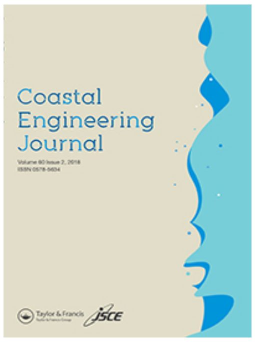

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TECHNICAL NOTE

Projection of decrease in Japanese beaches due to climate change using a geographic database

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ABSTRACT
This study models shoreline retreat due to sea level rise by using geographic data and applies the model to future projections of decreases in beach area for 806 beaches in Japan. The model uses a foreshore slope (angle) based on data from a digital elevation model, and influence of the present simplified method for estimation of the shoreline retreat is examined through comparisons with previous studies at typical locations. The proposed method gives a distance of shoreline retreat due to sea level rise similar to that predicted using the Bruun rule for minimal retreat less than 30 m, but the difference becomes substantial for more extensive decreases. The decrease in beach area is projected for different sea level rises based on four Representative Concentration Pathway (RCP) scenarios from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. The decrease in beach area becomes more severe for the RCP8.5 scenario, and the proposed method predicts that a third of current sandy beaches in Japan will disappear. The extent of the decrease depends not only on the sea-level-rise scenario but also on the SLR projection model.

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KEYWORDS
Climate change; sea level rise; shoreline retreat; Bruun rule; RCP scenario

1. Introduction

The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC 2014) states that climate change exacerbates the vulnerability on regional scales to average and extreme physical processes such as heavy precipitation, river flooding, coastal waves, storm surges, and sea level rise. IPCC AR5 WGI (2013) and WGII (2014) discuss the vulnerability of coastal regions to storm surges and rising sea levels including wave climate (e.g. Mori, 2012; Hemer et al., 2013). A decrease in beach area is expected to be one of the main impacts of sea level rise due to global warming. Between 1870 and 2004, sea levels rose at an average rate of 1.7 ± 0.3 mm/year, with a notable increase in the rate during the past decade (Church, White, and Hunter, 2006; Church and White, 2011). The major source of sea level rise is thermal expansion of sea water caused by warming of the ocean's upper layer, indicating that sea level rise is a long-term thermodynamic process resulting from climate change influencing the ocean and upper ocean regions (e.g. Yin, 2012). A direct consequence of sea level rise is inundation of low-lying coastal areas, which is a long-term problem that has been discussed in a wide variety of fields. Assessing the impact of shoreline retreat due to climate change is still difficult on a regional scale due to the scale of beach size (generally in the order of 100–500 m in length). It is expected that the next IPCC assessment report will consider the impact of climate change on regional scales.

The coastal impact of rising sea levels is generally considered in relation to the equilibrium cross section of a beach profile for a given sea level. Under the assumption of a given wave climate and alongshore sediment transport, the Bruun rule (Bruun, 1962) can be applied to estimate the shoreline change Δy:

$$\frac{\Delta y}{W^*} = -\frac{S}{h_c + B_h} \tag{1}$$

where S is the sea level change, h_c is the critical depth for sediment movement, W^* is the distance from the shoreline to the point of h_c, and B_h is the elevation of the beach, berm, or dune crest (maximum height of landward sediment transport). The Bruun rule has been used widely to assess the impact of rising sea levels on beach erosion (e.g. FitzGerald et al., 2008; Yoshida et al., 2013). Because the Bruun rule assumes an equilibrium cross-sectional profile of the beach from the shoreline to offshore, the beach elevation B_h and the critical depth for sediment movement h_c need to be given empirically as a function of sediment size (or bottom materials). Actually, each beach has various profiles, and it changes

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Supplementary data can be accessed here.

