PREDICTION OF FUTURE SHORELINE CHANGE WITH SEA-LEVEL RISE AND WAVE CLIMATE CHANGE AT HASAKI, JAPAN

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We developed a shoreline change model considering the effects of the wave regime, sea level, and time heterogeneity. The model predicts the shoreline change under changing global climate conditions: sea-level rise and wave climate change. The model predicted the future shoreline positions from 2008 to 2095 at the Hasaki coast on Japan's Pacific coast. The simulation results showed that the shoreline would retreat approximately 20 m by the end of this century owing to the rise in sea level; nevertheless, the wave climate change would not cause a worsening of the beach erosion, but would cause only a slight increase in the variation of the shoreline position.

Keywords: shoreline; shoreline change model; global climate change; Monte-Carlo method; future prediction

INTRODUCTION

Future sea-level rise and changes of wave climate due to global climate change will cause severe beach erosion. To make matters worse, it was reported that in the past 20 years, sea-level rise was greater than projected in IPCC AR3 or AR4 (Rahmstorf et al. 2012). The IPCC AR5 released in 2014 predicts a sea-level rise of up to 0.82 m in the coming 100 years. Mori et al. (2010) reported that in the future, the average wave height near Japan would decrease while the extreme height would increase.

Many studies focus on developing shoreline change models to predict the future shoreline position. Medium-term (from a few weeks to several years) shoreline change due to cross-shore sediment transport is being accurately simulated by some models (e.g. Miller and Dean 2004; Yates et al. 2009; Davidson et al. 2013). However, very few models that consider the influence of changes in sea level and the wave condition simultaneously have been used to predict future shoreline positions. Hence, shoreline responses to global climate change have not been thoroughly investigated. Bruun (1962) developed a model that predicts the coastal response to sea-level rises, known as the Bruun rule. Although the Bruun rule is widely used for predicting the future shoreline position under sea-level rise, it cannot simulate the non-equilibrium response of the shoreline to momentarily changing waves and sea levels. This is because the Bruun rule is a concept based on the equilibrium state after wave impinging on the coast for a long time.

Changes in beach topography are influenced by various factors through a complicated process. However, it is difficult in practice to determine a numerical model that considers all the factors involved. Latent variables that are not considered in the numerical model can change in time and cause variations in the objective variables. This effect due to latent variables is referred to as the 'random effect' in statistics (e.g., Crawley 2005). Statistical models that consider random effects are called 'generalized linear mixed effect models'. If a time series has time heterogeneity due to the latent variables, the model parameters cannot be estimated accurately without considering the random effects.

Hence, in this study we developed a shoreline change model in which the effects of changes in the wave regime and sea level are incorporated, to predict future shoreline positions. The model also considers the random effect of time heterogeneity. Using this model, which was calibrated using the daily measured shoreline data at the Hasaki coast, we predicted the future shoreline position from 2008 to 2095 with two scenarios of sea-level rise and wave climate change.

DATA DESCRIPTION

The data used for the model calibrations were measured shoreline positions, deepwater wave heights and periods, and tidal levels at the Hasaki coast of Japan, facing the Pacific Ocean (Fig. 1). The Hasaki coast consists of a 16-km sandy beach, with a mean grain diameter of 0.18 mm. We focused on shoreline changes at 1-day intervals; hence, only observed data of shoreline changes with time spans within 36 hours were used for the calibration (n = 4349).

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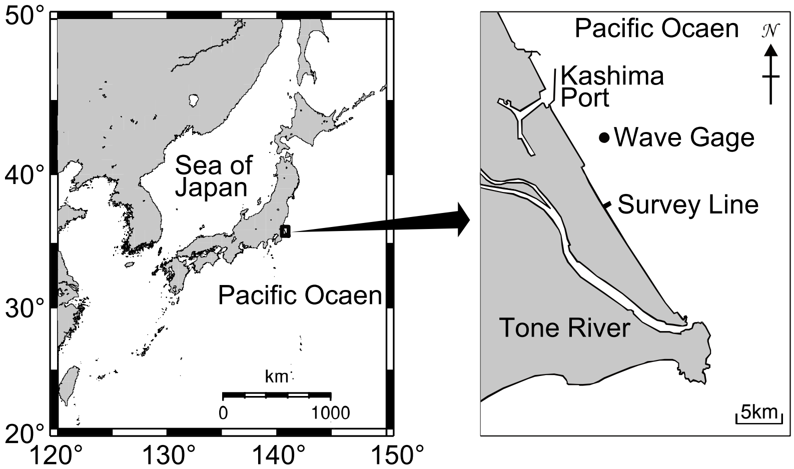

Figure 1. Location of the Hasaki coast, Kashima port and the wave gage.

