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Forecasts of seasonal to inter-annual beach change at Hasaki Coast, Japan, using a diffusion model

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Abstract

Hasaki Coast, located in the east coast of Japan, is a sandy beach exposed to cyclonic wave conditions of the South Pacific Ocean. The beach is longshore uniform and characterised by a highly dynamic longshore bar-trough system. Seasonal to inter-annual variability of beach change of the Hasaki Coast is examined and discussed using a one dimensional beach profile model. The beach profile model used here is developed based on the 'reduced-physics' modelling approach. The model uses a diffusion formulation as the governing equation and adopts an inverse modelling technique for solving the equation. The model is calibrated against historic measurements of beach profiles at Hazaki Oceanographical Research Station (HORS) of the Port and Airport Research Institute, Japan. It is then used to forecast seasonal to inter-annual scale beach change. The results are compared with beach change determined from measured beach profiles at Hasaki between 2007 and 2011. The simple modelling approach used yields encouraging results of seasonal to inter-annual scale beach change at Hasaki Coast.

Keywords: Hasaki Coast, Diffusion Equation, Inverse model, Beach modelling, Cross-shore morphodynamics.

1. Introduction

Beach change occurs as a result of complex interactions between beach morphology and a number of dynamic processes acting at a wide range of time and space scales. At short term time scales of a few hours to a few days, beaches change as a result of storms. Seasonal scale beach change occurs as a result of intra-annual variability of the incident wave climate resulting from local weather patterns. Inter-annual to decadal scale beach change can take place as a result of global climate variability or as a result of long term climate change.

As morphodynamic variability of beaches are directly linked to beach instability, coastal erosion, flooding and even breaching, it is important to be able to forecast beach change at timescales useful for making engineering and management decisions, with some confidence. However, as a result of the high levels of uncertainty involved in forecasting future hydrodynamic conditions and the limitations of existing modelling practice, forecasting beach change at time scales beyond several days with reasonable accuracy is extremely challenging and difficult.

Traditionally, empirical equilibrium models have been widely used for predicting beach change in the cross-shore direction. Those include Bruun (1954), Dean (1977, 1991) and Vellinga (1982). Even though these empirical formulae have a significant value when forecasting long term beach change, they have only a limited use in predicting beach change at short term time scales as they do not provide physical explanations of beach dynamics.

On the other hand, detailed process-based models modules (e.g. Reiners et al., 1995, Roelvink et al, 2009; Southgate and Nairn, 1993; Lesser et al., 2004) that combine hydrodynamics, sediment transport and morphodynamics provide useful insights into short term beach morphodynamics. They can be used to accurately simulate short term beach change. As a result, they are commonly used in assessing and predicting storm-driven beach change, which takes place at timescales of hours to days. Even though a few recent attempts have been made to use these models for making longer term forecasts (e.g. Pender and Karunarathna, 2013), uncertainties in hydrodynamic forcing, potential for over-sensitivity to initial and boundary conditions and computational intensity limit using them for predicting changes longer than a few days.

To make forecasts of seasonal to inter-annual scale beach change which is most useful for coastal engineering and management purposes, some alternatives are required. Amongst those are ‘reduced-physics’ models which have been proposed in literature (e.g. Stive and de Vriend, 1995; Reeve and Fleming 1997; Hanson et al., 2003; Karunarathna et al., 2008, 2009). In these models, governing equations are derived on physical arguments rather than from first principles. Their success depends on describing the key processes which are relevant to the timescale in question. As a result, they may not provide detailed process information of beach change (for example, storm-driven beach profile shape change) but give morphodynamic trends at timescales relevant to the processes retained in the governing equation. The application of these models to the problem of predicting beach profile change has shown significant promise (Karunarathna et al., 2012; Avdeev et al., 2010), despite the simplicity of this approach.

In this paper, we extend the Karunarathna et al. (2009) beach profile model to forecast seasonal to inter-annual scale cross-shore beach change at Hasaki Coast, Japan. The model essentially takes a ‘reduced-physics’ approach, where beach change is considered to be primarily driven by ‘diffusive’ and ‘non-diffusive’ processes. Non-diffusive processes include any effects of waves, tides and other dynamic processes which contribute to beach change but we do not resolve these processes in detail. The model makes use of historic measurements of beach profile to ‘calibrate’ a few site-specific unknowns, similar to that of any process-based model application.

The aim of the paper is two-fold: (i) to evaluate the success of the modelling method when applied to a beach subjected to complex combination of environmental variables; (ii) to forecast seasonal to inter-annual beach change at Hasaki Beach, which will be useful to future coastal management planning. The paper is organised as follows: Section 2 gives a description of Hasaki Coast and measurements of beach profiles at Hazaki Observation Pier. In Section 3, the model used to forecast inter-annual beach change is briefly described. Application of the model to Hasaki Coast and the results are presented and discussed in Section 4. Section 5 concludes the paper.

