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Contributed Paper

Climate Change Impact on Sandy Beach Erosion in Thailand

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ABSTRACT

This paper focuses on the spatial and temporal aspects of rising sea levels on sandy beach erosion in Thailand. The SimCLIM/CoastCLIM model with RCP 2.6 and RCP 8.5 was utilised to forecast changes in sea level and shoreline over the 1940 to 2100 period in Rayong, Nakhon Si Thammarat and Trang. Input parameters underlying the modified Brunn Rule were applied. Sand loss and forced people migration were estimated using fundamental equations. In the 1940 to 1995 period, estimated sea-level rise was 0.14 cm yr^{-1} and shoreline retreat was 5.33 m yr^{-1}. Sea level is predicted to rise by 124.38 cm by 2100, compared to the 1995 level. Trang is the most vulnerable area with 507.90 m of eroded beaches and 2.15 km^2 of sand loss. Rayong's population is the most susceptible, with 873 people being forced to migrate. These results could be beneficial to national-scale data and adaptation planning processes in Thailand.

Keywords: sea-level rise, sandy beach erosion, the SimCLIM/CoastCLIM model, sand loss, forced people migration

1. INTRODUCTION

Root potential causes for coastal erosion or accretion include physical parameters (e.g., coastal geomorphology, wind, waves, tides and vegetation), human activities and variation in storm frequency/magnitude. Coastal geomorphology represents the landform types and sensitivity of the coastline area and accounts for: sediment type, sediment grain size, beach gradient and depth of the near-shore zone. Wind and waves are crucial factors for surge generation and sediment transport. Waves lead energy to coastline and generate movement of sediment (longshore drift and cross-shore drift); the interruption of sediment transport probably causes erosion. Tide influences beach morphodynamics by altering wave action, controlling energy and influencing ground water fluctuation and tidal currents. The interaction between groundwater and tides in the coastal forest environment is crucial in understanding why coastal forest clearance causes intensive coastal erosion in particular environments. Vegetation is also crucial for enhancing coastal slope stability, consolidating sediments and providing some shoreline protection [1-4]. Moreover, three major human factors could lead to coastal erosion: activities along the coast, activities within river catchments/watersheds and onshore and offshore activities. Activities along the coast, such as building houses or land reclamation, port or harbor development, protective seawalls, groynes and jetties and the removal of vegetation and mangroves could lead to coastal erosion both in the short term (less than 5 years) and the long term (more than 5 years). Sediment supply to coastal areas is probably reduced by activities within river catchments and watersheds (e.g., dam construction and river diversion) with the mid- and long-term impacts (20 to 100 years) and spatial scales from approximately 1 to 100 km. Onshore and offshore activities (e.g., sand and coral mining/dredging) are also major factors leading to sediment deficit in the coastal system, modifying water depth and altering wave refraction and long shore drift in a short period of time (1 to 10 years) [4]. Furthermore, storm and sae-level rise (SLR) can cause shoreline erosion on a range of timescales. Variation in storm frequency and/or magnitude will cause rapid short-term erosion, while SLR can influence chronic long-term alteration of shoreline position [5, 6]. In regards to SLR, some studies identified that change in sea level is an important variable in explaining shoreline dynamics and accelerated coastal erosion rates are probably affected by higher rate of SLR; for example, changes along Scandinavian coastlines are influenced by glacial isostatic adjustment effects from melting of the Fennoscandian ice sheet [7, 8]. Furthermore, thespy9e will possibly affect several types of coastline (e.g., beach, sand dune, mangrove and lagoon) to change and re-establish the shoreline position [15]. Particularly, beaches of sandy landform types are highly vulnerable and will be threatened by coastal erosion. Various studies show that sandy beach and sandy mud coastlines are the most fragile and risky areas and approximately 70% of the world's sandy beaches are identified as eroding [3, 9]. This paper addresses both long-term and short-term beach erosion due to SLR and stochastic storminess.