daily due to cross-shore and alongshore sediment transport with different wave conditions. Therefore, it is difficult in general to obtain a local cross-sectional profile of a natural beach on a scale of 10–100 m. There have been numerous case studies of beach erosion at particular locations due to climate change (e.g. Dickson, Walkden, and Hall, 2007; Stive, 2004; Woodroffe et al., 2012; Kuriyama, Banno, and Suzuki, 2012; Yoshida et al., 2013; Barnard et al., 2015). However, because the Bruun rule depends ultimately on the sediment size, berm height, and critical depth for sediment movement at individual locations, it is difficult to extend the application of Bruun rule to a nationwide scale if the coastline is very long, such as in Canada, Indonesia, Japan, and the United States. Actually, sediment size has a dominant influence on beach erosion and should be considered especially for a regional scale projection. However, it is too difficult to use the Bruun rule to estimate beach erosion on a nationwide scale.

An alternative approach to projecting decrease in beach area is to estimate the foreshore slope (angle) by using topographic data such as a digital elevation model (DEM). Topographic data can be accessed more easily than bathymetry data and sediment size information. While this approach does not account for changes of equilibrium in cross-sectional beach profile from the shoreline to offshore, it does not require bathymetry data instead. This simple alternative approach can therefore be applied to a wide region if the appropriate topographic data set is available. The method of using the Bruun rule and the alternative approach have different merits and difficulties for estimating decreases/retreats in beach area. For this reason, we have to compare results based on the different methods.

This research deals with the bulk estimation of decrease in beach area based on a topographic database. We examine the sensitivity of the present alternative approach to the assumed cross-shore profiles for estimating the shoreline retreat. We also compare the results to predictions of the Bruun rule in several cases. Finally, we consider 806 major coastal sections in Japan in relation to projected changes in their beach area due to shoreline retreat and sea-level-rise scenario and assess vulnerable beaches to sea level rise around Japan.

2. Overview of the beach database

First, topographic data were collected for 806 Japanese coastal beaches that are longer than 1 km. The target coastal sections were selected from a list of Japanese beaches compiled by the Ministry of the Environment of Japan. The length, width, and location (longitude and latitude) of each coastal section were measured from Google Earth. The shoreline and inland boundary are determined visually based on the visible image. As the tidal range in the Pacific side of Japan ranges from 1 to 2 m generally (about 30 cm in the Sea of Japan side), tidal correction of shoreline is necessary for strict assessment. However, each correction is time-consuming to conduct within O(1 m). In this study, we assume that images of Google Earth were taken at the phase of mean water level. This gives about ±0.17 m error for elevation if the foreshore has a 10-degree slope with a 1-m tidal range. In addition, we focus on the estimation of the beach gradient around the shoreline. Therefore, the accuracy of the shoreline position is not so important if it oscillates between mean positions, since the gradient would not change remarkably in the intertidal zone in the long term. Consequently, the simplified assumption will not largely affect the results. The shoreline positions were given by Coastal Monitoring Data (CMD) in Japan (2005, Ministry of the Environment; denotes CMD-based shoreline location) and other components were obtained through combinations of Google Earth and DEM data. We use the GSI 5th mesh data set (ver.1.0; 10-m resolution) produced by the Geospatial Information Authority of Japan (GSI) to calculate the beach properties. The GSI 5th mesh data are an official topographic map data, including maximum, average, and minimum altitudes of 10-m resolution data in each 250 m mesh, mean angle of inclination in each 250 m mesh $<\theta>$ calculated from 10-m resolution altitude data, and so on. Each beach is composed of multiple GSI 5th meshes. Therefore, we calculated the mean and maximum elevations and mean $<\theta>$ for each beach.

- Length: B, width: W, and locations (four corners): Google Earth
- Shoreline positions: Coastal Monitoring Data in Japan
- Topography (slope): h_{mean}, h_{max}, and $<\theta>$ Global Map of Japan GSI 5th mesh

We used this set of topographical data, including lengths, widths, locations, and elevations of beaches longer than 1 km, as our beach database. The estimated error depends on targets. For example, the error of shoreline position depends on the spatial resolution of data and it is O(10 m) in this study.