2. Hasaki Beach, Japan

Hasaki Coast is a longshore uniform, sandy coastline located in the Ibaraki Prefecture of Japan facing the South Pacific Ocean (**Figure 1**). The beach consists of sediment with median diameter of 0.18mm. Grain size remains almost uniform along the beach profile. The beach is subjected to both sea and swell waves. Tropical cyclones (typhoons) that occur during September-October generate high energy wave conditions along the Hasaki Coast. Relatively small waves occur from May to June. High wave conditions also occur between January and March as a result of extra-tropical cyclones. Based on the datum level at Hasaki (Tokyo Peil- 0.69m), the high, mean and low water levels were recorded as 1.25m, 0.65m and -0.20m respectively. Kuriyama et al. (2008) demonstrated that due to the micro-tidal environment and the high energy incident wave conditions, beach changes are primarily driven by incident wave conditions.

Deepwater waves at Hasaki Coast have been measured with an ultrasound wave gauge for 20 minutes every 2 hours (**Figure 1**). The water depth at wave measuring location is 24m. Weekly beach profile surveys have been carried out at the Hazaki Oceanographical Research Station (HORS), initially at daily and subsequently at weekly intervals since 1986. The profiles have been surveyed at 5 m intervals along the observation pier, to the same datum level as that used for the tidal measurements. The measured beach profiles extend to an offshore distance of 497m.

Weekly beach profile surveys between 1993 and 2010 were used in this study. **Figure 2** shows the envelope of beach profiles measured between 1993 and 2010 and the mean profile.

Profiles measured between 1993 and 2007 were used for developing and calibrating the beach change model and profiles from 2007 to 2010 were used for model verification by comparison between predictions and observations.

The morphodynamics of Hasaki Coast is dominated by the nearshore bar-trough system. The beach profile variability of Hasaki Coast has been studied extensively. Using eight years of weekly measured beach profiles, Kuriyama (2002) studied the behaviour of nearshore bar-trough system and associated sediment transport using Principal Component Analysis (PCA). It was found that the bar is extremely dynamic and it's development, migration and decay was caused by the spatial and temporal variation of cross-shore sediment transport. Kuriyama et al. (2008) investigated linkage between environmental factors and medium-term bar properties using 15 years of daily beach profile measurements along HORS pier. They used Complex Empirical Orthogonal Function (CEOF) analysis to investigate bar migration and found that the bar migration frequency was weakly correlated with the bar amplitude and offshore wave energy flux. A relationship between the shoreline variability of Hasaki Coast and the incident wave climate was studied by Kuriyama et al. (2012), using a simple shoreline model. They found that the Hasaki shoreline has a very strong inter-annual signature. They were also able recognise numerous correlations between offshore wave climate at Hasaki and, the Arctic Oscillation index (AO); the Nino-West SST anomaly and the Southern Oscillation Index (SOI). The influence of climate change on the Hasaki Coast was examined by Hayashi et al. (2013) using a simple analytical model. They found that the temporal variability of beach volumes below and above mean sea level (MSL) were similar in magnitude.

3. Diffusion model

Following Stive and De Vriend (1995), Karunarathna et al. (2009, 2011, 2012) developed a beach profile evolution model based on a 1-D diffusion formulation. This model is adopted here to forecast seasonal changes at Hasaki Coast. In this model, the change of beach profile depth relative to a fixed reference level is given by:

$$\frac{\partial h(x,t)}{\partial t} = \frac{\partial}{\partial x}\left(K(x)\frac{\partial h(x,t)}{\partial x} \right) + S(x,t) \qquad (1)$$

In Equation (1), $h(x,t)$ is the cross-shore beach profile depth measured relative to a fixed reference line and x is the cross-shore position measured relative to a fixed point on dry land. $K(x)$ is diffusion coefficient that varies across the profile. $S(x,t)$ is a space and time dependent external source function. In this formulation, it is assumed that the beach profile changes as a result of ‘diffusive’ and ‘non-diffusive’ sediment processes. The first term in the RHS of Equation (1) gives the beach change from sediment diffusion. The second term represents the accumulation of all non-diffusive contributions to the profile evolution process. Both $K(x)$ and $S(x,t)$ in Equation (1) are site-specific variables, which need to be calibrated.

The problem is therefore to define $K(x)$ and $S(x,t)$ in a meaningful way. They can be estimated on the basis that Equation (1) is a good representation of the medium term profile morphodynamics and numerious observations of beach profiles. Estimating both $K(x)$ and $S(x,t)$ simultaneously from beach profile measurements is a difficult mathematical problem. Therefore, in Karunarathna et al. (2009), the following two-step inverse modelling approach was used to determine *K*(*x*) and *S*(*x*,*t*). In this process, we assume that all variables in Equation (1) can be separated into a time-mean and a time-varying component. Based on this assumption, *h*(*x*) and *K*(*x*) can be written as

$$\left.\begin{aligned} h(x,t) &= \overline{h}(x) + h'(x,t) \\ K(x,t) &= \overline{K}(x) + K'(x,t) \end{aligned}\right\} \tag{2}$$

In Equations (2), the over-bar denotes the time averaged components and the prime denotes the time varying residuals. Further, the average of the primed quantities are zero.