The shoreline positions were obtained from beach profiles measured during a 22-year period from 1986 to 2007. The beach profile was measured at 5-m intervals every workday with a 3- or 5-kg lead-weight line released from the pier (Fig. 2) located 4 km from the north edge, where is a seawall of Kashima port, of the coast along the shore (Fig. 1). This study defined the shoreline change as the cross-shore movement of the high water level contour (D.L. + 1.25 m). The bathymetry around the survey area was nearly uniform along the shore (Kuriyama 2002); thus, the shoreline change was assumed to be mainly due to cross-shore sediment transport.

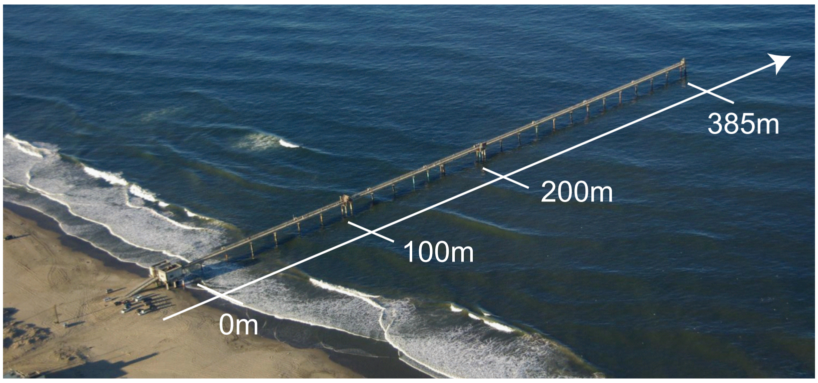

Figure 2. The pier at Hazaki Oceanographical Research Station (HORS) and the survey line of the beach profile. The cross-shore position is indicated by the seaward distance from the reference point close to the pier entrance.

Deepwater waves were measured for 20 minutes every 2 hours at a water depth of approximately 24 m near Kashima port (Fig. 1) with an ultrasonic wave gage. The average significant wave height and period from 2008 to 2007 were 1.34 m and 8.00 s, respectively. Offshore wave energy fluxes were calculated every 2 hours by the product of the wave height squared and the wave period, and daily averaged for the model calibration.

Tides were measured in Kashima port. The tidal levels at low water, mean water, and high water are −0.20 m, 0.65 m, and 1.25 m from the datum line (D.L. = Tokyo Peil −0.69 m), respectively. The daily-averaged tidal levels were used as the sea level data for the model calibration.

Time series data of the shoreline positions, the shoreline change rates, the offshore wave energy fluxes, and the sea level observations are shown in Fig. 3.

