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Projections of Future Beach Loss due to Sea Level Rise for Sandy Beaches along Thailand's Coastlines

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ABSTRACT

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Coastline recession caused by sea level rise due to climate change has become one of the most significant issues worldwide. Thailand's coastlines is also likely to face erosion, especially in the low-lying areas, and its future projection due to sea level rise is necessary. This study compiled a database of beach characteristics, including grain size diameter, beach slope and beach width, to assess the projections of future beach loss along Thailand's coastlines against sea level rise scenarios of the Coupled Model Intercomparison Project Phase 5 (CMIP5) in 2081-2100, relative to a reference period 1986-2005 by using the Bruun rule. Future national beach loss rates were projected to be 45.8% for RCP2.6, 55.0% for RCP4.5, 56.9% for RCP6.0 and 71.8% for RCP8.5. In addition, the rate against the sea level scenarios projected by each CMIP5 model for RCP4.5 ranges from 49.1% for MPI-ESM-LR to 73.4% for MIROC-ESM-CHEM. Based on the current beach situation, sandy beaches in 8 and 23 out of 51 zones will disappear for RCP2.6 and RCP8.5, respectively. These findings will help governors and stakeholders develop adaptation strategies against beach loss due to sea level rise.

ADDITIONAL INDEX WORDS: *Sea level Rise, Shoreline Retreat, Beach Loss, Bruun Rule, Sandy Beach*

INTRODUCTION

The estimation of the global sea level rise (SLR) was approximately 1 mm/yr − 2 mm/yr since the late 19th century (Church & White, 2011). Recently, the Intergovernmental Panel on Climate Change's (IPCC) fifth assessment report (AR5) suggested a likely rising rate of 8 mm/yr − 16 mm/yr for sea-level projections for the late 21st century (2081−2100) based on the highest Representative Concentration Pathway (RCP) scenario (IPCC, 2013). This means that the future rate of SLR is up to approximately 10 times the average rate of SLR during the 20th century (Church *et al*., 2013). Long term SLR causes shore line recessions (Bruun, 1962; Stive *et al.*, 2002) by passive submergence, and may even result in the flooding of low-lying coastal areas. The acceleration of SLR has already sparked concerns over global consequences. For instance, Hinkel *et al.*, (2014) estimated that 0.2%−4.6% of the global population will be flooded annually and that flood damages may reach a maximum US$210 trillion under RCP8.5 in 2100. The future SLR may cause natural and socio-economic losses, unless aqequate precautions are taken. Therefore, it is essential to study methods to predict future sea-level impacts and develop countermeasures to combat the loss.

Few researchers have already examined the sea level in Thailand. Putcharapitchakon and Ritphring (2012) analyzed the sea level change in Thailand from water level records from 22 tide gauge stations in the Gulf of Thailand (GOT) and the Andaman Sea during 1972−2011 and indicated that the sea level had risen at an entirely averaged rate of 6.5 mm/yr. Similarly, Sojisuporn, Sangmanee and Wattayakor (2013) investigated the sea level change over the period 1985-2009 and revealed a linear trend of approximately 5 mm/yr around the GOT in the last 25-year time span. These researches implied that the coasts of Thailand have already been experiencing a higher rate of SLR than the global average, which can lead to severe erosion in the future unless urgent attention is given to coastal management planning. However, none of these studies discussed projected beach loss or socio-economic damages.

The Bruun (1962) rule is the most widespread and simple method for projecting shoreline recession due to SLR. Many researchers employed the Bruun rule to project large-scale future beach loss, *e.g.,* Allenbach *et al.*, 2015 and Udo and Takeda, 2017; the former estimated the beach retreat in the inter-basin scale of the Black Sea, while the latter projected the beach loss for entire Japanese coastlines. The method does involve some restrictive assumptions (Cooper & Pilkey, 2004), that have been modified by some researchers (*e.g.,* Dean and Houston, 2016). The Bruun rule still remains a viable method for projecting the beach retreat on a large scale, although obtaining data on sediment size, beach slope or depth of closure (DoC) for an entire coastal zone may not always be feasible (Udo and Takeda, 2017).

