Paper:
Karunarathna, H., Horrillo-Caraballo, J., Kuriyama, Y., Mase, H., Ranasinghe, R. & Reeve, D. (2016). Linkages between sediment composition, wave climate and beach profile variability at multiple timescales. *Marine Geology, 381*, 194-208.
http://dx.doi.org/10.1016/j.margeo.2016.09.012

Marine Geology 381 (2016) 194–208

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margo

Linkages between sediment composition, wave climate and beach profile variability at multiple timescales

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ARTICLE INFO

Article history:
Received 20 April 2016
Received in revised form 11 September 2016
Accepted 21 September 2016
Available online 23 September 2016

Keywords:
Cross-shore beach profile
Beach morphodynamics
EOF analysis
Equilibrium profile

ABSTRACT

The paper analyses, compares and contrasts cross-shore morphodynamic behaviour of four diverse beaches that have very different regional settings, wave climates and sediment characteristics, with the aid of rarely available long term measurements of beach profiles and incident waves. The beaches investigated are Narrabeen Beach, New South Wales, Australia; Milford-on-Sea Beach, Christchurch Bay, UK; Hasaki Coast, Ibaraki Prefecture, Japan; and Joetsu-Ogata Coast, Niigata Prefecture, Japan. A statistical analysis, equilibrium beach profile analysis and Empirical Orthogonal Function analysis are used to investigate, compare and contrast spatial and temporal variability of cross shore beach profiles of the selected beaches at short-, medium- and long-term timescales. All beaches show evidence of multi-timescale morphodynamic change. Narrabeen Beach profile has the highest sensitivity to local weather patterns. Milford-on-Sea, Joetsu-Ogata and Hasaki profiles are sensitive to seasonal variation of the wave climate however, they also show some correlations with regional climate variabilities. The nature of sediment exchange across the profile, which contributes to profile shape change with time, is found to be related to sediment characteristics across the profile. At Milford-on-Sea and Joetsu-Ogata, both of which have composite profiles, sediment exchange between the upper beach and the inter-tidal zone dominates profile change, irrespective of the distinct differences in sediment composition found in the two beaches. On the other hand in Narrabeen and Hasaki where beach sediment comprises medium to find sand, sediment exchange and hence profile change occur mainly in intertidal and subtidal zones.

1. Introduction

Temporal variability of beach morphology is driven by sediment transport in cross-shore and/or longshore directions. Longshore beach change is mainly characterised by long term variability of shoreline position, beach rotation and development of rhythmic features. On the other hand, cross-shore change is characterised by changes in the shape of cross-shore profile and the area of beach cross section in time. While longshore beach changes have significant impacts on the medium to long term beach position and orientation, cross-shore change occurs over a wide range of timescales and can have detrimental impacts on the stability of natural and man-made sea defences, coastal eco-systems, infrastructure and safety. In this study we specifically focus on morphodynamic change in the cross-shore direction as cross-shore beach profile change spread over a range of time scales and is crucial to short-medium term beach stability and storm response, stability of coastal defences, wave overtopping and coastal inundation.

Beach profile morphology changes over a range of time and space scales. Here we define short term variability as that which occurs over a period of days to a month as a result of episodic events (storms); medium-term variability as that which over several months (e.g. winter-summer wave change) to several years (e.g. due to regional climate variability, engineering intervention and prevailing sedimentary processes; and long term variability as that which occurs over a period of a decade to a century, associated mainly with climate change impacts; and very long term millennial scale evolution as a result of quaternary sea level changes. Cross-shore beach change is widely thought to be controlled by the incident wave climate, water level variability, nearshore currents, sediment characteristics and sediment distribution across the profile (Niodoroda et al., 1995; Stive and de Vriend, 1995; Pedrozo-Acuna et al., 2006; and many others). The cross-shore variability of sandy beaches is distinctly different to that of coarse grain beaches and/or composite sand-gravel beaches in terms of profile shape and profile

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http://dx.doi.org/10.1016/j.margeo.2016.09.012

response to hydrodynamic forcing (Larson and Kraus, 1994; Pontee et al., 2004; Karunarathna et al., 2012).

Relationships between beach change and drivers that govern the change have been extensively studied in the past, using field measurements, experimental investigations and numerical models, covering a range of time scales spanning from short-term to long-term. For example, Lee et al. (1998) studied storm driven beach change using beach profiles measured at Duck, North Carolina. Ferreira (2005) investigated beach response to storms using a set of measured data from a Portuguese coast. More recently, Coco et al. (2014) investigated beach response to storm sequences using beach profiles measured at Truc Vert Beach, France. McCall et al. (2015) modelled storm response of gravel beaches and barriers. Karunarathna et al. (2014) investigated storm scale morphodynamic beach profile response using historically measured beach profiles of Narrabeen Beach Australia. They found that single storms or storm clusters predominantly change the supra tidal and inter-tidal part of the beach profile and that beach erosion volumes are strongly correlated to the power of the storm. In addition, many research results have been published on numerical modelling studies of storm scale beach change (e.g. Larson and Kraus, 1989; Roelvink et al., 2009; Ruiz de Algeria-Arzaburu et al., 2011; Williams et al., 2012; Callaghan et al., 2013; Pender and Karunarathna, 2013; McCall et al., 2015).