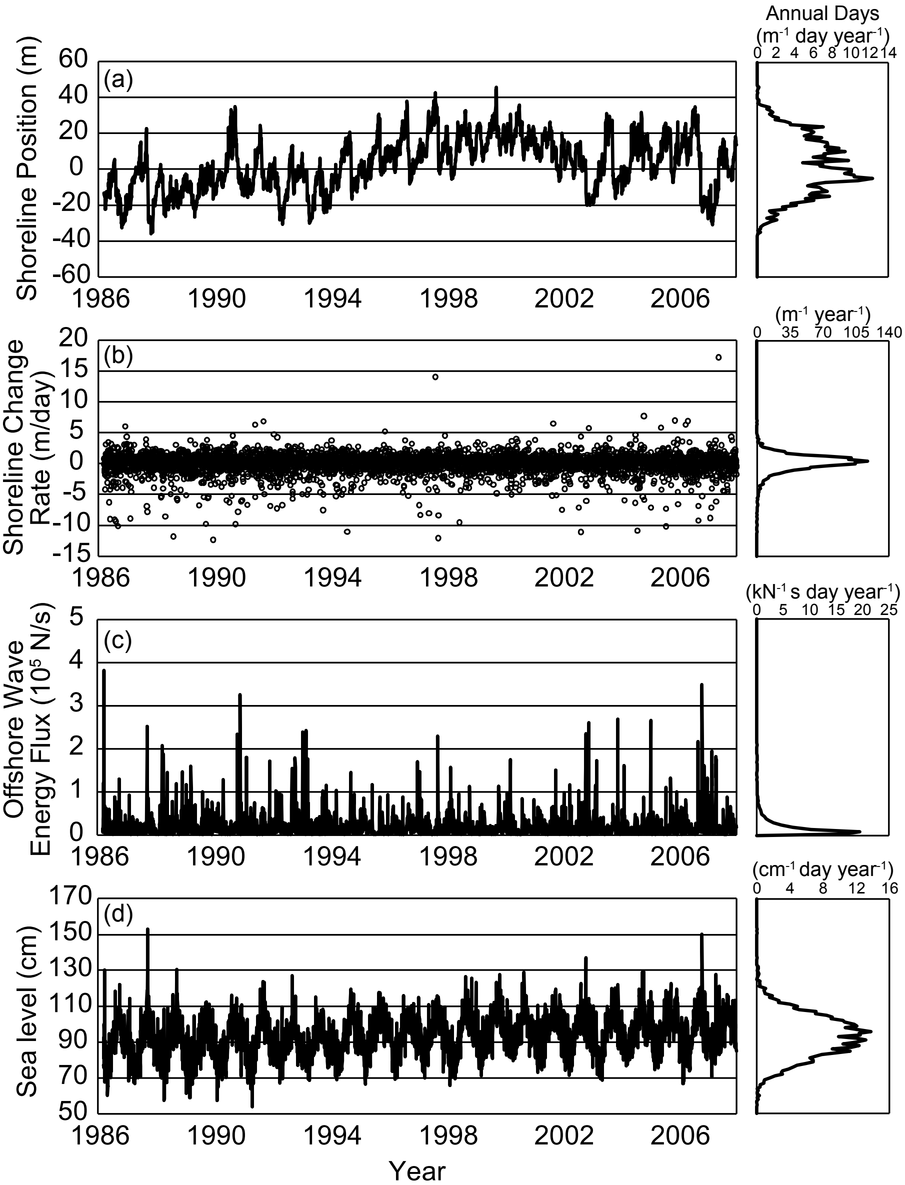

Figure 3. Daily time series data obtained at the Hasaki coast. (a) Shoreline position, (b) shoreline change rate, (c) offshore wave energy flux, and (d) sea level. The distribution of the data is indicated on the right side.

MODEL DEVELOPMENT

Distribution Form Approximation and Primitive Equation

Shoreline variations are mainly driven by wave energy. However, the distribution form of the shoreline change rate and the offshore wave energy flux differ completely (Fig. 4). The distribution of the offshore wave energy flux, which is the product of the significant wave heights squared and the periods, can be estimated as a log normal distribution by the central limit theorem. However, the distribution of the shoreline change is a normal distribution slightly distorted on the negative side. Because the mismatch of the distribution form reduces the accuracy of the model, the square of the logarithm of the offshore wave energy flux was taken to approximate the distribution of the shoreline change rate (Fig. 4).