Using Equation (2), Equation (1) can be re-written as

$$\frac{\partial\left[\overline{h}(x)+h'(x,t)\right]}{\partial t}=\frac{\partial}{\partial x}\left(\left[\overline{K}(x)+K'(x,t)\right]\frac{\partial\left[\overline{h}(x)+h'(x,t)\right]}{\partial x}\right)+S(x) \tag{3}$$

or,

$$\frac{\partial\left[\overline{h}(x)+h'(x,t)\right]}{\partial t}=\frac{\partial}{\partial x}\left(\overline{K}(x)\frac{\partial\left[\overline{h}(x)+h'(x,t)\right]}{\partial x}\right)+G(x,t) \tag{4}$$

where

$$G(x,t)=\frac{\partial}{\partial x}\left(K'(x,t)\frac{\partial[h(x,t)]}{\partial x}\right)+S(x,t) \tag{5}$$

In which both $S(x,t)$ and terms with time-varying residual of the diffusion coefficient is included. However, in a beach system like Hasaki where the gradient of sediment size is almost uniform across the profile (Kuriyama, 2008), the assumption that the time varying residual of the cross-shore diffusion coefficient is small is a reasonable one.

For brevity's sake we rewrite the Equation (4) in operator notation as

$$h_t = Dh + G \tag{6}$$

where the operator

$$D=\frac{\partial}{\partial x}\left(\overline{K}(x)\frac{\partial}{\partial x}\right) \tag{7}$$

Assuming that $G(x,t)$ slowly varies in time the formal solution of Equation (6) can be written as (Karunarathna et al., 2009).

$$h(x_i,t_{j+1}) \cong \left(\exp(D\tau)-1\right)D^{-1}G+\exp(D\tau)h(x_i,t_j) \tag{8}$$

in which τ is the interval between two consecutive time steps, $\tau = t_{j+1} - t_j$.

Based on a first order approximation, an expression for *G*(*x*,*t*) can be derived from Equation (8) as (Reeve and Spivack, 2000; Karunarathna et al., 2009)

$$G(x_i, t_{j+1/2}) = \frac{1}{\tau}\left[h(x_i, t_{j+1}) - \exp(D\tau)h(x_i, t_j)\right] \tag{9}$$

To solve Equation (9) to determine *G*(*x*,*t*), the operator *D*, which is a function of $\overline{K}(x)$ should be found. We use the time averaged equation (4) to determine $\overline{K}(x)$, through the following procedure: Following Karunarathna et al. (2009), as a first approximation, we take $\overline{G(x,t)} \approx 0$. Further, in approximate equilibrium, $\partial\overline{h}/\partial t \approx 0$. Then, the time average of Equation (4) gives

$$\frac{\partial}{\partial x}\left(\overline{K}(x)\frac{\partial\overline{h}(x)}{\partial x}\right) \approx 0 \tag{10}$$

The solution to Equation (10) is

$$\overline{K}(x) = \frac{\alpha}{\left(\frac{\partial \overline{h}(x)}{\partial x}\right)} \tag{11}$$

Equation (11) gives an explicit expression for the time-mean sediment diffusion coefficient.

In Equation (11), α is a constant of integration. $\left(\frac{\partial \overline{h}(x)}{\partial x}\right)$ is the gradient of the mean cross-shore beach profile, which can be calculated from the historic surveys of beach profiles.

It should be noted that the Equation (11) can be solved if the gradient of the mean profile is not zero at any cross-shore location within the model domain. To solve Equation (11) for $\overline{K}(x)$ a value for α must be specified. Here we adopt an optimisation procedure similar to that used by Reeve & Fleming (1997) and Karunarathna et al. (2009). Assuming that the beach profile shape will not deviate significantly during one time step (i) the historic profile shape was predicted using Equation (4) taking G ~ 0 as a first approximation, for all cases where historic measurements are available, for a range of α values; (ii) the error between measured and predicted profiles were determined; and (iii) the α which gives the smallest error was selected to be used equation (9). Physically, this process corresponds to selecting the value of the mean diffusion coefficient that explains as much of the observed change as possible. For detailed description of this procedure the reader is referred to Reeve and Fleming (1997).

Once $\overline{K}(x)$ has been determined from Equation (11), the operator D in Equation (7) can be calculated. Then, Equation (9) can be used to determine $G(x,t)$ for pairs of cross-shore beach profiles at time t_j and t_{j+1}. A detailed description of the procedure to determine $G(x,t)$ is described in Karunarathna et al. (2009).

To use this method, historic measurements of beach profiles at the chosen site are required for a reasonable length of time. Two consecutive beach profile measurements gives a $G(x,t)$ corresponding to those two profiles. If a time series of beach profile measurements are available, a discrete time series of $G(x,t)$ can be determined.

To solve Equation (4) in predictive form to forecast future beach change, future $G(x,t)$ values should be known either from a suitable parameterisation using historic values or by extrapolating them into future using a suitable form of extrapolation technique.