In Thailand, the national beach database, including sediment size, beach slope, or even the present beach width, has not been developed sufficiently to assess future beach loss. This study aims to develop the national database of beach characteristics at each coastal zone in Thailand, and to project future shoreline recession

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*Corresponding author: s.chatuphorn@yahoo.com against the SLR data, which are submitted to the Couple Model Intercomparison Phase 5 (CMIP5) (IPCC, 2013) using the Bruun rule. The uncertainties caused by different RCP scenarios and CMIP5 models are also discussed.

METHODS

64 Coastal Zones in Thailand

Thailand's coastlines covers approximately 3,148 km including 2,055 km in the GOT and 1,053 km in the Andaman Sea. The physical geology of Thailand's coastlines is categorized into 3 types: sandy coast, rocky coast and tidal flat. The Department of Coastal and Marine Resources (DMCR) (2014) have categorized beaches into 64 zones based on the physical characteristics of beaches, where 51 zones are composed of sandy beaches including 9 zones in the upper GOT (named E-zone), 11 zones in western GOT (S-zone) and 31 zones in the Andaman Sea (A-Zone) (Figure 1). Because of the difficulty in data collection, such as dry beach width or beach slope measurement for the other types of beaches, only sandy beaches are considered in this study.

The Database of Beach Characteristics

The beach characteristics, *i.e.*, sediment size, beach slope and beach width, were measured in this study. The grain size diameter (d_{50}) and beach slope (tan α) were measured at approximately 230 locations in the period of 2010-2017 (Figure 1). Those locations cover all the sandy beach zones in Thailand and each zone had at least one measurement location. At each location, sand samples were collected at the wet zone of the foreshore to find the grain size diameter (d_{50}) through standard sieve analysis. The beach slopes were obtained from beach profiles and measured by an angle meter in some areas where beach profiles were not measured. Angle meter was use at the same during sand sampling.

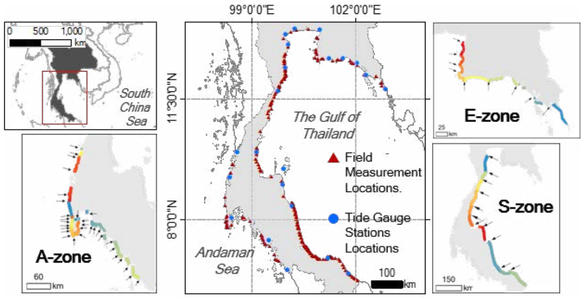

Figure 1. Sandy beach zones in Thailand and locations of data sampling (red dot) and tide gauge stations used in this study (blue dot).

The beach width at each coastal zone was measured using satellite images from the Google Earth application. The visible beach body bounded by the mainland area and the sea is defined as the existing beach area. The image of beach body was then digitized into a polygon by using GIS to calculate the area. The beach body area divided by its length formed the average beach width. However, there were concerns over the date and time of the captured image, which could result in an uncertainty in the beach width calculation because of variations in tidal conditions (Allenbach *et al.*, 2015). This study tried to avoid the problem by performing tidal corrections, which are intended to adjust the beach width at an actual tide to the beach width at mean sea level conditions. By acquiring the date and time (in hours) that the image was taken at a certain location, the actual water level was read through the nearest station's hourly water level record. The estimated capture time, in hours, of the image was based on the solar height and the length of the shadow of the vertical object on the horizontal surface on the earth (Hoang *et al.*, 2016). The difference between the actual water level and the mean sea level multiplied by the beach slope gives the corrected distance. The synoptic beach width was obtained through the combination of corrected distance and the averaged beach width from the satellite image. Although, the method of tide correction cannot provide highly accurate beach width, it is better than no tidal effect consideration. The satellite images were captured during 2009–2015. The water level records were obtained from the Marine Department of Thailand. Figure 1 shows the locations of the 22 tide gauge stations, and each station has at least 5 years of data.