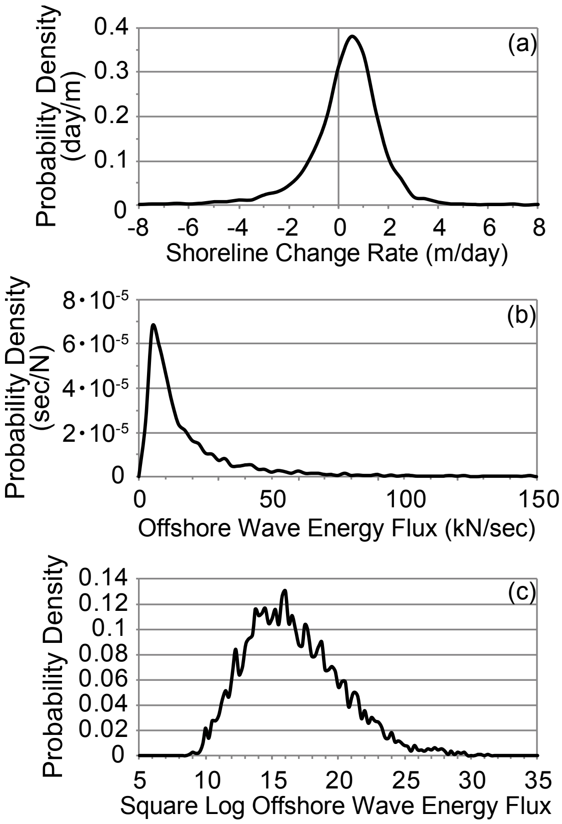

Figure 4. Distribution of (a) the shoreline change rate, (b) the offshore wave energy flux, and (c) the square log offshore wave energy flux.

In this study, the primitive equation of the shoreline change model was expressed by:

$$\frac{dy}{dt} = \alpha_1 \left(\log E_f\right)^2 + \alpha_2 + \varepsilon \tag{1}$$

where *dy/dt* is the daily shoreline change rate, α_1 and α_2 are the coefficients, E_f is the offshore wave energy flux and ε is the residual error. Using the log squared of the offshore wave energy flux as the external force, the non-linearity of the shoreline response to the wave energy is included in the model. The residual error is distributed normally (Eq. (2)).

$$\varepsilon \sim \mathrm{N}\left(0, \sigma_{error}^2\right) \tag{2}$$

Shoreline Response Sensitivity

The shoreline response sensitivity to the wave energy is not uniquely determined, but is affected by the sea level and the shoreline position at the time. In other words, the shoreline retreat increases as the sea level increases and/or the shoreline is being seaward position, even if the incident wave energy is constant (Banno et al. 2012). Variables such as the shoreline position and the sea level do not directly drive the shoreline change, but affect the response; the effects should be indicated by α_1 and α_2 in Eq. (1). In this study, the response sensitivity was expressed by the linear combination of the variables, as follows:

$$\frac{dy}{dt} = \left(\beta_1 + \beta_2 y + \beta_3 \eta_{ave}\right)\left(\log E_f\right)^2 + \left(\beta_4 + \beta_5 y + \beta_6 \eta_{ave}\right) + \varepsilon \tag{3}$$

where β_1 to β_6 are the coefficients, y is the shoreline position and η_{ave} is the sea level.

Random Effect of Time Heterogeneity

Latent variables also affect the shoreline response sensitivity. Even if the sea level and shoreline positions are constants, different time spans tend to have different response sensitivities due to the latent variables. This effect of the time heterogeneity is known in statistics as the 'random effect', whereas the effect considered explicitly in the equation is known as the 'fixed effect'. In this study, adding the random effect of the time heterogeneity to Eq. (3), we developed the shoreline change model as the mixed effect model:

$$\frac{dy}{dt} = \left(\beta_1 + \beta_2 y + \beta_3 \eta_{ave} + r_1\right)\left(\log E_f\right)^2 + \left(\beta_4 + \beta_5 y + \beta_6 \eta_{ave} + r_2\right) + \varepsilon \quad (4)$$

where r is the random effect of the time heterogeneity. The random effect has a normal distribution, as follows:

$$r_1 \sim \mathrm{N}\left(0, \sigma_1^2\right) \quad (5)$$

$$r_2 \sim \mathrm{N}\left(0, \sigma_2^2\right) \quad (6)$$

The random effect r and the residual error ε are not parameters having temporal values, but probability distributions having variations. While the random effect is similar to the residual error in that they are both probability distributions, the random effect has some merits when introduced in models, unlike the residual error. These merits are: (1) the random effect can be set in a free position in the equation and (2) the data can be grouped by category and the variation among the category can be considered. In this study, the data were grouped by year to focus on the long-term prediction. Thus, the random effects are distributed normally in each year, whereas the residual error is distributed normally each day. Using the mixed effect model, which includes the random effect, increases the accuracy of the estimate of the fixed effects parameters.

Estimating Parameters and Model Accuracy

The model parameters in Eq. (4) are β_1–β_6, σ_1, σ_2, and σ_{error}. The parameter estimation was based on a restricted maximum likelihood by using the lmer function from the lme4 package in R with the data obtained at the Hasaki coast. The random effects r_1 and r_2 were assumed to be a bivariate normal distribution.