4. Model Application and Results

The diffusion model described in Section 3 was then applied to investigate and predict beach change at Hasaki Coast, Japan. Beach profile surveys described in Section 2, measured from 1993 to 2006 was used to determine the diffusion coefficient and the source function, which are the key parameters in the model. The mean beach profile gradient to be used in Equation (9) to determine time mean diffusion coefficient was determined by averaging all profile surveys measured weekly profile surveys from January 1993 to December 2007. Following the optimisation technique mentioned in Section 3 (reader is referred to Karunarathna et al. 2009 for more details), the best value for α was found as 6.01×10^{-2}. Using this value for α, Equation (9) was solved to determine space-varying mean diffusion coefficient along the profile. It should be noted that the gradient of the mean profile should be non-zero for Equation (9) to be valid. Although the time mean beach profile at Hasaki is mostly concave, there are a few locations where the gradient was extremely small, leading to excessively high and unrealistic values of diffusion coefficient. In these cases, the diffusion coefficient was determined by smoothing the profile using the values at 4 neighbouring grid points. The results are shown in **Figure 3**.

Although some scatter is seen in the results, $\overline{K}(x)$ shows an increasing trend in the offshore direction. This could be expected as a result of the diminishing sea bed gradient prevailing in the mean profile.

Despite the prominent and highly dynamic bar-trough system present at Hasaki Coast (Kuriyama, 2002), the mean profile resembles a typical concave beach. We fitted Dean's equilibrium profile curve (Dean, 1991)

$$h(x) = Ax^{2/3} \tag{12}$$

to the mean beach profile below mean high water, in which x is offshore distance measured from still water line and A is a constant related to grain size D by $A = 0.21D^{0.48}$ with D given in millimetres (Moore, 1982). The result is shown in **Figure 4a**. Grain size D was taken as median grain size at Hasaki Coast which is 0.18mm (Kuriyama et al. 2008). It can be seen that the equilibrium profile closely resembles the mean beach profile above -2m but underestimates the depth of the profile below -2m.

Dean's equilibrium profile is directly linked to the sediment characteristics of the beach through Moore's (1982) expression. The sediment diffusion coefficient in the diffusion model also characterises beach sediment. Differentiating the profile depth given by Dean's equilibrium model [Equation (10)], and substituting this into Equation (9) yields the following relationship between sediment diffusion coefficient and sediment characteristics of the beach (Karunarathna et al, 2011):

$$\overline{K(x)} = \frac{3}{2A} x^{1/3} \tag{13}$$

Equation (13) shows that if the mean beach profile at Hasaki Coast follows Dean's equilibrium profile, $\overline{K}(x)$ should have a linear relationship with $x^{1/3}$, which is evident in **Figure 4b**. Relating the gradient of the $\overline{K}(x)$ vs. $x^{1/3}$ curve to Moor (1982) relationship, sediment size on the beach was found as 0.2mm, which closely agrees with the measured median sediment size at Hasaki Coast of 0.18mm. These results show that despite the presence of the bar-trough system, the concave shape of the mean beach profile allows the application of Dean's profile shape to describe the long-term equilibrium profile at Hasaki Coast.

To use the diffusion model in predictive form that is to forecast beach change in future, the source function $G(x,t)$ for the appropriate period should be determined. If the time mean diffusion coefficient recovered above is used in Equation (9), a discrete time series of $G(x,t)$ can be calculated using measured bathymetry data. It should be noted that G varies with x as well as in time. Using beach profile surveys from 1993 to 2007, $G(x,t)$ was calculated at 5 m intervals across the profile and the results are compiled in **Figure 5** as the space-varying envelope of all $G(x,t)$ calculated for this period. Mean beach profile is shown in the same figure to show reference to cross-shore location. The largest range of variability of $G(x,t)$ is observed between 175m and 350m offshore distances, where the bar movement has been identified by Kuriyama (2002).

It should be noted here that the source function $G(x,t)$ reflects all contributions to beach profile variability other than diffusion. Tidal influences on Hasaki Coast are small as the beach is micro-tidal. The high energy cyclonic wave climate is the dominant hydrodynamic process in this area (Kuriyama, 2002). We therefore infer that the source function primarily consists of the effects of incoming waves on beach morphodynamics. In order to assess the physical significance of the source function and its contribution to beach change, the space integrated source function (integrated across the profile) $[\int G(x,t)dx]$, which represents time-varying sediment erosion/accretion (negative/positive $[\int G(x,t)dx]$ represents erosion/accretion of the profile respectively) across the profile was calculated. Kuriyama et al. (2012) found that shoreline change at Hasaki Coast shows a strong seasonal signal of four monthly periods of March-June (MAMJ), July-October (JASO) and November-February (NDJF). Taking this into account, 4-monthly moving average of $\int G(x,t)dx$ was calculated. In addition, the moving averages of $\int G(x,t)dx$ at 12-monthly periods were also calculated to investigate potential links between beach change and climate-driven, inter-annual scale environmental processes. Both results are shown in **Figure 6**.