The Method of Future Beach Loss Projection

The projection of future beach loss due to SLR along Thailand's coastlines was determined through the 1D analytical model. This model was developed based on the Bruun rule (Bruun, 1962) by Mimura *et al.* (1994) and have already been applied to estimate the beach loss for entire Japan coasts (Udo and Takeda, 2017). The equations below demonstrate the formulae constructed for the model, and the parameters required to apply the formulae. In detail, the Bruun rule (Equation 1) could be applied under the assumption that the beach profile can maintain its equilibrium shape over a long term when sea level rises. It also assumes that sand is moved from the shore face to accumulate on the lower part of the profile with the amount equal to the SLR.

$$\frac{\Delta y}{y_*} = -\frac{S}{h_* + B_h} \tag{1}$$

where Δy is shoreline retreat, y_* = horizontal distance to the depth of closure, h_*, S = sea level rise, and B_h is the berm height. Equation 2 describes the equilibrium profile, which significantly relies on the grain size (Dean, 1991), and it is delimited by its seawards distance at the depth of closure (DoC), where sediment transport by waves is neglected.

$$h = Ay^{2/3} \tag{2}$$

where h = water depth, A = scaling parameter based on sediment size (d_{50}), and y = distance in the seaward direction. Equation 3 is used to determine the DoC (Nicholls *et al.*, 1996) by using a significant wave height and period with probability of 12 h per t years exceedance data.

$$h_* = 2.28H_{e,t} - 68.5\left(\frac{H_{e,t}^2}{gT_{e,t}^2}\right) \tag{3}$$

where $H_{e,t}$ = significant wave height that is exceeded 12 h per t years, $T_{e,t}$ = significant wave period with 12-hour-per-t-year exceedance, and g = gravitational acceleration. After obtaining the DoC (h_*), it is substituted into Equation 2 to find y_*. Equation 4 (Takeda and Sunamura, 1983) and 5 (Sunamura, 1983) are used to calculate the berm height (B_h), which requires an entire-period average significant wave data and period.

$$B_h = 0.125 H_b^{5/8} (g T_s^2)^{3/8} \tag{4}$$

where H_b = breaking wave height and T_s = mean significant wave period.

$$\frac{H_b}{H_s} = (\tan\alpha)^{0.2} (\frac{H_s}{L_s})^{-0.25} \tag{5}$$

where H_s = mean significant wave height, *tanα* = beach slope, and L_s = significant wave length. When all parameters are altogether collected with the SLR data (S), they are substituted into equation 1 to compute the distance of retreated shoreline (Δy).

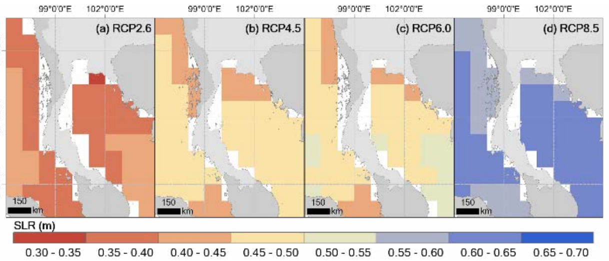

Figure 2. Ensemble-mean regional sea level rise (m) around Thailand's coastlines in 2081–2100 relative to 1986 – 2005 period projected by IPCC (2013) using 21 CMIP5 models for (a) RCP2.6, (b) RCP4.5, (c) RCP6.0 and (d) RCP8.5. The white space indicates no data.