The coastal lines were divided by large ports and river mouths. Supplement Figure S1 shows the locations of the 806 selected beaches along the Japanese coast. It was found from the obtained data set of 806 selected beaches that the entire length of the beach in each prefecture was the longest in Hokkaido, with length of 650 km, and was the shortest in Kumamoto, with length of 2 km.

It is important to have a parametric estimation of the cross-sectional profile of a beach in order to estimate shoreline changes due to sea level rise for static changes of shoreline retreat because the estimated value directly depends on the profile. Generally, a cross-sectional beach profile can be divided into a foreshore region and a backshore region. There is no

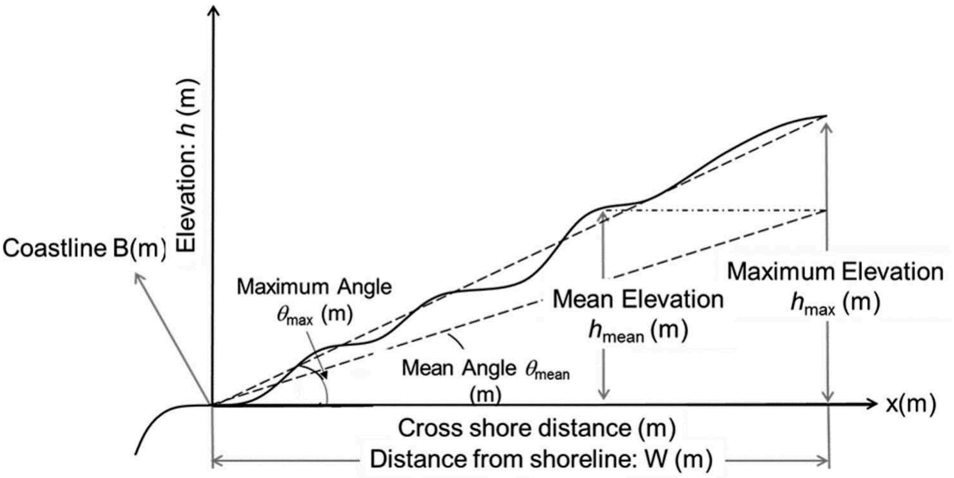

Figure 1. Definition of parameters to describe cross-shore beach profiles.

general monotonic beach shape. Instead, we examine the validity of the present approximated methodology for estimating shoreline change using simple parametric descriptions of a beach profile because of the difficulty in covering the entire shape of an individual beach from the shoreline to the end of the foreshore or beach depends on the shape of cross-sectional beach profile. Figure 1 shows an illustration of the parameters discussed in this manuscript. The length and width of the beach are defined as *B* and *W*, respectively, while the mean and maximum heights are defined as h_{mean} and $h_{\max}$, respectively. The definition of beach shape is based on data from CMD (2005). The length of beach *B* is defined as the length of the shoreline. Then, the width of beach *W* is defined as the mean width. The mean and maximum angles, θ_{mean} and $\theta_{\max}$, can then be calculated using *W*, h_{mean}, and $h_{\max}$.

$$\theta_{mean} = h_{mean}/W \tag{2}$$

$$\theta_{\max} = h_{\max}/W \tag{3}$$

Note that θ_{mean} does not correspond to the mean slope, $<\theta>$, which is obtained through averaging over the local slopes of the beach based on GSI 5th mesh data set. If the beach has a uniformly sloping straight profile, for example, θ_{mean} becomes a half of $<\theta>$. θ_{mean} is defined by Equation (2), then $<\theta>$ is the mean gradient calculated from the gradient of the fragment which composes each beach in the GSI 5th mesh data set. The mean angle $<\theta>$ is an actual mean gradient data and therefore is not equal to the macroscopic gradient θ_{mean} and $\theta_{\max}$. The parameterization of beach profile was examined using the linear profile of Equation (4) for θ_{mean}, $\theta_{\max}$, and $<\theta>$, the power-law profile of Equation (5), the exponential profile of Equation (6), and the quadratic profiles of Equations (7) and (8):

$$h(x) = ax \tag{4}$$

$$h(x) = ax^b \tag{5}$$

$$h(x) = ae^{bx} - a \tag{6}$$

$$h(x) = ax^2 \tag{7}$$

$$h(x) = ax^2 + bx \tag{8}$$

The coefficients *a* in Equation (4) can be expressed directly in terms of θ_{mean}, $\theta_{\max}$, and $<\theta>$, and *a* and *b* in Equations (5)–(8) can be determined from the following boundary conditions.