In Figure 6, strong cyclic signatures can be seen in both 4- and 12-monthly moving averaged space integrated source function time series. To determine the frequency of these signals, power spectral analysis was performed on $\int G(x,t)dx$. Power spectral density of $\int G(x,t)dx$ against spectral frequency is shown in **Figure 7**. The results show that there are prominent spectral density peaks at 4.9 years and 1 year. Many other spectral peaks can also be seen at higher frequencies however, as our focus here is on seasonal to inter-annual scale morphodynamics at Hasaki Coast, we will focus on these two peaks. Spectral densities at higher frequencies may correspond to complex cyclonic wave climate and individual cyclonic events. Annual cycles agree well with the annual cyclic beach change recognised by Suzuki and Kuriyama (2014). It should be noted that the 4.9 cycle corresponds to the cyclic signal visible in both 4-monthly and 12-monthly moving averaged and space integrated source function (red line in Figure 6). In an attempt to relate this signal to climatic variations that may contribute to beach change, power spectral density of El Nino/La Nina Sothern Oscillation Index (SOI) was determined. The results (not shown) indicate a spectral peak between 4-5 years. As a result, it can be stated that the 4.9 year cyclic variability of the source function (and hence beach change) may be driven by El Nino/La Nina climate variability.

Following the detailed analysis of the source function presented above, we will attempt to apply the diffusion model to forecast seasonal to inter-annual beach change at Hasaki Coast. In order to use the model governing equation as a predictor of beach change, a suitable parameterisation of the source function is needed. Focusing on prediction of seasonal to inter-annual beach profile change (beach profile volume change per metre width of the beach in the longshore direction), 4-monthly moving averaged $\int G(x,t)dx$ was extrapolated using the following simple procedure: First, $\int G(x,t)dx$ time series was divided into segments of 4.9 year period by taking into account the 4.9 year cyclic signal contained in it. Then, the mean signal was determined by taking the average of all segments. Mean signal was then extrapolated to obtain $\int G(x,t)dx$ from 2007 to 2011. The results are shown in **Figure 8**.

The predicted source function and the time-mean diffusion coefficient determined from Equation (9) were then used in the predictive form of the diffusion model to forecast inter-annual scale beach area change and Hasaki Coast. The initial beach profile required to drive the model was taken as the 4-monthly averaged beach profile in June 2006. Continuous simulations were carried out using time step as 120 days (approximately 4 months). A comparison of measured and forecasted 4-monthly averaged beach area change during the period between 2007 and 2011 is shown in **Figure 9**. The positive values of area change during this period showed that the beach is in an accretionary state, which in agreement with positive trend of shoreline position change observed by Kuriyama (2012) for this period.

The model forecasted the seasonally averaged beach area change very encouragingly. Deviations between the measured and forecasted values at some occasions can be attributed to a number of factors: (i) simplicity of the modelling approach which does not allow detailed processes to be modelled (ii) impact of any significant extreme cyclonic events that may have phased out due to the averaging process and (ii) simple approach used for forecasting the source function.

5. Conclusions

Modelling and forecasting of Hasaki Coast beach volume change is presented and discussed in this paper. Seasonal to inter-annual scale beach change, which is important to coastal engineers and managers, is the focus of the model application. The model applied to the Hasaki Coast was developed based on ‘reduced physics’ modelling principles where only key processes necessary to describe morphodynamics at a selected time scale are retained. The governing equation contains two unknown parameters to be calibrated by site measurements. Measured beach profiles at Hasaki Coast were used in this regard.

Model parameters showed that the mean diffusion coefficient, which represents ‘diffusion-driven’ beach change in the model governing equation was related to sediment characteristics of the site and that the Dean’s equilibrium profile (Dean, 1977) was a suitable parameterisation to the long term average beach profile at Hasaki Coast. The space integrated source function (integrated across the beach profile) which relates to time-varying beach profile volume change per unit length of the beach, shows cyclic signatures at a range of time scales in which 1 and 4.9 year cycles being the most prominent. One year cycle may correspond to annual variability of the cyclonic wave climate while 4.9 year cycle corresponds to climate-driven El Nino/La Nina Southern Oscillation.

The forecasts of seasonal to inter-annual scale beach change obtained using the diffusion model show good agreement with measured data. Considering the simplicity of the modelling approach used, the results are promising. Even though forecasts presented in this paper are limited to change in beach area, using a suitable approach to forecast space varying source function, it may be possible to predict beach profile change including the bar movement.

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Figure 9 - A comparison of modelled and measured average annual cross-shore beach area change at Hasaki Coast.