Regarding SLR data, this study uses the ensemble-mean regional SLR data (1 degree latitude-longitude resolution) of 21 CMIP5 models for the RCP2.6, RCP4.5, RCP6.0, and RCP8.5 scenarios and the data of each 21 CMIP5 model for the RCP4.5 scenario in 2081−2100 relative to 1986 - 2005 (IPCC, 2013). In total, the ensemble-mean sea level rise data range between 0.34 m − 0.41 m for RCP2.6, 0.21 m − 0.49 m for RCP4.5, 0.42 m − 0.51 m for RCP6.0 and 0.55 m − 0.65 m for RCP8.5. Figure 2 displays the ensemble-mean regional sea level rise data around Thailand's coastlines. The spatial distribution of sea level rise data around Thailand is generally similar. There are no significant differences among the gulf of Thailand, or the Andaman Sea side. The averaged ensemble-mean SLR along the entire coastline of Thailand are 0.39 m for RCP2.6, 0.46 m for RCP4.5, 0.48 m for RCP6.0, 0.61 m for RCP8.5.

For the wave data set, a 3-hour significantly reanalyzed wave data with 1 degree latitude-longitude resolution provided by The European Centre for Medium-Range Weather Forecasts (ECMWF) (ECMWF; see www.ecmwf.int) for 1980–2010 (30-year period) (Figure 2) are used to compute H_s, T_s, $H_{e,t}$, and $T_{e,t}$. H_s and T_s are determined using the significant wave height and wave period averaged over the 30-year period, respectively, while $H_{e,30}$ and $T_{e,30}$ are determined using the 12-h exceedance significant wave height and over the 30-year period. The time period 1980-2010 was selected, as these years overlap with historical referenced SLR data. According to Figure 3, the Andaman Sea side wave characteristics are noticeably larger than those in the Gulf of Thailand side. The H_s ranges between 0.37 m − 1.0 m, while the $H_{e,30}$ ranges between1.30 m − 3.72 m along the coastlines of Thailand. Although data in some areas are lacking (as shown in the white space in Figure 3), the SLR and the wave data are applied to the nearest center-point of the beach at each zone. It should be noted that for a nearly 100-year projection, consideration must be given to future wave conditions. However, the projection of potential future wave climate contains some major uncertainties (Wang and Swali, 2006). This study used the most recent and exact data set (*i.e.*, sediment size, slope, significant wave height and wave period) to avoid increasing significant uncertainties and attempted to analyze only sea level variations among 4 RCP scenarios, 21 CMIP5 models and sedment size.

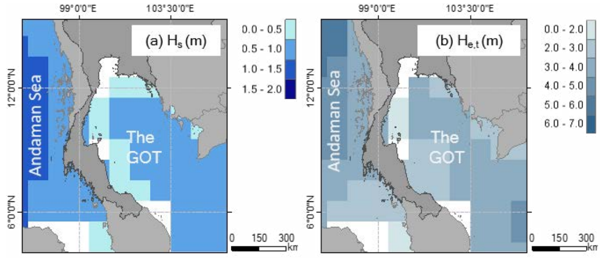

Figure 3. The 3-h significantly reanalyzed wave data with 1-degree latitude-longitude resolution provided by ECMWF for 1980 to 2010 period; (a) significant wave height (H_s) and (b) 12-h exceeded significant wave height for 30 years period ($H_{e,30}$). The white space indicates no data.

Regarding the protections, 10% of Thailand's sandy coastlines are protected by seawalls and revetments, and 3% are defended by other types of structures (DMCR, 2014). This study considered the presences of seawalls and revetments at each coastal zone by assuming that shoreline retreat stops at the landwards boundary where the protections exist. For the remaining areas, the shoreline can retreat onto the upland zone.