Thailand is a vulnerable country, which has 1,630.75 km of sandy beaches (more than 50% of total shoreline length) located in 18 coastal provinces (from a total of 23 provinces) along the Gulf of Thailand and the Andaman Sea coast. In the context of Thailand, SLR possibly also accounts for potential causes of coastal erosion, including coastal development projects, dams and upland deterioration, climate change, improper land-use activities, inefficient coastal utilisation and local coastal protection structures. The observation data of Department of Mineral Resources during the period 1967 to 2002 demonstrated and concluded that climate change, land subsidence, sediment supply, coastal processes, SLR and human activities could influence shoreline alteration along the coast on both the Gulf of Thailand and the Andaman Sea. Climate change likely affects coastal process (e.g., wind, waves and tides) and leads to extreme storms, in terms of frequency and magnitude. This obviously occurs on the coast of the Gulf of Thailand rather than the Andaman Sea during the monsoon season (October to December) when the Southwest monsoon changes to the Northeast monsoon. Land subsidence, by both from natural and man-made subsidence (e.g., groundwater drilling), also causes the coastal elevation to be lower and easily eroded. In regards to sediment supply, more major and minor rivers flow to the Gulf of Thailand than the Andaman Sea. Various rivers (e.g., Prasae River and Rayong Rivers of the Rayong Province, Pakpanang River of the Nakhon Si Thammarat province and Trang River of the Trang Province) transport sediment to coastal areas on both coastlines but some constructions (e.g., dams and reservoirs) could interrupt the process and cause erosion. Furthermore, port building in industrial areas and infrastructure and accommodation building related to beach-tourism sector and aquaculture in coastal areas could produce changes in shoreline geomorphology, coastal process and also interrupt sediment transport, leading to shoreline erosion. Sea level is also a factor that exacerbates coastal erosion. Nevertheless, SLR-induced erosion could not be confidently proved due to a lack of evidence [10, 11]. Sandy beaches represent a significant contribution to the socio-economic sector, in terms of human utilisation. Fishery and tourism activities are the major use in Thai society, whilst sandy beaches are a habitat for various marine species such as sea turtles, ghost crabs and shells [10, 11]. Regarding tourism and recreation, a number of renowned and attractive beaches are located in Thailand, for instance, Sai Keaw, Patong Pattaya, Railay, Khanom and Chao Mai. Beach tourism is one of the most important sectors contributing to Thailand's economy. Several of the aforementioned beaches are regarded as tourist destinations for both foreign and domestic travellers and generate great income for beach-related sectors (e.g., hotels, restaurants, transportations, souvenirs) and also overall economy. However, the utilisation and value of sandy beaches would be threatened and ruined by coastal erosion, as shown in a study [12] that reported both coastlines of Thailand continuously confront severe coastal erosion problems with more than 5 m of erosion per year (occurred in 18 critical or vulnerable areas). Previous studies [1, 9, 13] in Thailand primarily focused on erosion in coastal provinces (local scale) such as Surat Thani, Nakorn Si Thammarat, Krabi and Phuket. However, there are few studies on national-scale coastal erosion and as far as we are aware, there is no national estimation of sandy beach erosion caused by SLR [10, 11]. Thus, this paper attempts to fill this knowledge gap by using the coastal erosion model (SimCLIM/CoastCLIM) as a tool for estimation. The main objectives of this study are: (1) to forecast sandy beach erosion and (2) to estimate its impact on sand loss and forced migration of people due to global/regional SLR at the national scale for period the 1940 to 2100. The results are hoped to lead to contributions on national-scale data of sandy beach erosion (in terms of rate and potential impacts) resulting from SLR in future scenarios in Thailand. However, only three critical provinces are demonstrated in this paper (Rayong, Nakhon Si Thammarat and Trang) in order to represent the results in each coastline of Thailand; eastern and western coast of the Gulf of Thailand and the Andaman Sea coast, respectively. In scientific term, this paper attempts to distinguish the contribution of SLR to sandy beach erosion in the study areas, including ad-hoc short-term impacts from stochastic storminess. Moreover, it questions the relevance of SLR to shoreline alteration in comparison to other factors. These outcomes can be generated using the SimCLIM/CoastCLIM model.

2. MATERIALS AND METHODS

2.1 Research Data and Study Areas

The data for analysis in this paper are divided into 2 parts: (1) input parameters for SimCLIM/CoastCLIM analysis and (2) data for sand loss and forced people migration calculations. These 2 datasets were collected from relevant organisations in base year (1940) or nearby year in Thailand (due to a lack of historical data).

The input parameters of three study areas shown in Table 1 consist of six site parameters and two storm parameters. Site parameters are: shoreline response time (τ), closure distance (l), depth of material exchange (d), dune height (h), residual movement (RM) and vertical land movement (VLM). Storm parameters are storm surge cut mean (SSCM) and storm surge cut standard deviation (SSCSD). Shoreline response time refers to responsiveness of coastal system to SLR in a given year and influences the annual change in shoreline. Closure distance is the distance offshore after which processes of sediment exchange cease and the sediment is lost. Depth of material exchange is the water depth

Table 1. Input parameters of the 3 study areas for SimCLIM/CoastCLIM analysis.

Province	Site parameters						Strom parameters	
	τ (year)	l (m)	d (m)	h (m)	RM ($m\ yr^{-1}$)	VLM ($mm\ yr^{-1}$)	SSCM (m)	SSCSD (m)
Rayong	5	500	2.5 to 5.7	1.25	-1.5 to -3.5	1.31	15	10
Nakhon Si Thammarat	5	500	2.8 to 4.7	1.25	-2 to -5.3	1.46	15	10
Trang	5	500	1	1.5	-1 to -5	1.4	15	10

at 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 shoreline caused by storm in terms of mean and standard deviation of impacts (metres of erosion). Users are able to select and add values in storm surge cut mean (SSCM) and storm surge cut standard deviation (SSCSD) flexibly in representative for mean and standard deviation of erosion potential in any given year. In the SimCLIM/CoastCLIM model, actual storm erosion is assumed to be 10% of the value selected in the potential one. In analysis with CoastCLIM, all parameters mentioned in Equations (1) and (2) were used as input parameters as well as 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 in 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) [14, 15].

Several observation data [10, 11, 16-18] were obtained for the values of closure distance, depth of material exchange, dune height, residual movement and vertical land movement. The vertical land movement values of CLIMsystems data were generated from direct observations of continuous Global Positioning Systems (the SONEL program) and trend analysis of tidal observations (the PSMSL program). Due to a lack of observational and secondary data, the default/initial values of model were applied to shoreline response time and storm parameters (using model values initiating from 1940).

Sand loss was calculated using Equation (3) while forced migration of people was calculated in terms of area of sand loss multiplied by average density per segment. The segment length data were collected from various observational and secondary data [10, 11]. The erosion factor of sandy beach (assuming the value from 1940: constant overtime) is 1 according to several studies [2]. The population and area of the three study areas were obtained from local administration's data (e.g., Bureau of Registration Administration, Department of Provincial Administration).