Medium term beach profile change and its relationship with changes in wave climate have also been well studied and modelled my numerous researchers. For example, Vellinga (1983, 1984) developed a relationship between cross-shore distance and profile depth for erosive beach profiles, as a function of grain size. Inman et al. (1993) investigated winter/summer seasonal variability of beach profile shape. Kuriyama (2002) and Kuriyama et al. (2012, 2008) investigated the medium term cross-shore profile behaviour including shoreline position change, inter-tidal bar movement and profile shape variability using a set of regularly measured beach profiles over a few decades at Hasaki Coast, Japan. Their studies were able to form linkages between seasonal to inter-annual change in wave climate and profile behaviour. Relationships between incident wave conditions and medium term profile variability have also been examined and established using various techniques and field observations by, among others, Larson et al. (2000), Kroon et al. (2008), Horrillo-Caraballo and Reeve (2008, 2010), Karunarathna et al. (2012), using numerous field observations.

Long term adjustments of beach profiles associated with sea level changes have also received the attention of many researchers. Bruun (1954) investigated cross-shore profile change and developed the concept of equilibrium beach profile shape on sandy beaches. Using this concept as a basis, a simple empirical relationship between long term sea level change and profile shape (Bruun Rule) was developed by Bruun (1962). Dean (1977) provided the physical argument for the shape of this profile shape and developed Dean's equilibrium profile. Later, Dean (1991) included gravity effects to the Dean (1977) profile to get the linear upper beach retain the dependence on grain size. Bodge (1992) proposed an exponential beach profile model. Larson et al. (1999) provided physical reasoning for a linearly sloping upper beach but this result was independent of grain size. Long term adjustments of beach profiles to Quaternary sea level changes have also been studied by Carter (1986) and Carter and Orford (1993).

Even though numerous studies have been reported on change of cross-shore morphodynamics of different beach types under different wave and hydrodynamic conditions in isolation, studies on inter-comparison of sites with different characteristics are sparse. For example, two different sites with different site characteristics may behave very differently under the same wave and hydrodynamic condition. Also, there are still substantial gaps in our knowledge on how beach morphodynamics vary over the full range of timescales. For instance, profile variability of coarse sediment and mixed sediment beaches is largely unknown. In addition, studies on the effects of medium term climatic variability on profile shape changes are scarce. This study focuses on comparing and contrasting cross-shore morphological change of four very different beaches using historic measurements of beach profiles. The aim of this study is to identify commonalities and divergences in beach profile behaviour among the case study sites. Section 2 of the paper describes the four field study sites. In Section 3, general variability of beach profiles at the four sites is analysed. In Section 4, beach profiles are compared with Dean (1991)'s equilibrium profile. Section 5 analyses profiles using Empirical Orthogonal Functions (EOFs). In Section 6, a discussion of the results presented in Sections 3, 4, and 5 are given and those results are related to incident wave climate. Chapter 7 concludes the paper.

2. Study sites

The field sites used in the present study are Narrabeen Beach, New South Wales (NSW), Australia; Milford-on-Sea Beach, Christchurch Bay, UK; Hasaki Coast, Ibaraki Prefecture, Japan; and Joetsu-Ogata Coast, Niigata Prefecture, Japan. These sites have distinctly different characteristics in terms of exposure, sediment characteristics, tidal regime and incident wave climate. Historical beach profile surveys and wave measurements spanning a few decades are available at all 4 sites making them ideal candidates for this multi-time scale analysis and inter-comparison. The selected cross-shore transects selected from these sites reported to have the least impact from longshore sediment transport.

2.1. Narrabeen Beach, New South Wales, Australia

Narrabeen Beach is a wave-dominated embayed beach located 20 km north of Sydney, in New South Wales (NSW), Australia**.** The beach is 3.6 km long and bounded by two headlands, Narrabeen Head to the north and Long Reef Point to the south and is composed of medium to fine quartz and carbonate sands with $D_{50} = 0.3$–0.4 mm (see Fig. 1a).

The beach is exposed to a highly variable, moderate-to-high energy wind waves superimposed on long period, moderate-to-high energy south-easterly swell waves (Short and Wright, 1981). Waves are derived from three cyclonic sources: Mid-latitude cyclones pass across the southern Tasman Sea all-year-round, generating south-easterly swell; extra-tropical cyclones off NSW coast generating east and south-easterly waves peaking between May and August; tropical cyclones that generate moderate to high north-easterly and easterly swell during February and March. In addition, summer (December to March) sea breezes generate low to moderate north-easterly seas. On average, Narrabeen Beach is subjected to 12 storms per year (based on the local definition that $H_s > 3$ m lasting more than 1 h represents a storm (Callaghan et al., 2008)). Fig. 1b shows typical offshore wave climate measured at the wave buoy near Long-Reef Point located in around 80 m water depth offshore of Narrabeen Beach. The beach experiences micro-tidal, semi-diurnal tides with mean spring tidal range of 1.6 m and neap tidal range of 1.2 m. MHWS and MLWS are 0.9 m and −0.7 m above Australian Height Datum (AHD) respectively. The effect of tides on the morphology of Narrabeen Beach is considerably less than that of waves (Short, 1985; Short and Trembanis, 2004).