Comparing the variation of the model terms, calculated from the estimated parameters and the observed variables, the contributions of the model terms to the shoreline change were estimated (Fig. 5). The wave energy contributes to the shoreline change more through interactions with the shoreline position $\beta_2 y(\log E_f)^2$ and the sea level $\beta_3 \eta_{ave}(\log E_f)^2$, than through self-interactions $\beta_1(\log E_f)^2$. The contribution of the random effect is also relatively large in the model.

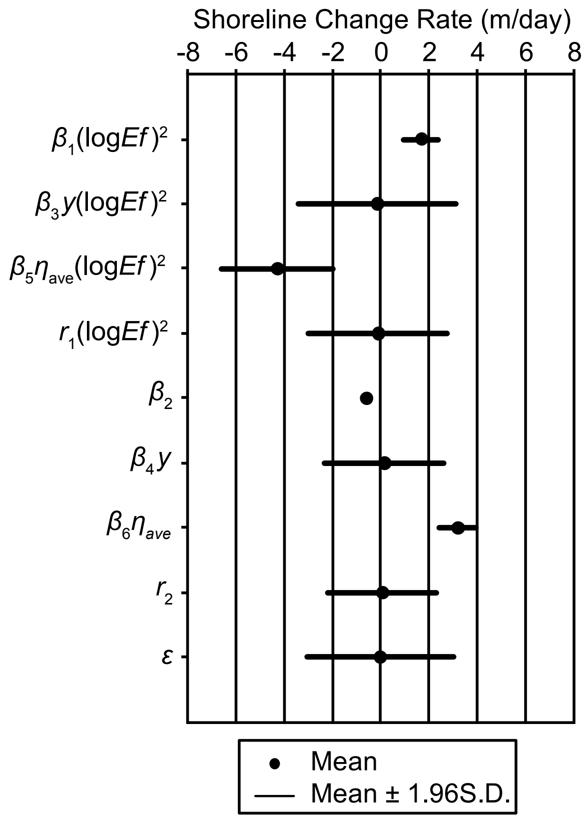

Figure 4. Means and variations of the model term. The amplitudes of the variations indicate the contributions to the shoreline change.

The shoreline positions from 1986 to 2007 were hindcast through the integration of the shoreline change rate by the developed model (Fig. 6). The calculations of the hindcast were repeated 10,000 times by Monte-Carlo simulations using normal random number generations for the random effects. Although the residual error should also be given as random numbers in the hindcast or prediction discussed later, the contribution to the long-term shoreline position was relatively small; therefore, it is ignored in this study. The determination coefficient R^2 between the measured shoreline position and the shoreline position hindcast by only the fixed effect is 0.24; the long-term trend of the measured position is not simulated. However, the variation (95% probability interval) of the shoreline position hindcast by the fixed effect and the random effect covers with the measured one and simulates the long-term trend. When using the random effect value estimated by the best linear unbiased prediction (BLUP), the hindcast shoreline positions (Fig. 6), namely one result of the Monte-Carlo simulations, agree well with the measured records (R^2 = 0.68). Based on the hindcasting result, the model is robust and accurately simulates the long-term shoreline change.