RESULTS

The Database of Beach Characteristics

The spatial distributed map of the average beach width for each coastal zone is depicted in Figure 4a; in general, existing dry beach widths are rather small. The entire average width is 35 m though 46 zones (out of 51) have less than 50-m width. The E-zone apparently has thinner widths (average of 20 m), while wider beach widths are apparently located in the S-zone (average of 34 m) and the A-zone (average of 37 m). The national total beach area at the current situation is calculated to be approximately 55 km^2 by the sum of the beach width multiplied by zone length at all the coastal zones. It should be remarked that beach width at each coastal zone is determined at the mean sea level condition. Figure 4b and 4c show distribution map of average beach slope and mean grain size diameter (d_{50}) for each coastal zone, respectively. In total, the spatial distributions of beach slope and mean sediment size are not significant. However, they indicate that, in most of the zones, sediment sizes range between 0.2 mm − 0.5 mm, and the entirely-averaged sediment size is approximately 0.3 mm. Meanwhile, the total-averaged beach slope is approximately 7°.

The Future Beach Loss Projection

The future projected beach loss rate in 2081–2100 relative to the reference period 1986–2005 for an ensemble-mean reginal SLR for 4 RCP scenarios are approximately 45.8% for RCP2.6 (25.36 km^2), 55.0% for RCP4.5 (30.49 km^2), 56.9% for RCP6.0 (31.51 km^2) and 71.8% for RCP8.5 (39.77 km^2) (Figure 5). The sensitivities of SLR and sediment size are shown in Figure 6a. It demonstrates the range of beach loss for entire coastlines when the same rate of SLR is applied. The points are the loss rates due to the national-averaged rate of SLR by the RCP scenarios; however, the line indicates the loss rate when the same sediment size of 0.3 mm is applied at all beaches. The shaded area is determined by uniformly applying the sediment size of 0.2 (upper bound) to 0.5 mm. (lower bound). At 1-m SLR, the total beach loss rate could be over 147%, and the uncertainty in sediment size could reach a maximum of 70%. Furthermore, the uncertainty caused by different CMIP5 models is approximately 22%, because the rates of projected beach loss range from 49.1% (27.22 km^2) using MPI-ESM-LR to 73.4% (40.63 km^2) using MIROC-ESM-CHEM for RCP4.5 (Figure 6b).

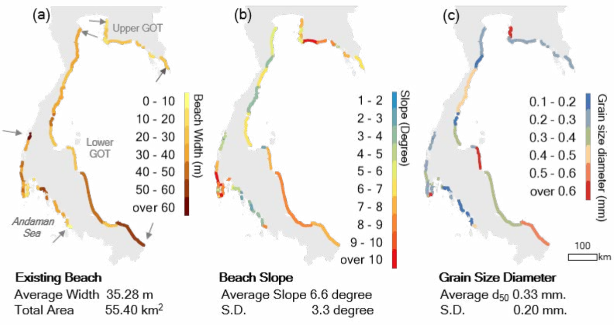

Figure 4. Distribution map of zone averaged (a) existing beach width, (b) beach slope and (c) sediment size

In this study, the loss rate is the proportion of retreat distance (Δy) over the present beach width. Figure 7 illustrates the present beach width for each zone compared with the future beach widths. The results indicate that, based on the SLR of 0.34 m – 0.41 m (the lowest RCP2.6 scenario), sandy beaches in 36 zones are projected to lose 50% of their existing beach widths, among which 8 zones will retreat by their maximum widths and shifted landwards (see Figure 7a). The highest SLR scenario (RCP8.5) of 0.55 m – 0.65 m along Thailand's coastlines will further exacerbate the situation. The beaches in 48 zones are projected to retreat by 50% and 23 zones will disappear in the future (see Figure 7b). The future shoreline retreat is projected to be larger at the A-zone (zone average of 24 m for RCP2.6 and 38 m for RCP8.5) compared to the E-zone (16 m for RCP2.6 and 25 m for RCP8.5) and the S-zone (15 m for RCP2.6 and 23 m for RCP8.5). The retreats at the E-zone and S-zone are similar; however, beaches in the E-zone seem vulnerable to erosion because they have smaller widths than beaches in the S-zone at present. Furthermore, the wave regime plays an important role on the projections. The projected retreats at the A-zone are larger than those at the GOT side because the wave energy is larger at the Andaman Sea side.