$$h_{mean} = \frac{1}{W}\int_W^0 h(x)\,dx \tag{9}$$

$$h_{\max} = h(W) \tag{10}$$

Supplement Figure S2 shows an example of an approximated beach profile in the landward direction from the shoreline ($x = 0$) given θ_{mean}, $\theta_{\max}$, and $<\theta>$. It is clear that the erosion distance from the shoreline is highly dependent on the assumed cross-sectional shape of the beach profile. The coefficients in Equations (4)–(8) are estimated from the shoreline position and maximum elevation. Given a value of $\theta_{\max}$, the estimated cross-sectional beach profile of Equation (4) is the highest of all the approximations. The rank order of elevations estimated by Equations (5)–(8) depends on the target location; there is no coherent result based on the approximations. The validity of these approximations of beach profile shape is discussed briefly in the next section.

3. Results and discussion

3.1. Validation of the beach profile approximation and relation to the Bruun rule

The aim of this study is to understand the sensitivity of shoreline retreat due to sea level rise and to identify which beaches in Japan are most vulnerable. It would be difficult to validate the approximation of all beaches in the data set. Therefore, we have selected

Table 1. Examples of estimated beach elevation by different estimation methods. Bold values indicate the lowest mean error at each location.

No.	Location	Max. Elevation θ_{max}	Mean Elevation θ_{mean}	GSI data $< \theta >$	Power law	Exponential law	Polynomial (1)	Polynomial (2)
58	Yubetsu	**0.31**	1.59	1.67	1.69	1.27	1.41	1.41
132	Mukawa	**0.03**	0.46	0.45	0.51	0.25	0.42	0.43
236	Ohsuga	2.11	**0.36**	**0.36**	0.73	0.97	0.98	0.98
276	Miyazawa	0.99	**0.17**	0.23	0.44	**0.16**	0.29	0.29
290	Yotsukura	3.83	**0.18**	0.24	0.87	2.29	2.31	2.31
369	Kobarihama	0.75	0.28	0.38	0.54	**0.14**	0.31	0.32
517	Shirahama	**0.05**	0.40	0.42	0.46	0.31	0.42	0.42
523	Kaike	1.65	0.20	**0.03**	0.15	0.94	0.70	0.70
589	Ariake-kaigan	**0.31**	0.43	0.44	0.47	0.38	0.46	0.46
619	Aki	0.87	1.50	1.53	1.29	**0.53**	0.65	0.65
647	Karatsu	1.55	**0.11**	0.40	0.56	0.94	0.77	0.77
661	Ogurahama	1.44	0.18	**0.03**	0.28	0.38	0.29	0.29
694	Fukiage	3.27	0.77	**0.11**	1.80	2.21	2.12	2.12
736	Seishu	**1.13**	2.48	1.90	1.90	2.05	2.26	2.26
	Average	1.31	0.65	0.59	0.84	0.92	0.96	0.96

14 beaches from different regions and checked their approximation accuracies against the GSI 10-m-resolution DEM. The alongshore averaged cross-sectional profile was calculated, and related slopes θ were estimated for the GSI 10-m-resolution DEM. The estimated elevations of the target beaches are listed in Table 1, along with the mean errors in comparison with the DEM database.

