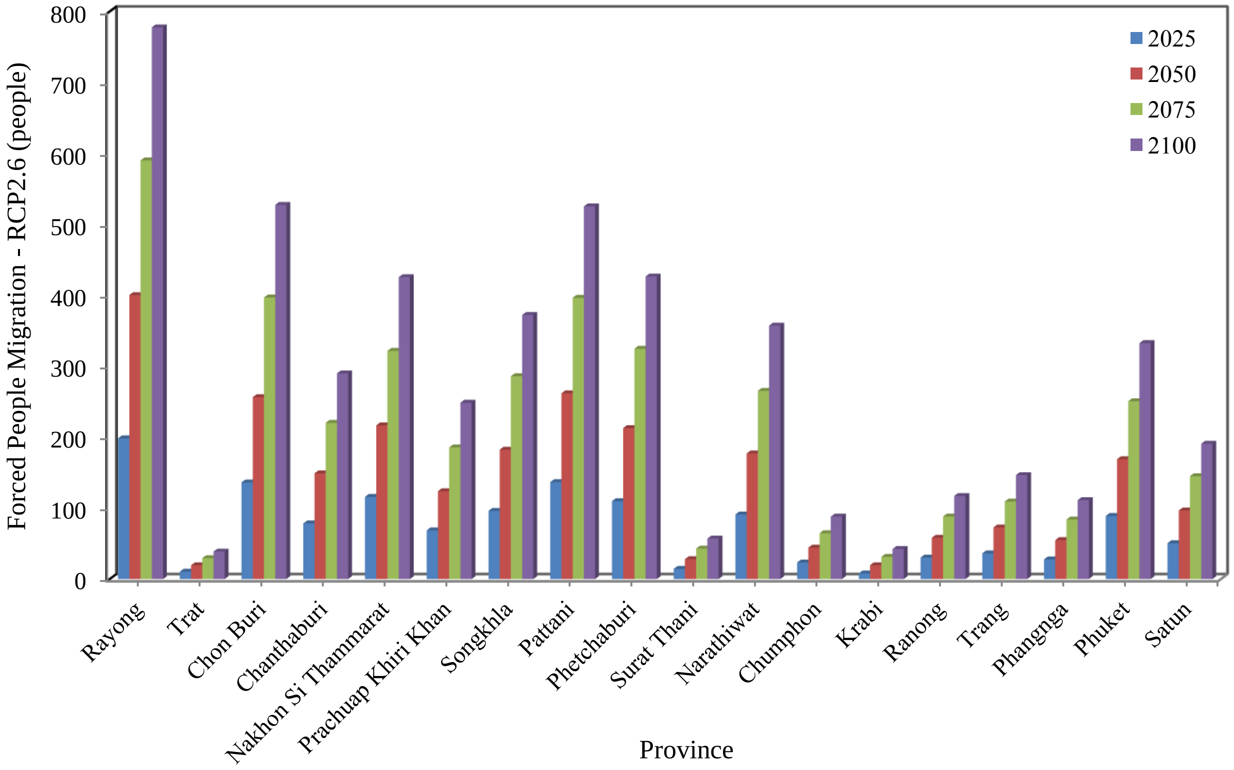


Figure 4. Sand loss in 2025, 2050, 2075, 2100 (comparison to 1995) at high climate sensitivity under RCP2.6 (a) and RCP8.5 (b)

(a)



(b)