Three critical provinces and 27 sandy beaches were selected as the study areas from a total of 18 coastal provinces with 152 sandy beaches in Thailand. In regards to the 27 sandy beaches, 11 beaches are located in Rayong: Pla, Phayun, Namrin, Suchada, Laem Charoen, Mae Ramphueng, Sai Kaew, Phe, Suan Son, Pak Khlong Klaeng and Mae Phim. Nakhon Si Thammarat has 11 beaches: Kanom, Thung Sai, Sichon, Hin Ngam, Piti, Baan Roh, Pothong, Sai Kaeo, Tha Soong Bon, Ban Ko Fai and Chan Chaeng. In addition, other 5 beaches are located in Trang: Leam Makham, Hua Hin, Khlong Son, Pak Meng and Chao Mai. These three provinces are listed among the 18 critical/vulnerable areas where erosion rates exceed 5 $m\ yr^{-1}$ [12]. In Thailand, critical areas are defined by coastal erosion rate. Coastal areas with severe erosion rate (more than 5 m yr^{-1}) will be defined as “critical areas”. In addition, “risky areas” are areas that face moderate erosion rate (between 1 to 5 m yr^{-1}) [19, 20]. From recent observational data (2003 to 2011), Rayong, Nakhon Si Thammarat and Trang suffered high impacts from erosion, which resulted in 21.75, 53.46 and 43.7 km of eroded shoreline, respectively [21]. Furthermore, the three provinces are renowned for beach tourism with several beautiful and famous beaches, such as Mae Ramphueng, Sai Kaew, Mae Phim beach in Rayong province, Hin Ngam, Sai Kaeo, Kanom beach in Nakhon Si Thammarat province and Pak Meng and Chao Mai in Trang province.

2.2 The SimCLIM/CoastCLIM Model

This study utilised 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 modelling system developed by CLIMsystems Ltd. The model can assess and examine the biophysical and socioeconomic consequences of future climate change, SLR, coastal erosion, coastal flooding and extreme climatic events, including potential adaptation options. It also considers storm effects, local sea-level trends and lag effects in order to provide a time-dependent response of the shoreline to SLR at specific sites. The “open-framework” feature allows users to customise the model in applications of climate scenario generator (climate sensitivity, greenhouse gas (GHG) scenarios or RCPs and GCMs and SLR generators (with or without vertical land movement) [14].

CoastCLIM is based on the modified Bruun Rule, which focuses on the change of the equilibrium shoreline position of a beach-and-dune system due to variation in sea level. The equilibrium shoreline position will re-adjust or re-establish landward and will be eroded with SLR, 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 two main drawbacks: inability to estimate change of actual yearly shoreline position and lack of storm parameter consideration [15].

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

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

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/berm 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.

By employing the SimCLIM Model based on two forcing scenarios (RCP 2.6 and RCP 8.5) for the period 1940 to 2100, SLR and coastline retreat is projected. Preselected presumptions are high climate sensitivity and an averaging of the 24 GCM models. The output scenarios consist of vertical land movement. RCP 2.6 and RCP 8.5 stand for ‘Best’ and ‘Worst’ case scenarios, respectively, for the analysis in this paper. RCP 2.6 represents the ‘peak and decline’ pathway of radiative forcing and atmospheric GHG concentrations, which peak at approximately 3 Wm^{-2} and 475–490 ppm CO_2-eq in 2050 and decline to 2.6 Wm^{-2} in 2100. On the other hand, RCP 8.5 shows ‘rising’ pathways of the two parameters, leading to approximately 8.5 Wm^{-2} and 1,313–1,370 ppm CO_2-eq in 2100 [22]. These scenarios could be applied as extreme scenarios (in term of high and low extremes future climate) for various climate-related analyses. Countries (including Thailand) can use the 'extreme scenario' as input for climate modelling, atmospheric chemistry modelling and thread and impact analysis including future climate-related planning.

Nevertheless, SimCLIM/CoastCLiM is unable to estimate sand loss (SL) and forced people migration (FPM). Thus, SL was calculated under the following equation [5] and FPM was calculated in terms of area of SL multiplied by average density per segment.

$$SL = s * C * E_f \qquad (3)$$

Where s is the segment length; C is erosion rate and E_f is Erosion factor. E_f stands for the factor used for estimating the proportion of s that is composed of sandy beaches and could be inferred to be sand supply.

In this paper, the root mean square error (RMSE) and the mean absolute error (MAE) were together used 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 of the metrics are beneficial when used for model performance measurement in areas of meteorology, climate and environmental data analysis [23, 24]. The RMSE and MAE were calculated by following equations:

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

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

Where e_i is model estimation error of n samples (e_i, i = 1,2,…,n) and is equal to difference between observed value (o_i) and 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 Discussions

3.1 Historical Trend

Empirical studies with regard to sea-level change and coastal erosion are represented in observation data of several organisations (e.g., Hydrology Section Engineering Bureau, Marine Department, Department of Marine and Coastal Resource). The observed SLR in Rayong (1978–1995), Nakhon Si Thammarat (1986–1995) and Trang (1968–1992) were −0.37 to 0.12, −0.28 to 0.55 and 0.11 to 0.39 cm yr^{-1}. Observed coastal erosion at Rayong (1952–1995), Nakhon Si Thammarat (1952–1995) and Trang (1974–1995) were 1.4 to 5, 1.74 to 8 and 2.5 to 3.5 m yr^{-1}. Average values of SimCLIM/CoastCLIM estimation in the 1940 to 1995 period for the three provinces were 0.12, 0.14 and 0.13 cm yr^{-1} (SLR) and 3.61, 5.33 and 5.27 m yr^{-1} (erosion rate). For the same period of observational data, estimated values of SLR and beach retreat were 0.13 to 0.14, 0.14 to 0.15 and 0.14 cm yr^{-1} and 0.63 to 7.65, 1.50 to 11.48 and 2.95 to 7.33 m yr^{-1}. Moreover, estimated values of sand loss at the three provinces in the period 1940 to 1995 was 0.03, 0.04 and 0.02 km^2 yr^{-1}, while around 18, 15 and 3 people yr^{-1} were forced to migrate. It was noted that there are few observation data of shoreline retreat in Thailand, which are conducted every 5–10 years using GIS images, while observed data of SLR are collected more often (at least every year).