Cross-shore beach profiles at five alongshore locations along the Narrabeen Beach have been regularly measured first at bi-weekly intervals and then, at monthly intervals since 1977, by the Coastal Studies Unit, University of Sydney. Surveys were undertaken at low tide and profiles were recorded at 10 m cross-shore intervals from a fixed bench mark at the landward limit of the active beach at 10 m elevation. Beach profiles measured at monthly intervals from 1977 until 1992 were used in this study. Hourly non-directional (1976–1992) and directional (1992–2005) wave data were also measured at an offshore wave buoy located at the Long Reef Point, at a depth of 80 m. Cross-shore beach profile surveys carried out at Profile 4, situated in the central part of the Narrabeen Beach (Fig. 1a), which is the least likely location

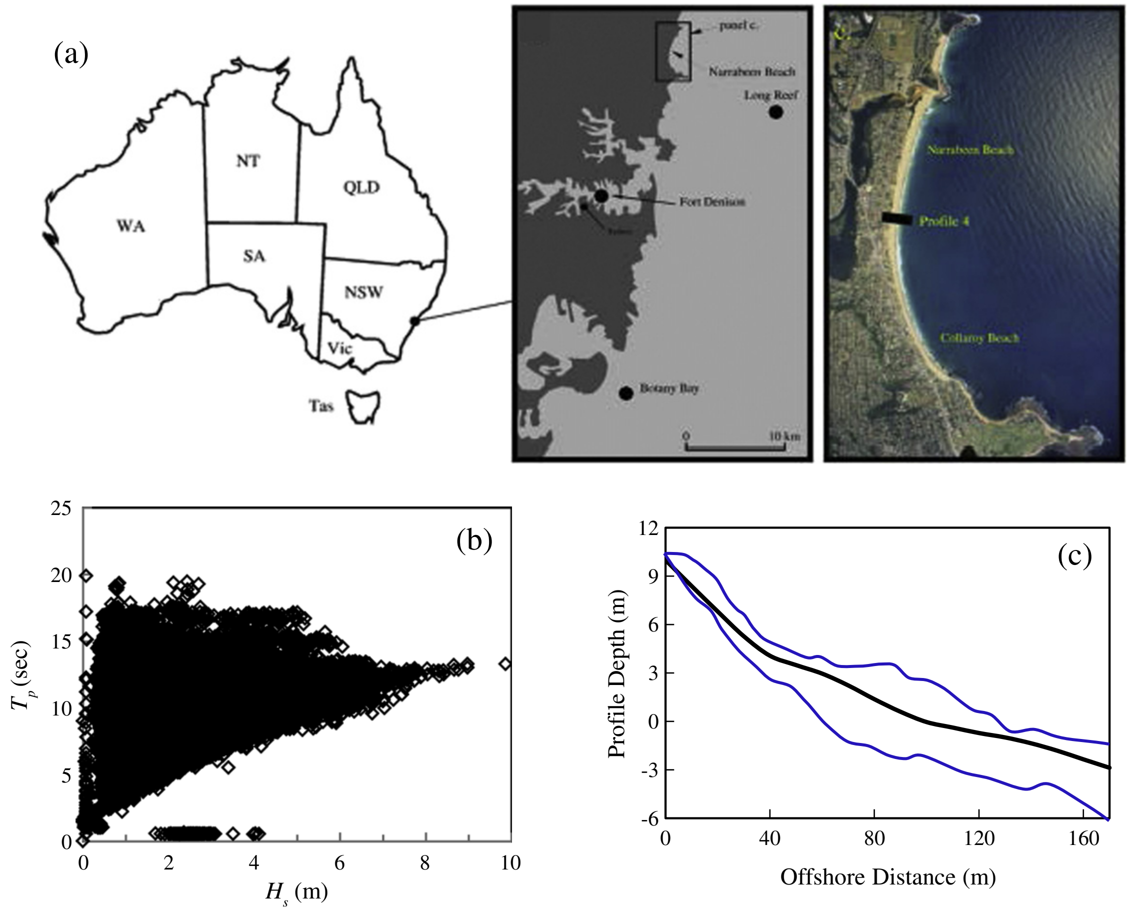


Fig. 1. Narrabeen Beach, New South Wales, Australia. (a) Location and a view of the beach with the location of Profile 4, (b) incident waves measured at Long Reef Point, and (c) mean and envelope of measures profiles at Profile 4.

to be affected by the cyclic beach rotation phenomenon that occurs at Narrabeen Beach is selected for this study (Short and Trembanis, 2004; Ranasinghe et al., 2004a). The cross-shore extent of profile measurements at Profile 4 does not surpass the depth of closure which is approximately 10 m (Hallemeier, 1981) and therefore measured profiles do not cover the entire active profile. A summary of the cross-shore profile surveys at Profile 4 from 1976 to 1992 are shown in Fig. 1c.

2.2. Milford-on-Sea beach

Milford-on-Sea is a sand-gravel composite beach that forms a part of the Christchurch Bay beach system facing the English Channel, UK. The beach extends about 3 km to the west from Hurst Castle Spit (Fig. 2a). The sub-tidal beach is characterised by highly mobile and segmented multiple alongshore bars. The sediment grain size at Milford-on-Sea beach significantly varies along the cross shore profile. Coarse shingles and pebbles with a median grain diameter (D_{50}) around 16 mm dominate the upper beach. A sand-gravel mix which has D_{50}-gravel = 10 mm and D_{50}-sand = 1 mm with only 62% sand fraction, dominates the upper inter-tidal areas (Martin Grandes et al., 2009).