The seven cross-sectional approximations of beach profile are validated for each of the 14 beaches, as shown in Table 1. First, we prepared reference data from the GSI 10-m-resolution DEM database. We made one-dimensional elevation data at representative 10 traverse lines for each beach. Then, we modeled the profile data from an ensemble average of them using Equations (4) through (8). The position of the shoreline was estimated by a linear extrapolation from the inland topography (DEM-based shoreline location). We assume that the CMD-based and DEM-based shoreline locations are the same. The root mean square errors of the approximations compared with the DEM data are given in Table 1. Since the main target is quantifying decreases in beach area due to sea level rise, we focus on only elevations lower than 1.0 m for validation. Approximation with Equation (4) using θ_{max} shows the largest error, and the power law of Equation (5) and the quadratic functions of Equations (7) and (8) produce underestimations in general. The estimations with the linear function of Equation (4) using θ_{mean} and $<\theta>$ give the lowest mean relative errors. This is because of the limited target elevation (less than 1 m) and a foreshore profile in front of the berm that can be approximated as a smooth linear slope in general. Thus, we use two approximations – the linear function of Equation (4) using either θ_{mean} or $<\theta>$ – to assess the impact of climate change on decreases in beach area.

It is important to discuss the connection of the proposed method to the Bruun rule. For example, Mimura et al. (1994) and Udo et al. (2013) discussed the application of the Bruun rule to shorelines that are retreating (which can be regarded as a form of erosion) at particular locations because of sea level rise. Their predictive skill was investigated through comparison with the observed shoreline retreat due to land subsidence, and it was found that their predictions of the shoreline change were within the error of 50 m. Figure 2 shows a comparison of the shoreline change (positive in the landward direction) for a 65-

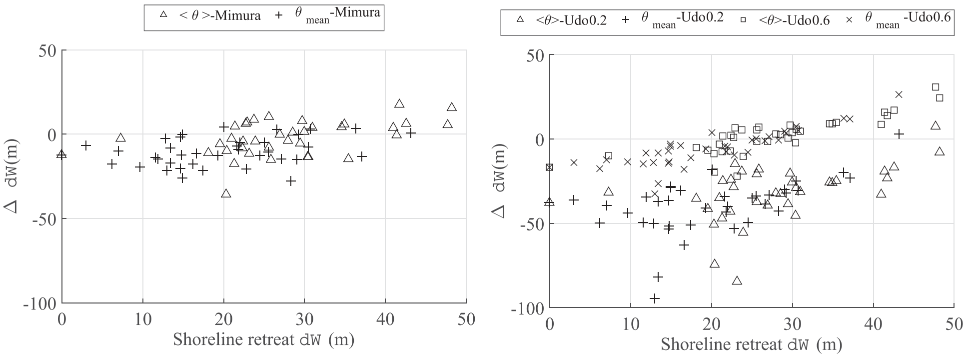

Figure 2. Comparison of shoreline change estimation for 65-cm sea level rise by previous studies using the Bruun rule (Mimura et al., 1994; Udo et al., 2013) and proposed methods.

(a) Comparison to Mimura et al. (1994).
(b) Comparison to Udo et al. (2013).