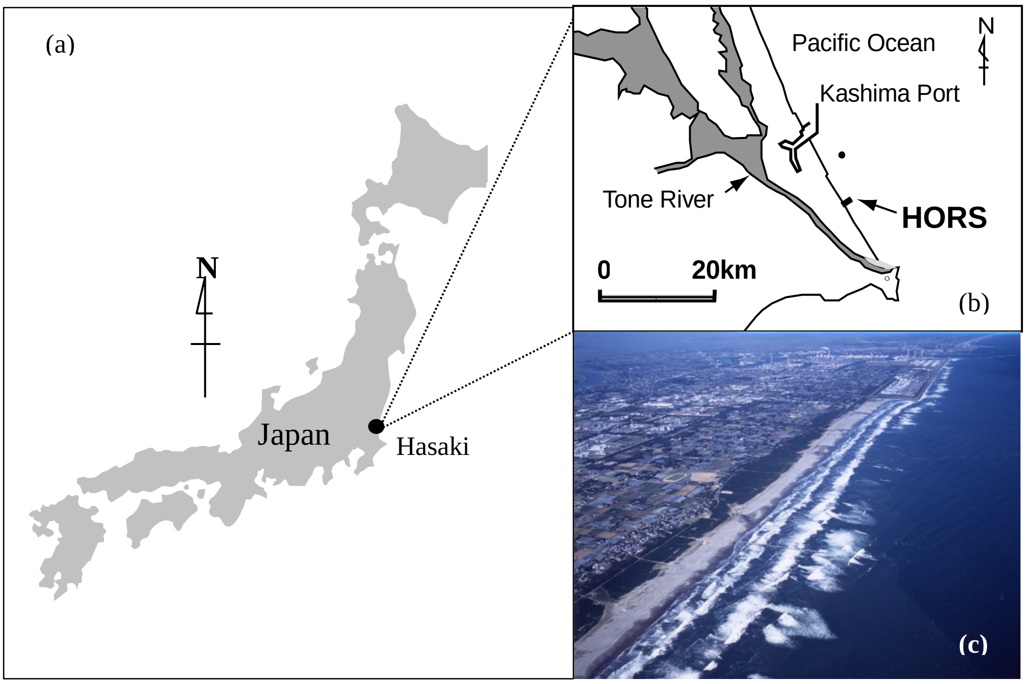

Figure 1 –Field Site at Hasaki, Japan. (a) Location of Hasaki Coast (b) Location of Hazaki Oceanographical Research Station and wave gauge (c) view of Hasaki Beach.

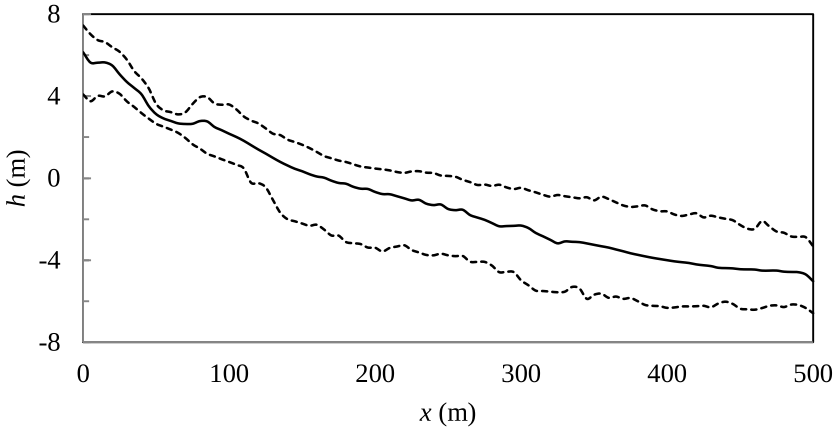

Figure 2 – Beach profile envelope and mean beach profile at Hasaki Coast. Envelope and mean profile were determined from profiles measured between 1993 and 2010. Dotted line – profile envelope, dark line – average beach profile.

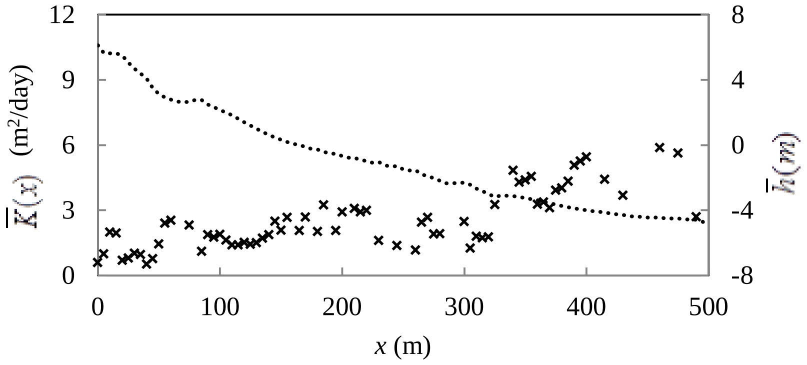

Figure 3 – Mean diffusion coefficient at Hasaki Coast vs. profile distance. Mean beach profile is shown by the dotted line.