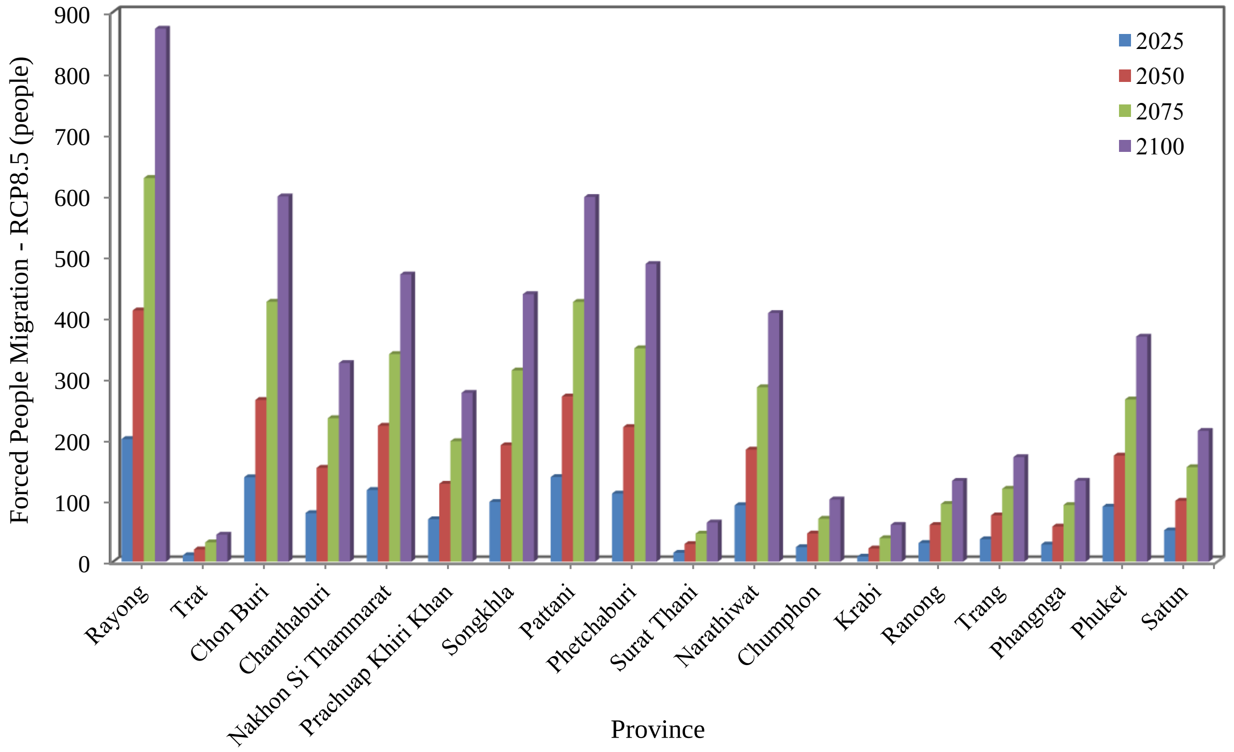


Figure 5. Forced people migration in 2025, 2050, 2075, 2100 (comparison to 1995) at high climate sensitivity under RCP2.6 (a) and RCP8.5 (b)