Waves reach the beach predominantly from the SSW direction with occasional SSE waves. The wave climate has a clear winter-summer seasonal signature. SCOPAC (2003) quotes the typical (one year return period) and extreme (1 in 100 year) significant wave heights at Milford-on-Sea as 2.5 m and 3.4 m respectively. Fig. 2b shows nearshore significant wave heights measured at a depth of 12 m offshore of the Christchurch Bay beach between 1986 and 1994. Christchurch Bay experiences semi-diurnal tides with a spring tidal range of 2.0 m, reducing to 0.8 m during neap tide, making it a meso-tidal beach. Mean high water spring (MHWS), Mean low water spring (MLWS) and Mean water level (MWL) are 0.87 m, −1.13 m and 0.14 m above Ordnance Datum Newlyn (ODN), the standard UK reference level.

Cross-shore beach profiles along the Christchurch Bay have been surveyed by the UK South-East Regional Coastal Monitoring Programme at 45 beach transects. Profiles were measured since 1987 until 2006 on average at 3 surveys per year at 5 m cross-chore intervals. All profile heights were recorded relative to ODN. Surveys at beach transect 5f00107, (Fig. 2c), were selected for the present analysis as this corresponds to where net longshore transport is minimal (SCOPAC, 2003). The depth of closure of Milford-on-Sea beach is around 5.0 m which is further offshore from the truncation point of the measured profiles and therefore, measured profiles do not cover the entire active profile.

2.3. Hasaki Coast, Japan

Hasaki Coast is a longshore uniform sandy coastline located in the Ibaraki Prefecture of Japan, facing the Pacific Ocean (Fig. 3a). The intertidal and subtidal beach consists of multiple sand bars that are highly mobile under the current sediment transport regime. The beach consists of sediment with median diameter of 0.18 mm. Sediment grain size is almost uniform along the beach profile, (Kuriyama et al., 2008).

The beach is subjected to both wind 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

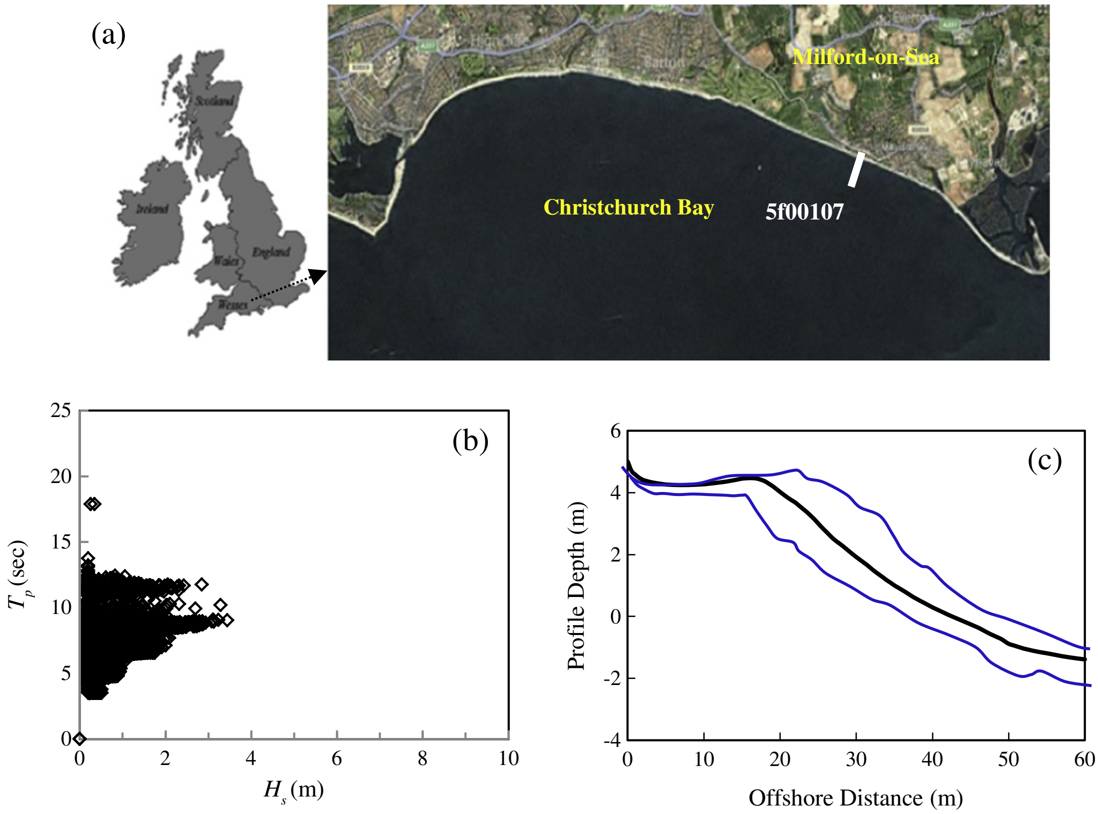


Fig. 2. Milford-on-Sea Beach, Christchurch Bay, UK. (a) Location and a view of the beach with the location of Profile 5f00107, (b) incident waves measured at Christchurch Bay, and (c) mean and envelope of measures profiles at Profile 5f00107.

on the datum level at Hasaki, (Tokyo Peil- 0.69 m), the high, mean and low water levels were recorded as 1.25 m, 0.65 m and −0.20 m 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 since 1986 with an ultrasound wave gauge for 20 min every 2 h (Fig. 3b). The water depth at wave measuring location is 24 m.

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 cross-shore 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 497 m. Weekly profiles measured from 1986 to 2010 were used in this study. Fig. 3c shows a summary of the beach profiles measured at the Hazaki Observation pier. The depth of closure of Hasaki Coast is around 8–9 m (Banno and Kuriyama, 2014) and therefore, the measured profiles include most of the entire active beach. However, the measured profile envelope in Fig. 3c reveals some profile variability at 8 m water depth.