To validate/calibrate the model for future projection of SLR and sandy beach erosion, RMSE and MAE were introduced using Equation (4) and (5), accompanied with the historical data mentioned above. RMSE and MAE represent the difference between the observed value and the estimated value and also describe the accuracy of model prediction. In this paper, RMSE and MAE of SLR are 0.17 to

0.33 and 0.14 to 0.30 cm yr^{-1} (Figure 1), whist these values for sandy beach erosion are 1.06 to 1.94 and 0.75 to 1.90 m yr^{-1} (Figure 2). In an ideal case, these two values would be closer to 0, which is indicative of a higher accuracy of model prediction. Thus, the accuracy of SimCLIm/CoastCLIM prediction is quite satisfactory and a reliable comparison to high accuracy level (0.5–2 of referred unit) [25, 26].

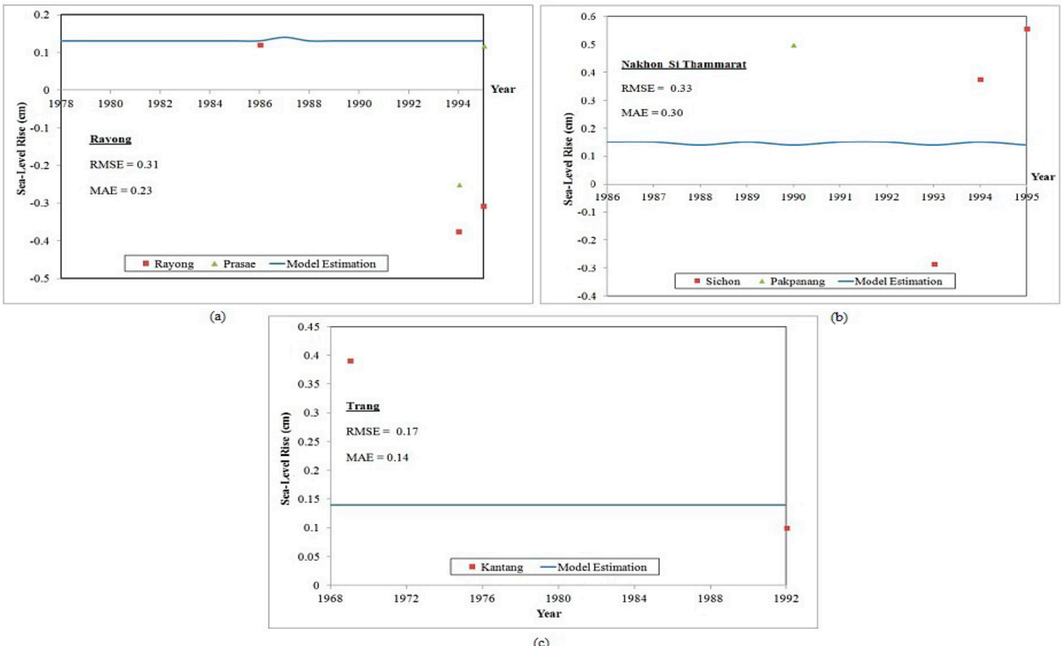

Figure 1. Scatter plot of estimated and observed sea-level rise (cm yr^{-1}) for SimCLIM/CoastCLIM model calibration/validation of (a) Rayong, (b) Nakhon Si Thammarat and (c) Trang.

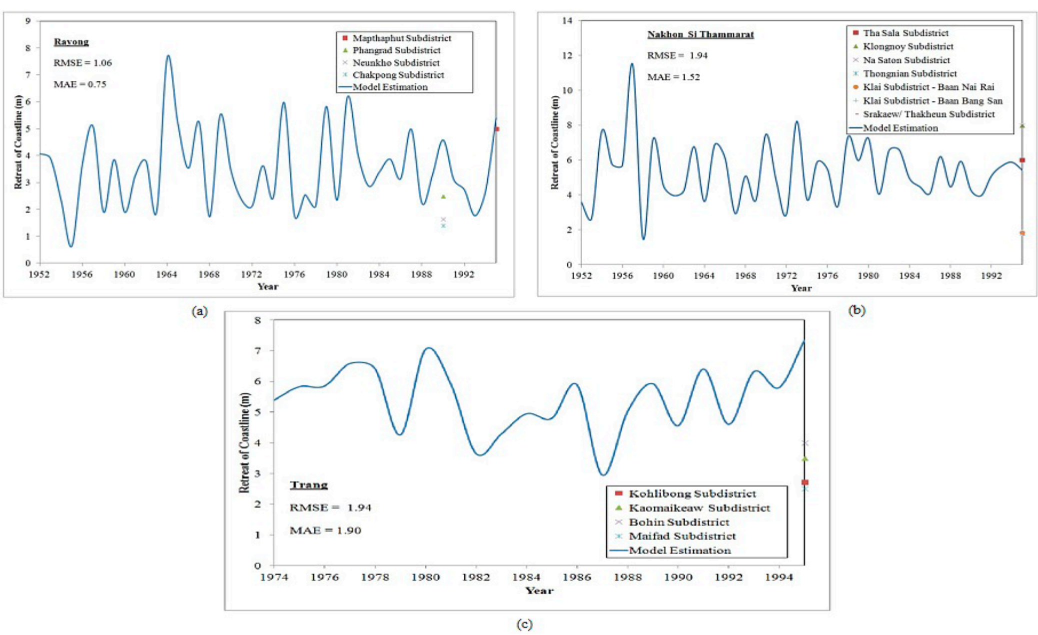

Figure 2. Scatter plot of estimated and observed retreat of coastline (m/yr) using for SimCLIM/CoastCLIM model calibration/validation of (a) Rayong, (b) Nakhon Si Thammarat and (c) Trang.