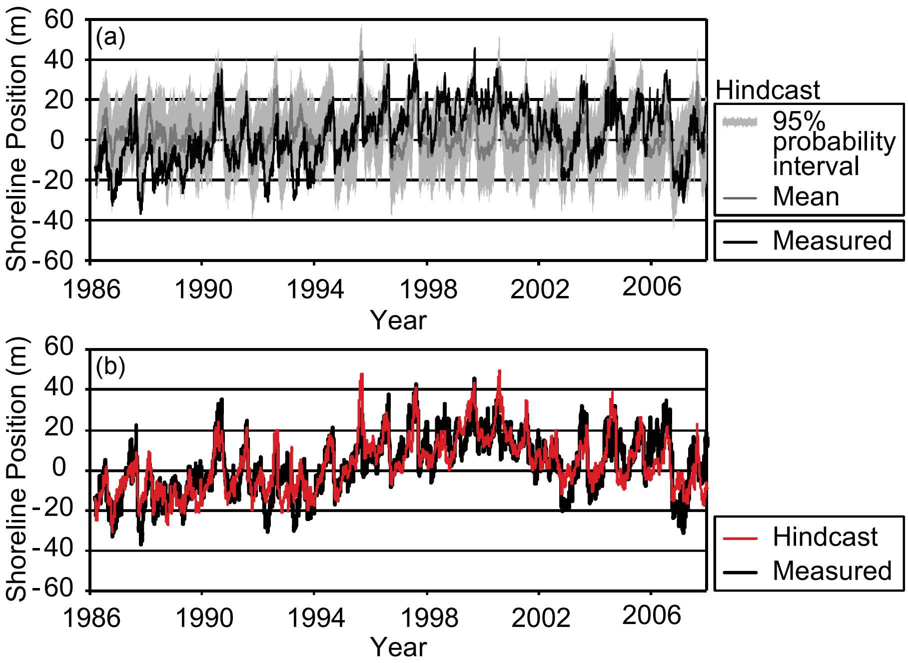

Figure 6. Comparison between the shoreline positions hindcast by the model and measured ones. (a) The result using the Monte-Carlo method, and (b) the result using the random effect value estimated by best linear unbiased prediction.

MODEL PREDICTION

Future Scenarios

Using the developed model, the future shoreline positions at the Hasaki coast from 2008 to 2095 were predicted with the scenarios of sea-level rise and wave climate change, which reflected future trends (Table 1). The scenario data on sea levels and waves were created by repeating the data measured from 1986 to 2007 four times and adding the future trends of sea-level rise and wave climate change.

Table 1. Future scenarios of sea-level rise and wave climate change.

Scenario	Sea-level Rise	Wave Climate Change
A	IPCC AR4	-
B	IPCC AR4	Mori et al. (2010)

The future scenarios of sea-level rise are based on the maximum prediction of IPCC AR4 (59 cm / 100 years). The rate of the sea-level rise is accelerated linearly from the present trend (4.8 mm / year) to obtain a rise of 59 cm from 1995 to 2095.

We used two future scenarios of wave climate change. The wave data measured from 1986 to 2007 were used repeatedly every 22 years for the scenario A. The wave climate change of the scenario B follows the result of the high-resolution atmospheric general circulation model and the global wave model, which Mori et al. (2010) used to predict that the future mean wave heights would decrease near Japan, whereas the extreme wave heights would increase. In our scenario, we decrease the average wave heights 0, 1, 2, and 3% every 22 years and increase the extreme wave heights 0, 5, 10, and 15%. In other words, on the log normal distribution of the offshore wave energy flux, the mean μ is changed $1.00^2\mu$, $0.99^2\mu$, $0.98^2\mu$, and $0.97^2\mu$, and the variation is changed so that the value of the 1% exceedance probability would be multiplied by 1.00^2, 1.05^2, 1.10^2, and 1.15^2 every 22 years. Subsequently, we obtain the future offshore wave energy fluxes from the future distributions.

Future Shoreline Position

The calculations were implemented 10,000 times by Monte-Carlo simulations using normal random number generations for the random effects as well as the hindcasting. The distributions of the future shoreline position predicted by each scenario at the Hasaki coast are shown in Fig. 7. The mode and the exceedance and non-exceedance probability position are shown in Table 2.