cm sea level rise estimated by previous studies using the Bruun rule (Mimura et al., 1994; Udo et al., 2013) and by the proposed methods using Equation (4) with θ_{mean} or <θ>. The x-axis is shoreline retreat calculated by the proposed model and the y-axis is difference to previous models (the results of proposed model – that of previous model). The marker means average shoreline retreat in each prefecture. Although Mimura et al. (1994) used a fixed profile scale parameter A = 0.1 (this condition corresponds to a sediment diameter that is fixed to 0.3 mm, approximately), Udo et al. (2013) varied sediment diameter over 0.2–0.6 mm. The latter study pointed out that shoreline change is more sensitive to sediment size than it is to sea level rise. Figure 2 indicates that there are large differences among the present and previous methods, and the two previous models based on Bruun rule tend to predict the larger shoreline retreats than the present model (positive shoreline change). Basically, the proposed method should underestimate the shoreline retreat because it does not take the change of equilibrium beach profile into account. The majority of shoreline change predicted by the present model tends to be lower than those by the existing three models. However, in some regions, the predicted value of the present method exceeds that of previous method, and these results also indicate the uncertainty in estimating shoreline retreat. Therefore, it is interesting to discuss these differences. The result of comparison to Mimura model shows that this difference has positive correlation with the shoreline retreat predicted by the present method. The slope of this positive correlation is larger when the present model applies <θ>. In some regions, the shoreline retreat predicted by the present model based on <θ> becomes larger than that by Mimura model. The result of comparison to Udo model also shows positive correlation. This slope of positive correlation becomes large when we compare to the result of Udo model using sediment size d = 0.6 mm. Almost of all results of Udo model using sediment size d = 0.2 mm is larger than that of the present method. However, when we compare to the result of Udo model using sediment size d = 0.6 mm, the present model exceeds the result of Udo model in some regions. In the Bruun rule, a smaller sediment size results in a longer predicted shoreline retreat and vice versa. Therefore, this irrational difference of shoreline retreat between previous model and the present model might show the uncertainty of sediment size. Note that the above comparison is qualitative because of a lack of reliable field data or an exact solution to be validated for this application. The relative accuracy of the database depends on the length and width of beach due to the spatial resolution of the geographic data set source, O(10m). Thus, the data set is reliable for longer and wider beaches more than O(100 m) generally.

The proposed model uses landside geographic parameters to predict the extent of shoreline retreat and is therefore convenient for use in a nationwide impact assessment. The projection of future beach erosion due to sea level rise in Japan is discussed in the next section.

3.2. Projection of future beach erosion due to sea level rise

t is important to know the influence of climate change on rising sea levels and the related decreases in beach area around the coast of Japan. The sea level rise is important in the assessment of the impact of climate change on coastal regions. Regional sea level rises are not necessarily the same as the global average. For example, phase 3 of the Coupled Model Intercomparison Project (CMIP3) predicts a slightly lower rise in the level of the Sea of East Asia than the global average of 0.27 m from B.C. 2000 to 2100 (Mori et al., 2013). Although this difference is not substantial, the standard deviation for the East Asia region is much larger than that of the global results. Uncertainty in sea level projection becomes notable at the regional scale and should be considered carefully in impact assessments. However, as there is yet no widely available regional-scale sea level projection by CMIP5 for the western North Pacific Ocean, we have used the global ensemble-averaged value of sea level rise for the projections of decreases in beach area based on the geographical model proposed in the previous section. These projections were conducted for four different Representative Concentration Pathways (RCPs). However, only the RCP2.6 (low emission; sea level rises of 0.26–0.55 m; mean value of 0.4 m) and RCP8.5 (high emission; sea level rises of 0.45–0.82 m; mean value of 0.6 m) scenarios used by the IPCC-AR5 WGI (2013) are discussed here.

Figures 3 and 4 show future decreases in beach area in Japan estimated by θ_{mean} and <θ> based on the RCP2.6 and RCP8.5 scenarios, respectively. The mean values by IPCC-AR5 for sea level rise were used for projection in Figures 3 and 4, respectively. The numbers indicate decreasing areas of defined beach in comparison with the present conditions (a value of 1 means vanishing beach). The more gently sloping beaches (e.g. Kuju-Kurihama in Chiba Prefecture) would disappear even under the RCP2.6 scenarios. In that case, Equation (4) with θ_{mean} predicts that approximately 10% of all Japanese beaches will lose more than a half of their present area, while Figure 3 predicts approximately 20% when <θ> is used. Likewise under RCP8.5, Figure 4 projects that 20% and 45% for θ_{mean} and <θ>, respectively. Approximately a third of the entire current coastline would disappear according to Equation (4) with <θ>, but much less according to Equation (4) with θ_{mean}. The fraction of current