3.2 Future Projection

3.2.1 Sea-level rise and sandy beach erosion

In the best-case scenario (RCP 2.6) with a peak-and-decline pathway of radiative forcing and atmospheric GHG concentrations, global temperature will rise by 1.79 $^{\circ}$C by 2100 (compared to the 1995 level) (SimCLIM/CoastCLIM data), leading to a change in sea level (accompanied by local VLM shown in Table 1) in the three study areas. The estimated values of the 106-year sea level rise are approximately 0.13 to 83.48 cm (compared with the 1995 level), as shown in Figure 3. Future scenarios indicated that sea level will rise 18.01, 38.70, 61.66 and 83.48 cm by 2025, 2050, 2075 and 2100, respectively (Table 2). At this rate of SLR (accompanied by stochastic storminess shown in Table 1), current shoreline (sandy beach) in the long-term estimation (the 1995–2100 period) will tend to be eroded and result migration inland. The estimated value of the three study areas ranges from 1.09 to 675.58 m, as exhibited in Figure 3. Sandy beach erosion (provincial-average value) in future scenarios is predicted to be worse and shoreline will retreat about 107.30, 216.41, 324.91 and 436.11 m by 2025, 2050, 2075 and 2100.

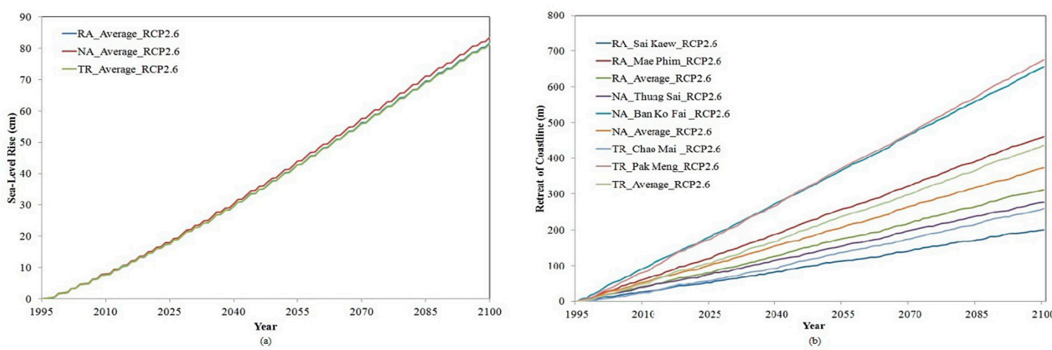

Figure 3. (a) Estimated sea-level rise (cm yr^{-1}) and (b) retreat of coastline (m yr^{-1}) for the best-case scenario (RCP2.6) of the study areas during the 1995-2100 period. (Note: RA stands for Rayong; NA stands for Nakhon Si Thammarat and TR stands for Trang).

Table 2. Estimated sea-level rise and retreat of coastline (m) (1995-2100).

Impact	Year	RCP2.6			RCP8.5		
		Rayong	Nakhon Si Thammarat	Trang	Rayong	Nakhon Si Thammarat	Trang
Sea-level rise (cm)	**2025**	17.50	18.01	17.52	18.63	19.15	18.63
	2050	37.74	38.70	37.67	42.27	43.25	42.11
	2075	60.24	61.66	60.04	77.20	78.70	76.69
	2100	81.61	83.48	81.3	122.33	124.38	121.26
Retreat of coastline (m)	**2025**	80.65	102.32	107.30	81.13	102.87	108.27
	2050	161.35	191.02	216.41	165.27	194.92	224.10
	2075	237.11	282.46	324.91	251.51	296.84	353.13
	2100	312.00	372.96	436.11	348.31	409.44	507.90

In the worst-case scenario (RCP 8.5) with continuous increasing of the two parameters, global temperature will increase 5.4 $^{\circ}$C by 2100 (comparison with the 1995 level). Sea level in the 106-year period tends to increase in the three study areas but with higher magnitude. Figure 4 shows that estimated value of 106-year SLR could reach up to 124.38 cm by 2100 (compared with the 1995 level). Future scenarios indicate that sea level would rise 19.15, 43.25, 78.70 and 124.38 cm by 2025, 2050, 2075 and 2100 (Table 2). At this rate of SLR, sandy beach at the three study areas would be highly eroded, at a magnitude of 747.05 m, by 2100 (Figure 4). Sandy beach erosion (provincial-average value) in future scenarios is predicted to be worse and the shoreline is estimated to retreat approximately 108.27, 224.10, 353.13 and 507.90 m by 2025, 2050, 2075 and 2100.

Regardless of scenario, Rayong is the province least at risk in terms of sandy beach erosion (16.72% below average values) of the three study areas by 2100, whist Trang is the most affected (17.62% above average values) (Table 2). According to Figure 3 and 4, there are six sandy beaches with low risk of erosion (Sai Kaew, Thung Sai, Sichon, Hin Ngam, Piti and Chao Mai), while Mae Phim, Ban Ko Fai, Chan Chaeng and Pak Meng are highly affected beaches. Furthermore, Ban Ko Fai, Chan Chaeng and Pak Meng are defined as critical areas, which has the highest predicted erosion (over 600 m by 2100 or equivalent 5–6 m yr^{-1}) (Figure 5).