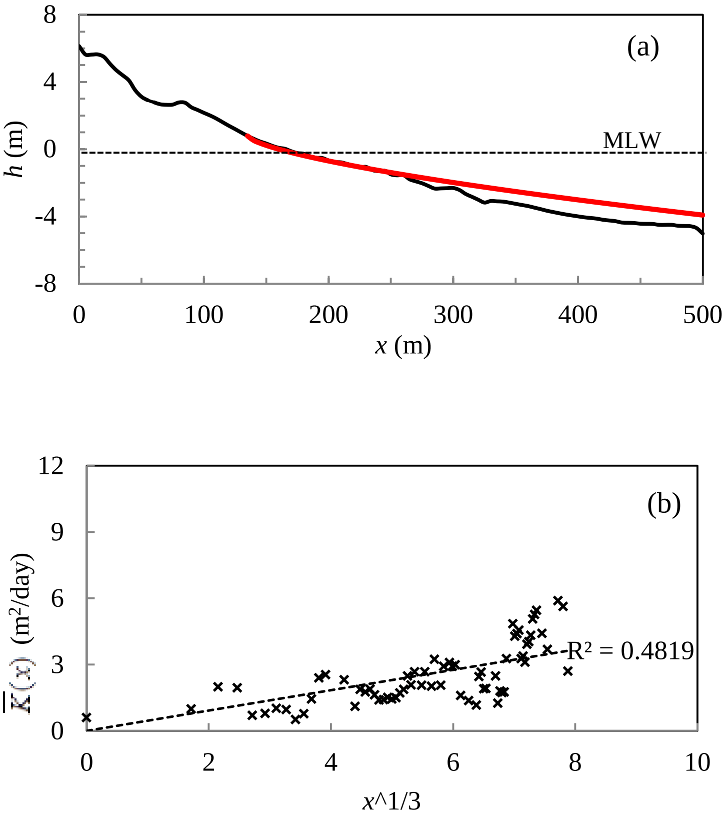

Figure 4 – (a) A comparison of mean beach profile at Hasaki Coast and Dean's equilibrium profile (Dean 1991), black line – mean profile, red line – Dean's equilibrium profile, black broken line –Mean Low Water level (MLW) (b) relationship between mean diffusion coefficient and Dean (1991) model. Broken line shows the linear fit to data.

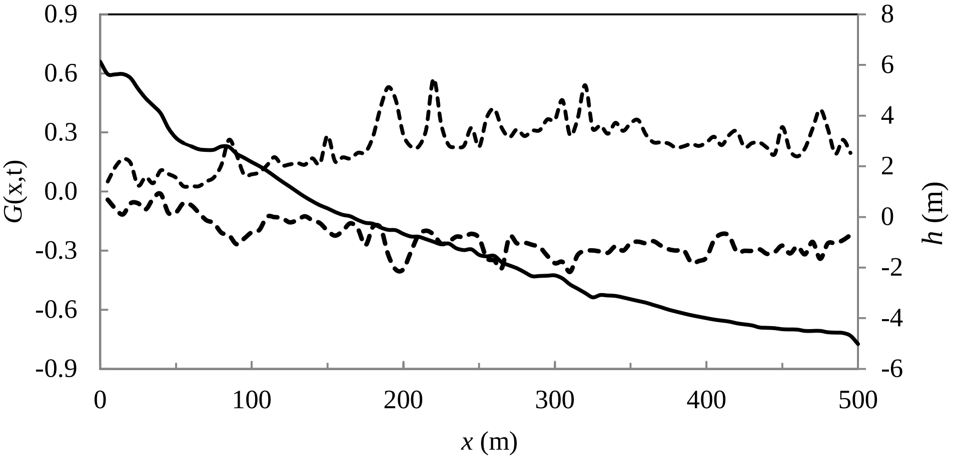

Figure 5 – Spatial variation of the envelope of the source functions calculated for the period 1993-2007. Mean profile shape is shown in dark black line.

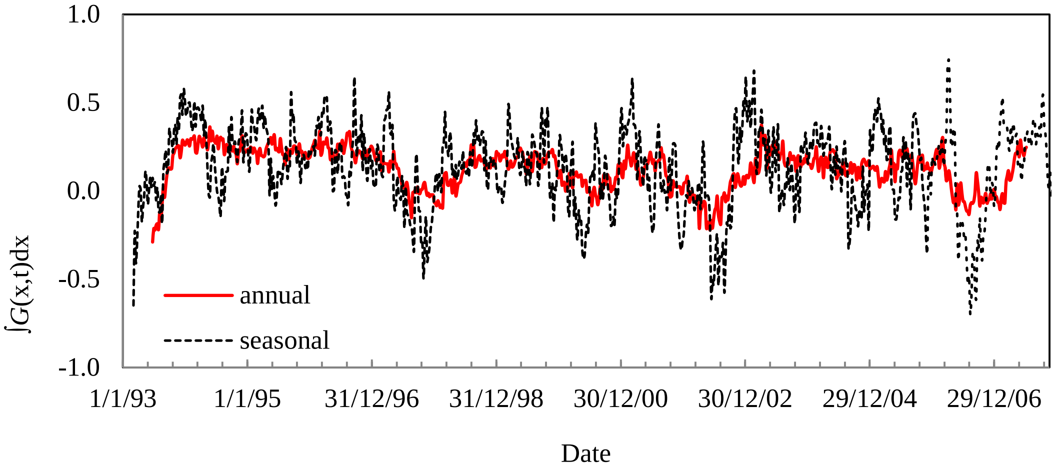

Figure 6 – 4-monthly and 12-monthly moving averaged, space integrated source function. Space integration was done across the entire profile. Black line – 4-monthly moving averaged signal. Red line – 12-monthly moving averaged signal.