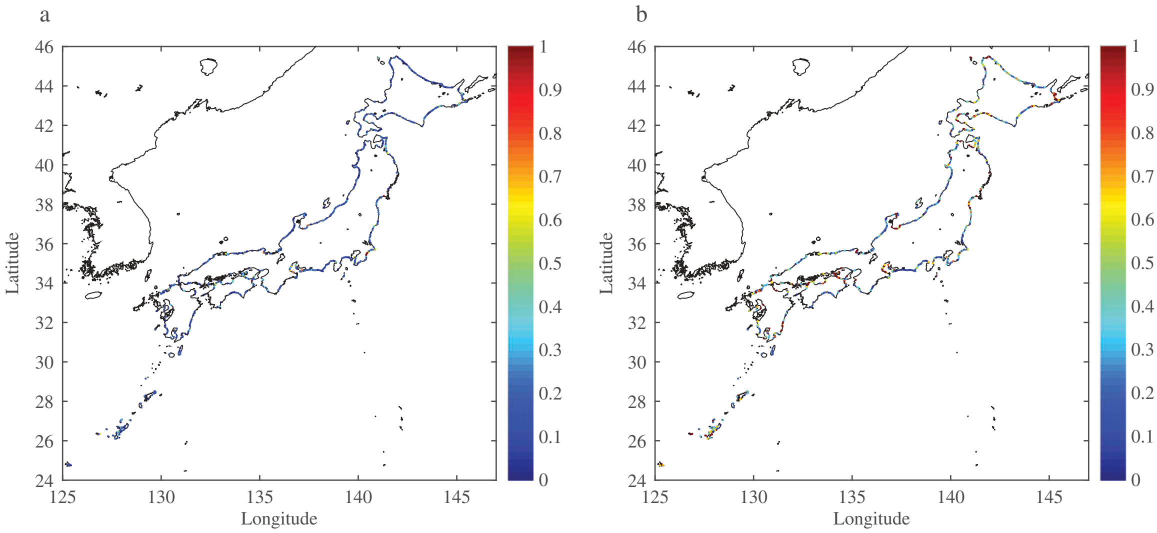

Figure 3. Projected future change ratio of beach area decrease by RCP2.6 scenario.

(a) Equation (4) with θ_{mean}.
(b) Equation (4) with $<\theta>$.

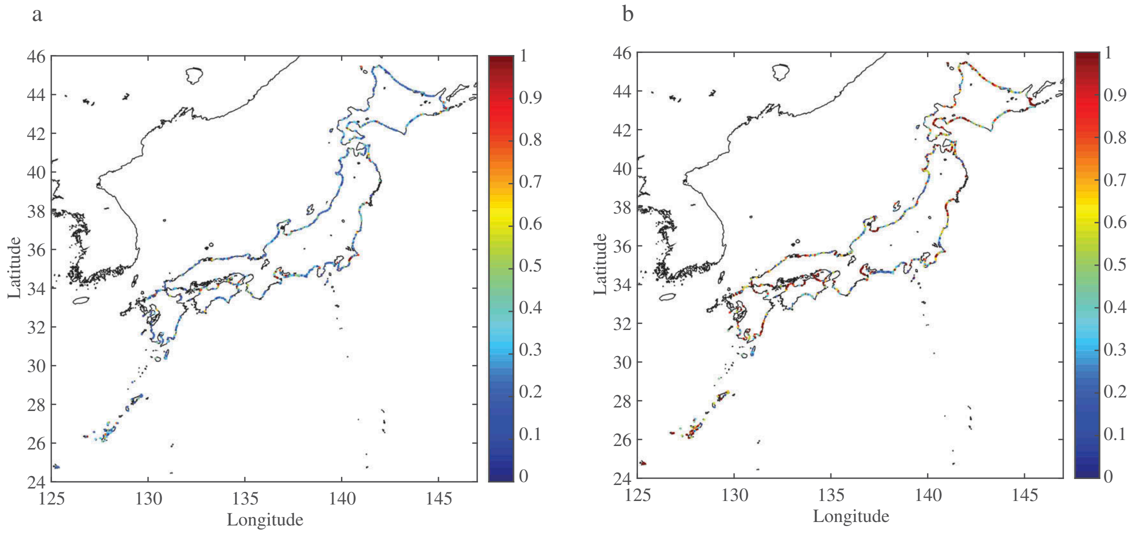

Figure 4. Projected future change ratio of beach area decrease by RCP8.5 scenario.