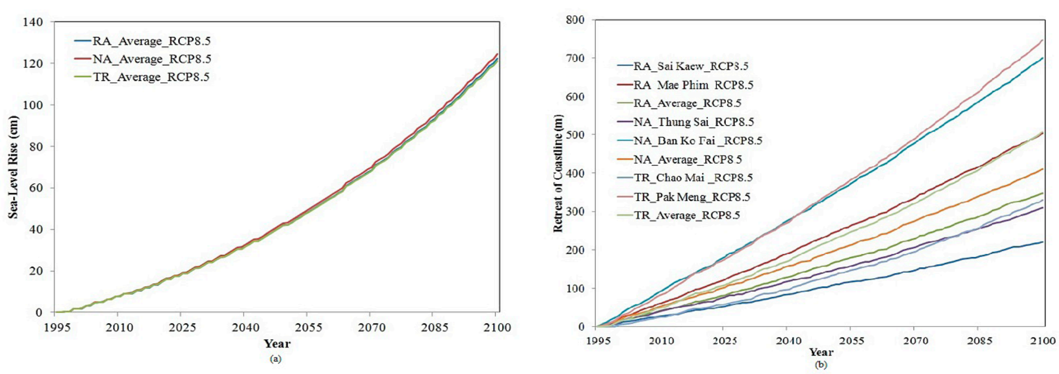

Figure 4. (a) Estimated sea-level rise (cm yr^{-1}) and (b) retreat of coastline (m yr^{-1}) for the worst-case scenario (RCP8.5) of the study areas during the 1995-2100 period.

3.2.2 Sand loss and forced people migration

In this paper, sand loss and forced people migration are the major considered impacts of sandy beach erosion. In regards to rapid short-term erosion from stochastic storminess, loss of coastal land and population could appear in ad-hoc manner. Thus, we applied a constant value of beach length and population density in base year (or nearby) as a "baseline" in order to calculate potential changes in these two impacts. In the best-case scenario (RCP 2.6) with 675.58 m of alteration in sandy beach position, the value of change in land area of the three study areas in the period 1995 to 2100 could vary from 0.01 to 5.20 km^2, as shown in Figure 6. This would lead to changes in the coastal population over the same period of approximately 1 to 2,431 people. In future impact simulations, sandy coastal areas (provincial average value) undergo alteration of 0.46, 0.92, 1.38 and 1.85 km^2 by 2025, 2050, 2075 and 2100 (Table 3). Furthermore, estimated values of changes in coastal people are 200, 402, 591 and 778 people over the same period.

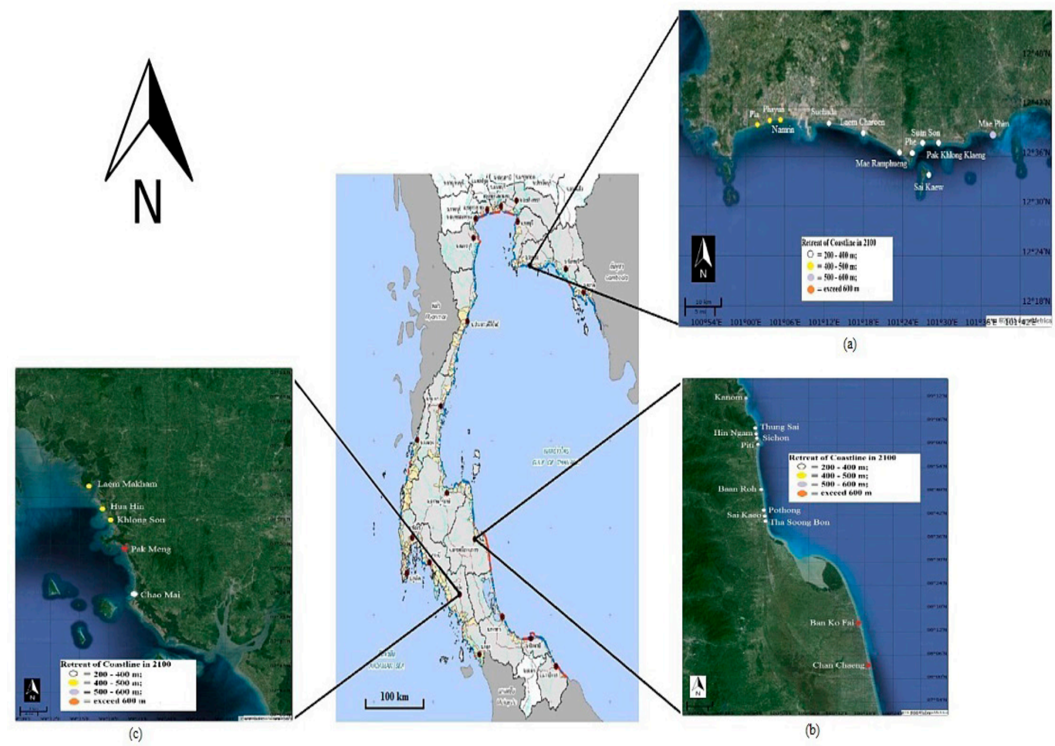

Figure 5. Estimated change of current shoreline (m) in 2100 of the 27 sandy beaches in (a) Rayong, (b) Nakhon Si Thammarat and (c) Trang (in the counterclockwise direction) – critical beaches showing in purple and red colors.