2.4. Joetsu-Ogata Coast, Japan

Joetsu-Ogata Coast, located between Joetsu and Kashiwazaki cities facing the Sea of Japan, is a 28 km long sandy beach with predominantly straight and parallel bottom contours (Fig. 4a). The beach consists of sand with median diameter varying between 0.3 mm to 2.7 mm in the cross shore direction (Baba and Uchiyama, 2001).

Joetsu-Ogata Coast is subjected to stormy wave conditions during winter months. On average, 3–4 storms per month reach the coastline during winter months. The average duration of winter storms is 2–3 days. The significant wave height during these storms can reach as high as 3.0 to 3.5 m. Intensive wave measurements have been carried out at the Ogata Wave Observation (OWO) pier for a short duration between November–December 1987 and January 1989, (Mase et al., 1990). However, long term wave measurements, carried out by the Nation-Wide Ocean Wave Information Network for Ports and Harbours (NOWPHAS), are available from 1999 to 2005 at Naoetsu Port, located 5 km west of the OWO pier. It is reasonable to assume that these waves are representative of the waves at the profile measurement site as Joetsu-Ogata Coast is predominantly longshore uniform. Wave measurements have been carried out for 20 min at every 2 h between 2002 and 2005. Significant wave heights (H_s) and periods (T_s) of the measured waves are shown in Fig. 4b. The analysis of wave data reveals that significant wave heights vary between 0.3 and 3.4 m while significant wave periods vary between 2.4 and 13.5 s. The average values of H_s and T_s are 1.1 m and 5.6 s respectively. The beach is micro tidal with spring tidal range not exceeding 0.4 m (Karunarathna et al., 2015).

Field surveys of cross shore beach profiles at Joetsu-Ogata Coast have been carried out by the Disaster Prevention Research Institute of Kyoto University, Japan at the Ogata Wave Observatory (OWO) pier located at the central part of the coast (Fig. 4a). The pier was 256 long in the cross shore direction and was supported by truss girders to minimise its effects on the nearshore hydrodynamics and sediment transport processes (Mase et al., 1990). Measurements have been done with respect to a reference line located 25 m landward of the beach crest. Cross-shore profiles measured at OWO are considered to be typical of this beach. The profiles had been measured once a month since October 1986 until March 2006, with a cross shore resolution of 1.25 m. However, it should be noted that the data prior to 1997 has significant gaps (Mase et al., 1990). In Fig. 4c, a summary of the measured beach profiles at OWO Pier is shown. Offshore wave data is not available at JOETSU-