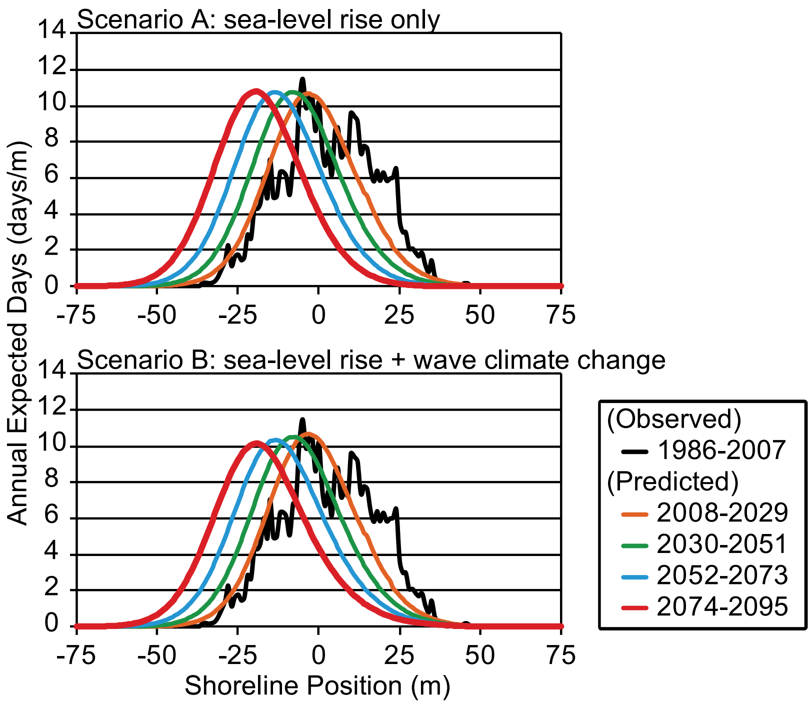

Figure 7. Distribution of the future shoreline position predicted by the model with scenarios A and B.

Table 2. Predicted shoreline position from 2074 to 2095.			
Scenario	Non-exceedance probability (5%) Position	Mode Position	Exceedance probability (5%) Position
A	−42 m	−19 m	5 m
B	−43 m	−19 m	10 m

The results showed a shoreline retreat of approximately 20 m by 2095 caused by sea-level rise. Given the rise in the reference sea level, the future shoreline position at high water would be located further backward from its current position.

By contrast, the future wave climate change created only a slight increase in the variation of the future shoreline positions, mostly at the advancing side of the distribution. This is because the seaward shoreline change will be enhanced by the decrease in the average wave height, but the retreating motion caused by the increase in the extreme wave height will be suppressed by the non-linearity of the shoreline response to the wave energy.

COMPARING THE MODEL WITH THE BRUUN RULE

The Bruun rule (Bruun 1962) is widely used for predicting the future shoreline change in response to sea-level rise. The rule is based on the assumption that the beach profile shifts back and up because of a rise in the sea level as it balances accumulation and erosion. According to the Bruun rule, the profile will shift landward as follows:

$$s = \frac{la}{(h+B)} \tag{7}$$

where s is the landward movement of the beach profile, l is the length of the beach profile, a is the sea-level rise, h is the closure depth, at which significant exchanges of the sediment do not occur, and B is the berm height. Hence, the shoreline change due to the sea-level rise is also indicated by s. Based on field measurements we set l = 900 m, h = 8 m, and B = 2.5 m. Using the Bruun rule (Eq. [7]) with a sea-level rise of 59 cm we obtain a shoreline retreat of 51 m. This shoreline change includes retreats due to erosion and the rise in the reference sea level.

In contrast, our model predicts a shoreline retreat of 21 m, which includes only the retreat due to erosion, comparing the mode of the positions from 1986 to 2007 with that from 2074 to 2095. Given the retreat due to a rise of 59 cm in the reference sea level, and assuming the foreshore slope is 1/35 throughout the period of rising sea level, a shoreline retreat of 42 m is estimated. This result includes the retreat during the period in which the sea-level rise is below 59 cm; therefore, the result of our model is smaller than the result of the Bruun rule. Taking this into account, both amounts of shoreline retreat are roughly the same. Thus, this model contains the mechanisms of the Bruun rule and can also simulate non-equilibrium shoreline positions, responding to momentarily changing wave conditions and sea levels.

CONCLUSIONS

We developed the shoreline change model, which considers the effect of the sea level and the latent variables in the shoreline response sensitivity to wave energy. The model was calibrated with data obtained at the Hasaki coast of Japan and demonstrated good prediction accuracy. This is a versatile model in predicting the momentary change of the shoreline and the variation due to the time heterogeneity, and estimating the influence of changes in sea level and the wave condition on the shoreline change. The model is consistent with the mechanism of the Bruun rule, which is traditionally used for prediction of the shoreline positions.

The future shoreline position at the Hasaki coast was predicted by the model with two scenarios of sea-level rise and wave climate change. The model prediction shows that future shoreline positions would retreat owing to the rise in sea level, and the variation of the shoreline position would increase owing to wave climate change.

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