(a) Equation (4) with θ_{mean}.
(b) Equation (4) with $<\theta>$.

coastline lost to shoreline retreat depends on the model used as well as the sea-level-rise scenario. For example, beaches with a 50% decreasing area using Equation (4) are 10% with θ_{mean} but 20% with $<\theta>$ for the RCP2.6 scenario. Since the proposed geographical method is directly connected to beach slope, the projected beach will retreat. Therefore, a database of accurate measurements of nearshore topography and bathymetry is necessary for assessing the impact of climate change on decreases in beach area. Regardless of the accepted level of accuracy of decreases in beach area estimates, there are clear danger areas for severe beach retreat in Japan. These are located along the Pacific coast and the Seto Inland Sea, where there are long, gently sloping beaches. Clearly, gentler sloping beaches experience more severe beach retreat than steeper beaches, and longer beaches tend to be more significantly impacted than shorter beaches. The main Japanese beaches at risk from sea level rise are on the east coast of Hokkaido, the Pacific side of Chiba Prefecture, Ise Bay, and Seto Inland Sea. Hence, these areas are appropriate for monitoring the impact of sea level rise on beach retreat because of their sensitivity to changes in sea level. It is not enough to project future changes of decreases in beach area using the proposed model or existing methodology (e.g. the Bruun rule). We must develop models and create a database in order to make a quantitative impact assessment of climate change on decreases in beach area.

4. Conclusions

It is important to understand the influence of climate change on decreases in beach area at a nationwide scale. In this study, we modeled beach retreat due to sea level rise by using geographic data and applied the technique to future projections for 806 beaches in Japan. The geographic database method is an alternative to the standard Bruun rule for estimating the decreases in beach area due to climate change. Whereas the Bruun rule considers the equilibrium beach profile from the shoreline to offshore, the proposed geographic database modeling uses the angle of the foreshore from a DEM of an individual site without requiring any bathymetry or sediment size information.

We examined the sensitivity of approximations of the cross-sectional beach profile to different geographic data and their parameterizations at 14 typical locations. The linear approximation of the foreshore profile from the shoreline using the mean angle estimated from high-resolution DEM data gave the best results for beach profiles whose landward elevation from the water level was lower than 1 m. In the case of relatively minimal erosion (less than 20–30 m), the proposed method gives a similar shoreline retreat distance due to sea level rise to that given by the Bruun rule, relatively. However, the difference becomes substantial for more extensive erosion (more than 20–30 m) because of a lack of information about the equilibrium cross-sectional beach profile. The sources of uncertainty are different for the two methods; the Bruun rule is sensitive to sediment size, while the proposed method depends on the resolution of the geographic database.

Decreases in beach area were projected for different sea level rises based on four RCP scenarios of the IPCC AR5. Approximately 10–20% of beaches in Japan would lose more than half of their current area, depending on which model and scenario are used. The decrease in beach area becomes more severe for the RCP8.5 scenarios, and the proposed method predicts that a third of the current coastline would lose half of its area. The extent of coastal erosion depends more on the model used than on the sea-level-rise scenario. Therefore, a database of accurate measurements of nearshore topography and bathymetry is necessary for assessing the impact of climate change on shoreline retreat. Such a database is necessary for making a quantitative impact assessment of climate change on decreases in beach area, as is the further development of modeling.

Although we discussed static changes of cross-sectional beach profiles, it is important to implement dynamic changes of beach morphology including tide, wave climate, nearshore currents, and sediment supply changes. A further study using a dynamic projection could improve the projection of beach erosion due to climate change. This database will be open to the public.

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Disclosure statement

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