Sensitivity analysis is a method to identify contribution of inputs or parameters of a model to model output including uncertainty analysis. Several modeling studies (e.g., earth observation model, sequential decision model, climate impact model) applied this method for the purpose (Chen et al., 2016; Lu et al., 2017; Petropoulos and Srivastava, 2017; Amin and Martinez, 2018). In regards to sensitivity analysis of this study (Table 3), contributions of major factors (in the model) to the future shoreline retreat and loss of coastal land were analyzed. Residual movement (RM) has the most contribution-ranging from 70.02 to 75.44 percent, while 6.76 to 8.02 percent and 20.31 to 23.26 percent are attributed to storm and sea-level rise parameters, respectively. In SimCLIM/CoastCLIM, RM should be added based on the data of very long-term changes of coastline position (multi-century). Unfortunately, this kind of data in Thailand at the local scale (appropriate for using as inputs) is limited and the longest period of observation is about 35 years (1967-2003) (Department of Mineral Resources, 2001; Department of Mineral Resources, 2002). The relatively large value of RM in the short-term data could contribute to a high portion of future changes in shoreline (around 70 percent, as mentioned). Thus, further works should be aware of this issue and seek to find a longer period of this value, which will reduce the high portion caused by RM. Furthermore, uncertainty and variation of the two main factors (SLR and storm) in the model were assessed by also using a sensitivity analysis approach. Based on empirical data of the Marine Department during 1995-2014, the variation of sea-level rise was about four percent. However, there are no observation data or studies about the issue of storms in Thailand. Thus, the researcher applied the same value of uncertainty for storm parameters. After analysis, the results showed that when storms varied in a range of +4 to –4 percent, shoreline retreat altered approximately +0.17 to +0.21 and –0.17 to –0.21 percent, respectively. In addition, the same value of variation in sea-level rise influenced beach erosion to change by about +0.11 to +0.18 and –0.11 to –0.18 percent. The RMSE and MAE values of sandy beach erosion in the nearby period (1952-2010) are 2.58 to 2.59 and 1.52 to 1.53 meters per year, respectively, for ±4 percent-uncertainty in both SLR and storms. These values are quite acceptable in comparison to the high accuracy levels mentioned previously in Marghany (2013); Murdukhayeva et al. (2013). Nevertheless, these quite high values of errors (of the model estimation in future scenarios) should not be neglected and perhaps, some other models could be selected in terms of error/uncertainty-reduction options.

Future work should apply other coastal impact models such as Dynamic Interactive Vulnerability Assessment model (DIVA) and MIKE Wave Modelling (MIKE) to integrate more factors and aspects of beach erosion analysis and uncertainty reduction. DIVA can be used for analysis of cost-benefit analysis of adaptation to the retreated coast while MIKE has ability to conduct wave and current analysis. Downscaling model or approach is also recommended for precise analysis at local scale. In term of impacts, loss of sandy beach area and population are mainly calculated by simple equations and assumed to be linear function in term of impacts from sandy beach erosion. The economic loss due to these 2 impacts is not included. In addition, it tends to be overestimated particular in term of migration number. Further works should seek more sophisticated formulations using only population of affected sectors (e.g., tourism and beach-related activities) and investigate interaction between socioeconomic development and local factors (e.g., freshwater inflow). Nevertheless, the SimCLIM/ CoastCLIM model also has other impact models for climate-relevant impacts analysis (hydrology, heat accumulation and water use models) that could be useful for further works.

In this study, the Bruun Rule was applied in SimCLIM/CoastCLIM to estimate the change of shoreline/erosion in sandy beaches due to SLR. The Bruun Rule has two important limitations. Firstly, the Bruun Rule omits consideration of alongshore sediment transport that influences sediment budget and erosion/accretion rate (Hinkel et al., 2013). There is also the lack of ‘total/complete’ erosion analysis due to all factors. The Bruun Rule merely considers a ‘component/portion’ of the factors that affect a beach-and-dune system; only sea-level rise with storm characteristics. Other factors such as the variation of sediment budgets due to coastal protections on rivers (e.g., dams), types of coastal vegetation (as shoreline protection), and land use in coastal areas are not included (Warrick, 1998). Moreover, the model also has uncertainties in projections/ estimations/ simulations for future scenarios, due to the uncertainty in translating GCMs and RCPs to the local scale (CLIMsystems, 2013).

A further limitation was the scarcity and unavailability of input parameters for SimCLIM/CoastCLIM analysis in the base year (1940). Several input parameters required expert advice and proved difficult to acquire, particularly shoreline response time (τ), storm parameters (SSCM and SSCSD), closure distance (l), and depth of material exchange (d) (Warrick, 1998). Both τ and storm parameters required historical data of storm frequency and intensity. Several studies estimated the value of τ as ranging from 3 to 15 years (Leatherman, 1984; Addo et al., 2011), while the values of SSCM and SSCSD were estimated at 4.5 to 10, and 1.57 to 5 meters of erosion (Department of Mineral Resources, 2002; Addo et al., 2011). Furthermore, difficulties were encountered in the estimation of l and d, due to lack of available data, and several empirical formulations as mentioned by Ranasinghe and Stive, 2009. Several studies estimated the values of l and d as varying between 4.19-10 and 595-1,000 meters (Batten et al., 2007; Farrel, 2007; Addo et al., 2011).