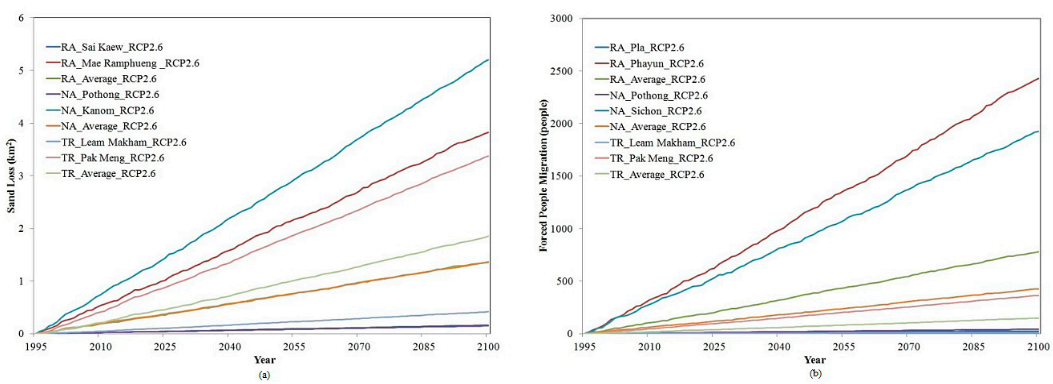

Figure 6. (a) Estimated sand loss (km^2 yr^{-1}) and (b) forced people migration (people yr^{-1}) for the best-case scenario (RCP2.6) of the study areas during the 1940-2100 period.

In the worst-case scenario (RCP 8.5) with 747.05 m of alteration in sandy beach position, the value of change in land area could reach up to 5.61 km^2 by 2100, compared with the 1995 level (Figure 7). In a 161-year period, the estimated values of changes in coastal populations (of the three study areas) tend to be higher and reach up to 2,753 people by 2100. For provincial scale, sandy coastal area will be altered (average value) by 0.46, 0.95, 1.50 and 2.15 km^2 by 2025, 2050, 2075 and 2100, respectively and will cause alteration in human settlement of approximately 202, 412, 628 and 873 people in the same period.

Table 3. Estimated sand loss and forced people migration (1995-2100).

Impact	Year	RCP2.6			RCP8.5		
		Rayong	Nakhon Si Thammarat	Trang	Rayong	Nakhon Si Thammarat	Trang
Sand loss (km^2)	2025	0.36	0.37	0.46	0.36	0.38	0.46
	2050	0.71	0.70	0.92	0.72	0.71	0.95
	2075	1.04	1.03	1.38	1.09	1.08	1.50
	2100	1.36	1.36	1.85	1.50	1.49	2.15
Forced people migration (people)	2025	200	117	37	202	118	37
	2050	402	218	74	412	223	76
	2075	591	323	110	628	341	120
	2100	778	427	148	873	471	172

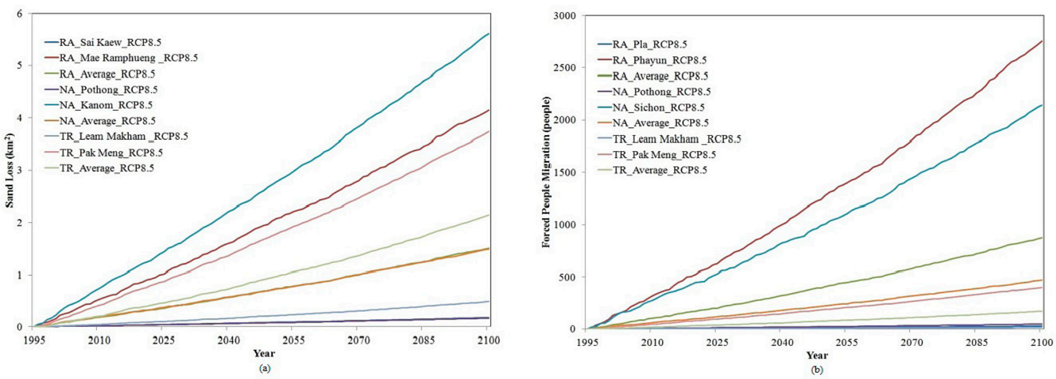

Figure 7. (a) Estimated sand loss (km^2 yr^{-1}) and (b) forced people migration (people yr^{-1}) for the worst-case scenario (RCP8.5) of the study areas during the 1940-2100 period.

In 2100 (both RCP 2.6 and 8.5 scenarios), Nakhon Si Thammarat is the least affected province with 11.53% below average values of land variation, whilst Trang suffers the highest impacts (22.22% above average values) (Table 3). Trang experiences the least impact on coastal populations (67.59% below average values), whilst Rayong is the most affected province with values 73.04% above average in terms of population change by 2100 (Table 3). In terms of beach-scale analysis (Figure 6 and 7), Sai Kaew, Pothong and Leam Makham are the beaches at lowest-risk, while Mae Ramphueng, Kanom and Pak Meng saw the greatest degree of erosion. Furthermore, populations close to Pla, Pothong and Leam Makham have lowest forced migration probability, while several households in Phayun, Sichon and Pak Meng are facing high risk of displacement.

3.3 Evidence Comparison and Sensitivity Analysis

In case of SLR, results of SimCLIM/CoastCLIM in Rayong and Trang (0.30 and 0.31 cm yr^{-1}) are consistent with various observational data for the 1968 to 2014 period but this is not the case Nakhon Si Thammarat, as shown in Table 4. The underlying reasons are: (1) vertical land movement inclusion in the model analysis does not extend to tidal stations and (2) limitations of the model in translating/downscaling SLR scenarios (in s) from a global to local scale. The estimated value of beach erosion rate in Trang (5.37 m yr^{-1}) is quite

Table 4 Historical long-term sea-level rise from tide-gauge stations and beach erosion rate from GIS data of the 3 study areas.