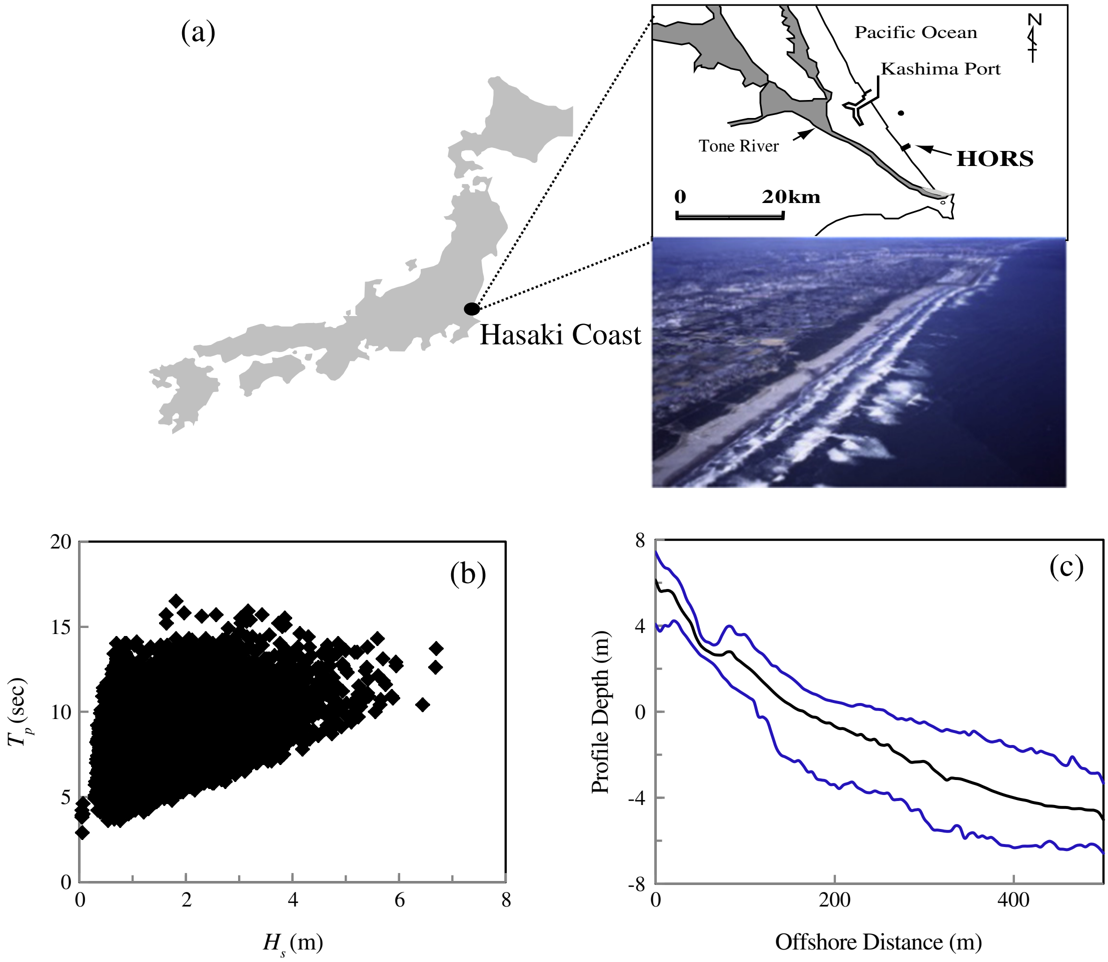


Fig. 3. Hasaki Coast, Ibaraki Prefecture, Japan. (a) Location and a view of the beach, (b) incident waves measured offshore of Hasaki, (c) mean and envelope of measures profiles at Hazaki Pier.

OGATA Coast to determine the depth of closure and hence the length of the active profile however, the profile envelope shown in Fig. 4c reveals profile variability at 8 m depth where most profiles are truncated.

A summary of beach characteristics of the four study sites is given in Table 1.

3. General profile variability

In this section, a general statistical analysis of cross-shore profiles at the four selected sites is presented, using the mean beach profile and standard deviations around the mean. The main results are shown in Fig. 5.

Mean profile shape at the four sites show remarkable differences. It is interesting to see that the Narrabeen Beach mean profile (Fig. 5a) shows three distinct slopes at dune face ($0 < x < 50$ m), upper beach (50 m $< x <$ 90 m) and inter-tidal/subtidal zone ($x > 90$ m), even though sediment size does not significantly vary across the profile. Overall, the mean profile seems to fit with an intermediate beach profile state with the lower beach showing characteristics of a classic dissipative profile and the upper beach showing the shape of a reflective profile (Short, 2006). The standard deviation around the mean profile is strongest in the intertidal zone which shows that most wave activity takes place in this zone. The second largest variability is seen at the foot of the dune, which may be due to high waves reaching the dune foot during stormy conditions (storm surge at this location is minimal (Callaghan et al., 2008).

Milford-on-Sea Beach (Fig. 5b) shows two distinct slopes where the gradients of the upper beach and intertidal zones ($x < 50$ m) are significantly steeper than that of the subtidal beach ($x > 50$ m). This is not surprising due to the sand-gravel composite nature of the beach. The overall beach profile shape follows a classic reflective profile defined by Short (2006). The largest standard deviation from the mean profile is seen in the supratidal zone, which indicates swash dominance (25 m $< x <$ 35 m). The second largest standard deviation is seen in the intertidal-subtidal boundary where wave breaking takes place during low tide, which shows that tidal water level fluctuations play an important role in the morphodynamics of this beach.

The mean beach profile of the Hasaki Coast (Fig. 5c) is relatively uniform across the profile and shows characteristics of a classic dissipative beach (Short, 2006). However, a gradual decline of profile gradient can be seen in the subtidal zone ($x > 200$ m). The largest standard deviation around the mean profile is seen in the subtidal zone well below low tide level (300 m $< x <$ 450 m) which characterises the highest wave activity in this area. In addition, a large secondary peak can be seen at the crest of the profile ($x < 40$ m) which indicates significant profile change in this area, which is due to aeolian sediment transport processes and the variability of the dune vegetation cover (Kuriyama et al., 2005).

The mean profile shape in Joetsu-Ogata Coast (Fig. 5d) also shows a composite profile with distinctly different gradients at the upper ($x < 50$ m) and lower ($x > 50$ m) part of the profile. This is characterised by the coarse sediment (1-2 mm) found in the upper beach and finer sediment (0.5 mm) found in the lower beach (Baba and Uchiyama, 2001). The profile contains characteristics of an intermediate profile