Table 3. Sensitivity analysis of major factors (high climate sensitivity with RCP8.5 scenario)

Major factors	Contribution (%)	Variation					
		Percentage		RMSE		MAE	
		+4% of uncertainty	–4% of uncertainty	+4% of uncertainty	–4% of uncertainty	+4% of uncertainty	–4% of uncertainty
Sea-level rise	23.26	0.18	–0.18	2.58	2.59	1.52	1.53
Storm	8.02	0.21	–0.21	2.58	2.59	1.52	1.53
Residual movement	75.44	N/A	N/A	N/A	N/A	N/A	N/A

Pertaining to the main purpose of this research, the endeavor to generate national-scale data of sandy beach erosion resulting from sea-level rise (SLR) in a future scenario (the 1940-2100 period) of Thailand is quite satisfied. The analysis of contribution among various factors (e.g., sea-level rise, storm) on erosion using sensitivity analysis is partially achieved due to limited factors included in the model. However, some aspects can be improved in the future stage. First, lack of input parameter data (e.g., shoreline response time, storm parameters, and depth of material exchange) causes incomplete pictures of the analysis. Second, as mentioned previously, the contribution of “residual movement” parameter to beach erosion (in the model) is quite large in reference to short-term period of data. This leads to a question on the exact portion of shoreline alteration that could be attributed to sea-level rise. And last, the model is applicable for other purposes of analysis related to flooding and adaptation option assessment depend on the requested license. Hence, future works should be concerned about these points and apply more precise data and tools (if applicable) for this type of analysis.

Nevertheless, sandy beach is the transition zone between land and sea and also is the dynamic system that changes overtime (complex-adaptive systems). In the sandy beach system, there is the natural balancing process of sediment transport during monsoon and normal seasons. Erosion occurs in monsoon season (with severe winds and waves) and accretion occurs in normal season (with low levels of winds and waves). The eroded beach areas could be restored in a few years by this natural process and returned to dynamic equilibrium as shown in Samila beach, Songkhla province (Prince of Songkhla University, 2011). Absence of sediment transport analysis could be possible causes of “incomplete picture” of beach erosion. Modeling techniques of sediment transport/load estimation should be introduced, such as a hybrid double feed forward neural network (HDFNN) model, artificial neural networks (ANNs), adaptive neuro-fuzzy inference system (ANFIS), coupled wavelet and neural network (WANN) (Olyaie et al., 2015; Chen and Chau, 2016).

4. CONCLUSIONS

This paper simulated the possible impacts of sea-level rise in terms of sandy beach erosion. These impacts included loss of sand area and the number of people forced to migrate. Several input parameters were added into the SimCLIM/CoastCLIM model to generate variations in sea level and shoreline, while the two major impacts were calculated using fundamental equations.

The results identified that Chanthaburi, Narathiwat and Satun has the highest change in terms of future estimated retreat of coastline on the eastern coast, the western coast of the Gulf of Thailand and the coast of the Andaman Sea. The model and sensitivity analysis approach was together applied for contribution and uncertainty analysis of major parameters; residual movement, storm and sea-level rise. Nevertheless, other parameters (e.g., human activities along the coast/river watersheds, harbor development, onshore and offshore activities) were not considered. As mentioned in the discussion section, this paper considers a ‘component/portion’ of the factors that affect a beach-and-dune system (SLR and storm) due to limitations of the model and the Bruun Rule. Thus, further studies should apply other coastal impact models (DIVA, MIKE) accompanied with the SimCLIM/CoastCLIM model to integrated more factors/aspects and represent ‘total/complete’ picture of beach erosion analysis.

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