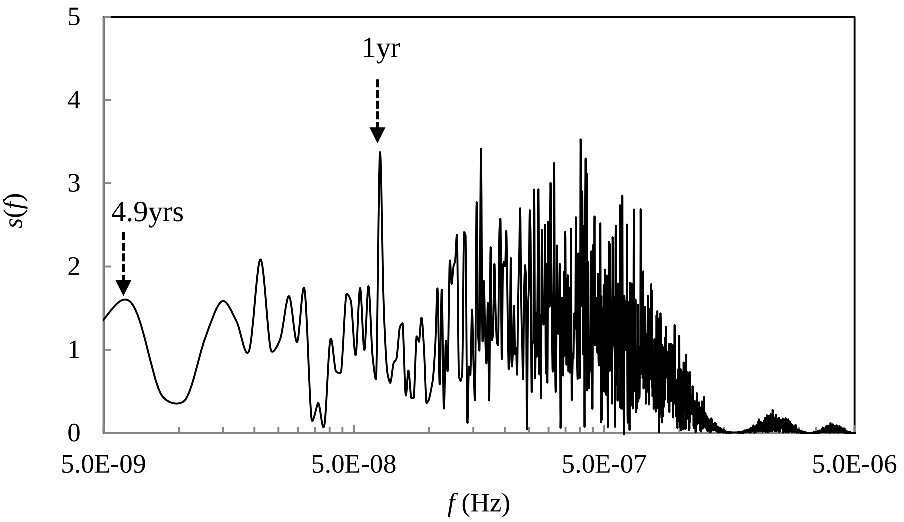

Figure 7 – Power spectra of depth integrated source function.

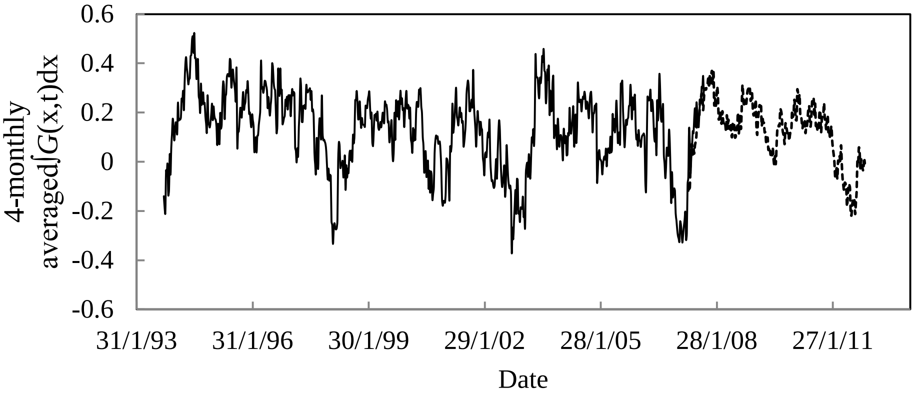

Figure 8 – Extrapolation of 4-monthly moving averaged $\int G(x,t)dx$. Dark line – calculated from historic beach profile data, broken line – extrapolation from the mean signal.

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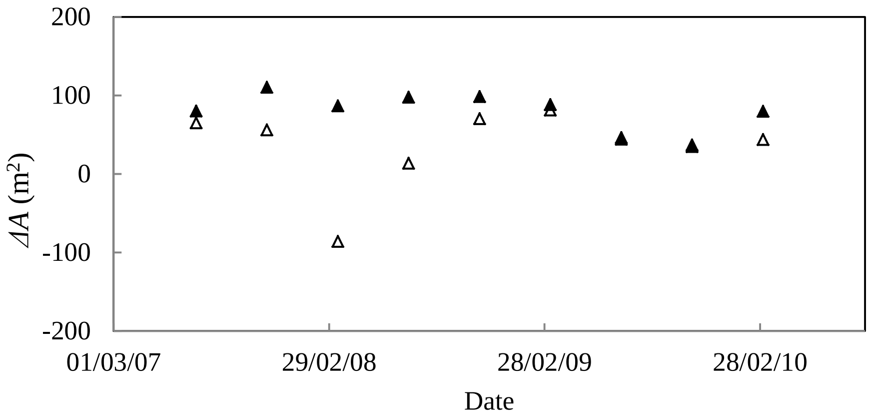

Figure 9 - A comparison of modelled and measured seasonally averaged cross-shore beach area change at Hasaki Coast. Measured - hollow triangles, modelled- solid triangles.

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