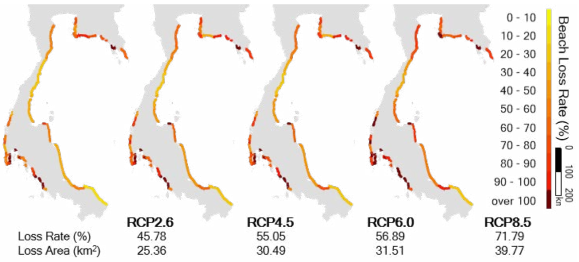

Figure 5. The projected beach loss rate and area in 2081–2100 relative to 1986–2005 based on ensemble mean sea level rise for 4 RCP scenarios.

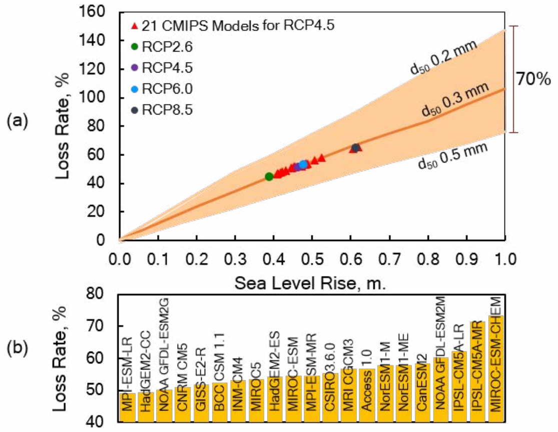

Figure 6. The projected beach loss rate (a) when apply the same rate of SLR along Thailand's coastlines. The points show the projected rate using SLR in 2081-2100 for RCP scenarios. The line means the projected loss using 0.3-mm sediment size for entire beaches and uncertainty based on sediment size of 0.2 mm – 0.5 mm is shown in shading area. (b) The projected loss rate based on ensemble mean SLR calculated by 21 CMIP5 models for RCP4.5 scenario.

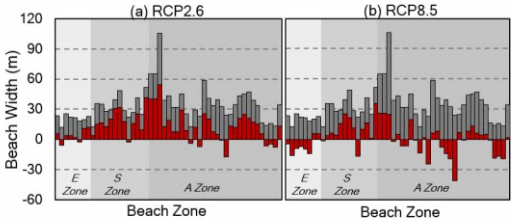

Figure 7. Present and future beach widths after SLR (gray and red bars, respectively) in 51 coastal zones for (a) RCP2.6 and (b) RCP8.5. The horizontal axis represents the landward boundary and the minus value means the distance that shoreline shifts onto the mainland area.

DISCUSSION

This study projected the future beach loss due to SLR based on different RCP scenarios; however, the projections include some uncertainties. The beach slope, grain size and the beach width used in these projections were measured in different years and seasons. These parameters have temporal variation and the beach loss can be sensitive with varying sediment sizes (Udo and Mano, 2010). In addition, there is an uncertainty regarding the DoC. Owing to the different methods used for DoC calculation, the output recession can be varied (Ranasinghe, Callaghan and Stive, 2012). It is impossible to confirm the applicability of the DoC equation to the Thailand coasts because sufficient data do not exist; however, it is necessary for future studies.

CONCLUSIONS

The study developed a database including grain size, slope and beach width of sandy beaches along Thailand's coastlines, and projected the future beach loss due to sea level rise in 2081-2100 based on RCP scenarios using the Bruun rule. The results indicated that present beaches have rather small widths, and national beach loss rates in the future are projected to be more than 45.8% even for the lowest RCP2.6 scenario. The projected loss rate may reach a maximum of 71.8% where 23 beach zones will be completely lost. The SLR could cause significant shoreline recession along all of Thailand's coasts in the future, and this requires urgent attention. The results will be helpful for coastal managers or/and policy-makers to assess further adaptation strategies corresponding to each SLR scenario, such as the construction of seawalls, dykes or supplementing beach nourishment.

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