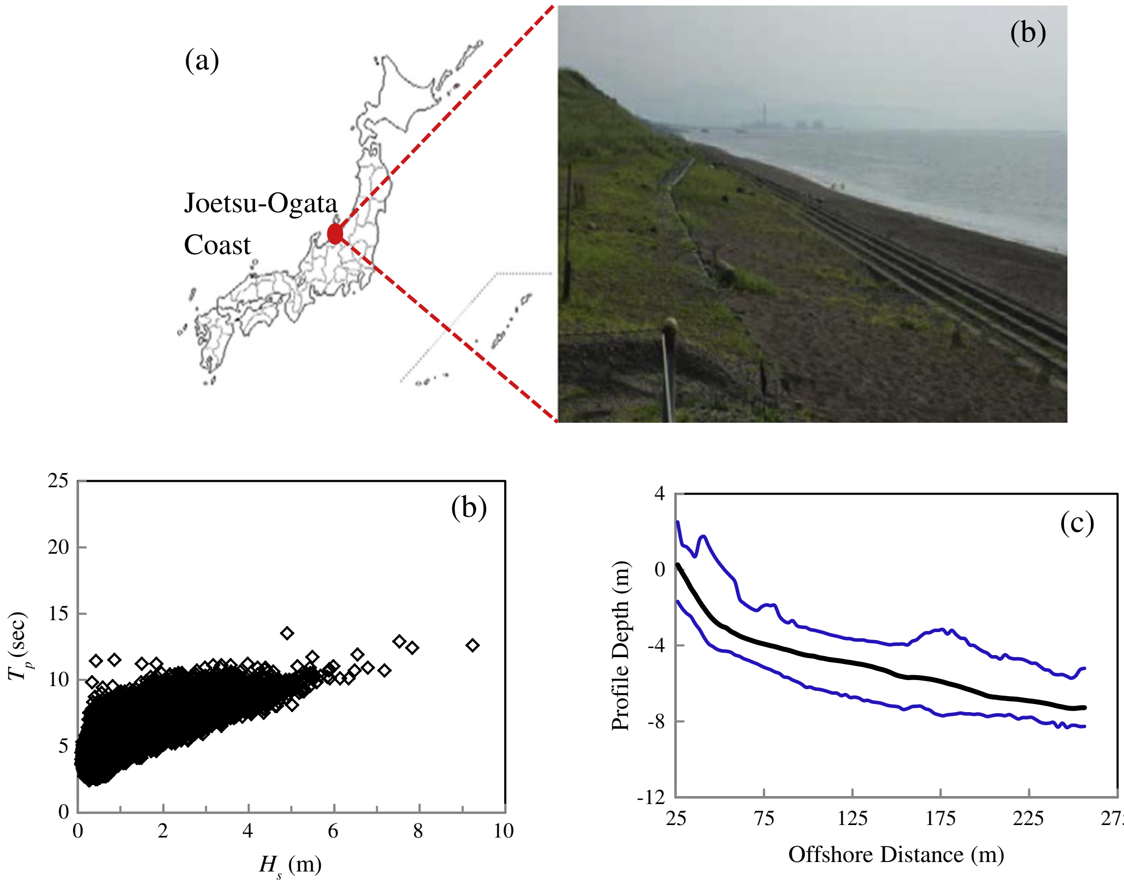


Fig. 4. Joetsu-Ogata Coast, Niigata, Japan. (a) Location and a view of the beach, (b) incident waves measured at a site 5 km from the coast, (c) mean and envelope of measures profiles at OWO observation pier.

with a dissipative lower beach and a reflective upper beach. It is worth noting that the still water line at this site was not marked during field measurements and therefore some ambiguity prevails about the shoreline position. The standard deviation around the mean profile is at its highest between 75 m–200 m cross shore subtidal zone which indicates high wave activity over a wide surf zone. A secondary peak in standard deviation is seen around the still water line, which may be due to the approach of storm waves at the upper beach.

The above analysis shows that the four selected study sites show some distinctly different beach profile characteristics in terms of profile shape and variability.

4. Long term equilibrium profile shape

In this section the morphological nature of the long term equilibrium beach profiles at the four study sites is investigated. Traditionally, empirical equilibrium profile models have been widely used for predicting beach change in the cross-shore direction. Those include Bruun (1954) and Dean (1977, 1991) equilibrium profiles. Dean's equilibrium beach profile (Eq. (1)) provides a relationship between profile change and beach sediment characteristics:

$$h = Ax^n \qquad (1)$$

Where h = profile depth measured with respect to MWL, x = cross-shore distance measured offshore from mean water shoreline, A = profile scale parameter and n = profile shape parameter. By analysing a large number of profile data, mainly from mildly sloping sandy beaches, Dean (1977) found that $n = 2/3$. The profile scale parameter A was determined from Moore's (Moore, 1982; Dean, 1991) relationship, which is the most widely used expression that correlates A and median sediment grain diameter D_{50} (or sediment fall velocity w).

Table 1
A summary of beach characteristics of the four selected study sites.

Beach characteristic	Narrabeen Beach	Milford on Sea Beach	Hasaki Coast	Joetsu-Ogata Coast
D_{50}	0.3–0.4 mm	1.6 mm sand 10 mm gravel	0.18 mm	0.3–1.5 mm
Profile type	• Sandy • Mean slope-composite • Wave dominated	• Sand-gravel composite • Mean slope- steep, composite • Wave/tide dominated	• Sandy • Mean slope-gentle • Wave dominated	• Sandy • Mean slope-composite • Wave dominated
Approximate overall mean profile gradient	1:14	1:10	1:50	1:25
Wave conditions	High energy, frequent storms all year round	Seasonal winter storms, calm in summer	Seasonal storms – sea and swell	Seasonal winter storms, calm in summer
Tide range	Micro tidal Tidal range 1.6 m	Meso tidal Tidal range 2.0 m	Micro tidal Tidal range 1.4 m	Micro tidal Tidal range 0.4 m