Tide-gauge station/district	Sea-level trend (cm yr^{-1})	Beach erosion rate (m yr^{-1})
Rayong	**0.17-0.27**	**5-10**
- Rayong station (1994-2014)	0.27	NA
- Prasae station (1978-2014)	0.17	NA
Muang district (1952-2008)	NA	5-10
Nakhon Si Thammarat	**0.74-0.85**	**6-12**
- Sichon station (1993-2014)	0.74	NA
- Pakpanang station (1986-2014)	0.85	NA
Tha Sala district (1952-2008)	NA	6
Pak Phanang district (1952-2008)	NA	8
Hua Sai district (1952-2008)	NA	12
Trang	**0.18**	**2-5**
- Kantang station (1968-2014)	0.18	NA
Sikao district (1995-2010)	NA	2-5

similar to the observed value of 59-year-period reports [19] (Table 4). Nevertheless, the sandy beach erosion value of Rayong and Nakhon Si Thammarat (3.62 and 5.51 m yr^{-1}, respectively) are slightly underestimated in comparison with the observation data. This is possibly caused by: (1) the inability of the model to estimate 'total erosion' and (2) the limited data regarding the depth of material exchange (d) in Thailand in the base year.

Sand loss and forced people migration are the main potential impacts of sandy beach erosion considered in this paper. The sand loss value of Trang (0.03 km^2 yr^{-1}) and Nakhon Si Thammarat (0.04 km^2 yr^{-1}) reinforces the conclusion in a study [9] mentioned that the estimated net change of the coastal area in the 30-year period (1967–1998) should be accounted for 0.01–0.32 km^2 yr^{-1} and 0.03–0.06 km^2 yr^{-1} for the east and west coast of Southern Thailand. Unfortunately, there are no direct measurements or research on the change in human settlement caused by sandy beach erosion in Thailand. Few studies [13] attempted to measure the impacts but only in terms of infrastructure loss (e.g., houses and roads).

With regards to sensitivity analysis, the contributions of major factors in the model to the future shoreline retreat and loss of coastal land were analysed. Residual movement (RM) has the greatest contribution, ranging from 70.02 to 75.44%, while 6.76 to 8.02% and 20.31 to 23.26% are attributed to storm and SLR parameters, respectively. In SimCLIM/CoastCLIM, RM should be added to the base data of very long-term (multi-century) change of coastline position. Unfortunately, this kind of data in Thailand, at local scale appropriate for use as model input, is limited and the longest period of observation is about 35 years (1967–2003). As shown in Table 1, RM values at Rayong, Nakhon Si Thammarat and Trang were −1.5 to −3.5, −2 to −5.3 and −1 to −5 m yr^{-1}, in that period [10-11]. The relatively large value of RM could account for a high portion of future change in shoreline (around 70%, as mentioned). Thus, further work should be aware of this issue and seek to determine this value for longer periods, which will reduce the high portion caused by RM. Furthermore, uncertainty and variation of two main factors (SLR and storms) in the model were also assessed through sensitivity analysis. Based on empirical data during the period 1995 to 2014, variation of SLR was about 4%. However, no observational data or studies exist regarding storms in Thailand. Thus, we applied the same value of uncertainty to the storm parameter. After analysis, the results showed that when storm varied in range of +4 to –4%, shoreline retreat altered by approximately +0.17 to +0.21 and −0.17 to −0.21%, respectively. In addition, the same value of variation in SLR caused beach erosion to change by about +0.11 to +0.18 and −0.11 to −0.18%. 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 m yr^{-1} with ± 4% uncertainty in both SLR and storm variables. These values are quite acceptable in comparison to the high accuracy level mentioned previously.

The main outcome of the analysis in this paper (using the SimCLIM/CoastCLIM model) is an assessment of relevance and contribution of SLR to sandy beach erosion. Storm alteration is also considered. In term of impacts, loss of sandy beach area and forced population migration are mainly calculated by simple equations and assumed to be linear functions in term of impacts from sandy beach erosion. The economic loss due to these two impacts is not included. In addition, these impacts tend to be overestimated particularly in terms of migration numbers. 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, other coastal management approaches and analysis as well as extreme wave analysis or more sophisticated numerical modelling of the current state and change of the beach could be possibly applied [27, 28].

4. Conclusions

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

The results showed that the historical trend of sea-level rise was between 0.12 to 0.14 cm/yr, and sandy beach erosion was 3.61 to 5.33 m yr^{-1} from 1940–1995. During the same period, the historical sand loss was between 0.02 to 0.04 km^2 yr^{-1}, and forced people migration was 3 to 18 people yr^{-1}. Future projections indicated that the sea level will rise 122.33, 124.38, and 121.26 cm in Rayong, Nakhon Si Thammarat, and Trang, respectively by 2100 compared to the 1950 level. Sandy beaches will be eroded by between 348.31 to 507.90 m. Sand loss values varied from 1.49 to 2.15 km^2. Moreover, 172 to 873 people will be forced to migrate because of erosion. Many sandy beaches will be affected by this rate of erosion including Mae Phim, Pla, Phayun, Namrin, Sichon, Ban Ko Fai, Kanom, Pak Meng, Leam Makham, and Hua Hin. Moreover, high population density areas, including industrial provinces like Rayong will be more affected in terms of change in coastal population, despite having lower rates of erosion and sand loss. The interaction between economic activities and population migration due to sand loss must be considered.

These results can be applied and used for the comparison of different Thai coastal areas. The researcher hopes that the results will be of benefit for both local and national policy makers, and stakeholders through the extension of available data.

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