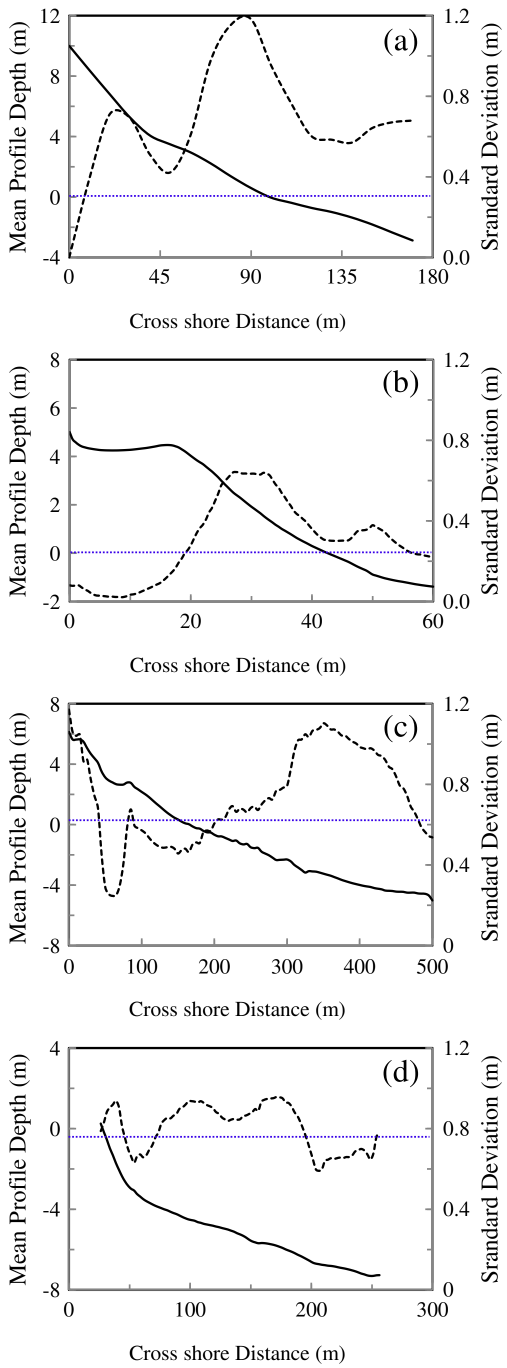


Fig. 5. Time mean beach profiles and standard deviation. (a) Narrabeen Beach, (b) Milford-on-Sea Beach, (c) Hasaki Coast, and (d) Joetsu-Ogata Coast. Blue dotted line shows the mean water line.

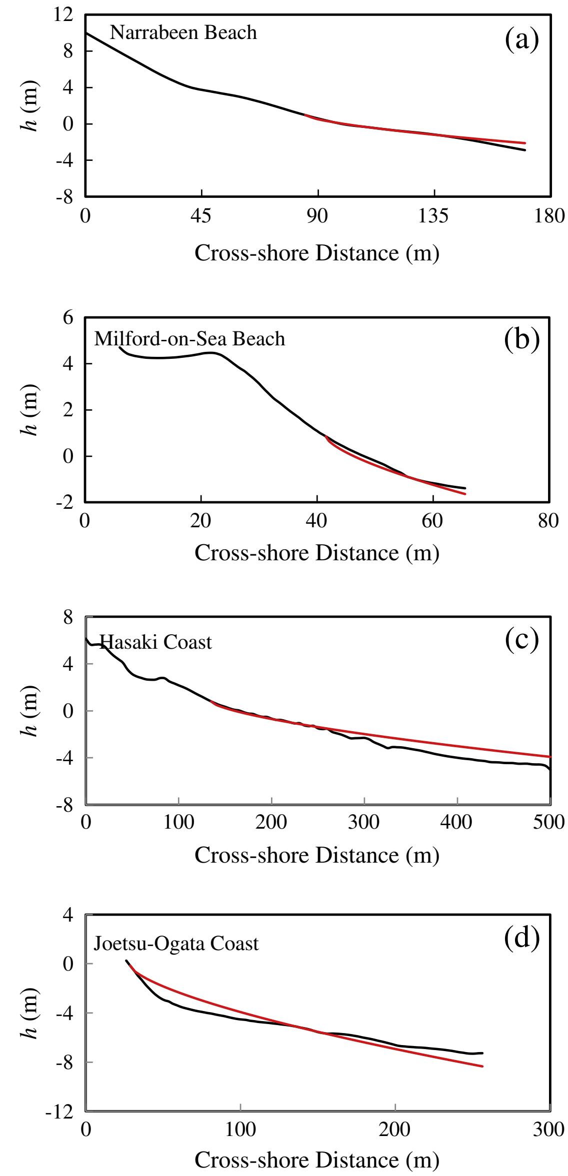


Fig. 6. Comparison of measured mean beach profile and Dean's Equilibrium profile. (a) Narrabeen Beach, (b) Milford-on-Sea Beach, (c) Hasaki Coast, and (d) J-O Coast. Black line – mean profile, red line – Dean's equilibrium profile.

Assuming that beach profile measurements at all four sites are long enough and that the time averaged subaqueous profile closely resembles the long term equilibrium beach profile, here we compare the time beach profiles with Dean's equilibrium profile.

To determine Dean's equilibrium profile for subaqueous Narrabeen Beach, the average D_{50} was taken as 0.35 mm, which gives $A = 0.13$. The mean beach profile at Narrabeen is in good agreement with the Dean's equilibrium profile (Fig. 6a), with root mean square error (RMSE) of less than 5%. This could be expected as intertidal region of the Narrabeen Beach consists of uniformly distributed sediment. This result indicates that Dean's profile can be used to characterise long term subaqueous profile change at Narrabeen Beach.

D_{50} for Milford-on-Sea was taken as 10 mm as sediment sample from the inter-tidal beach contains only 12% sand fraction (Martìn-Grandes - unpublished data). This value thus gives $A = 0.3$. A comparison of subaqueous mean profile and Dean's equilibrium profile for Milford-on Sea (profile 5f00107) is shown in Fig. 6b. It can be seen that the Dean's equilibrium profile model marginally over-estimates the subaqueous mean profile depth with RMSE of 11%. This could be attributed to the fact that Moore's (1982) relationship is based on a uniform grain size to determine profile scale parameter whereas the subaqueous region of the Milford-on-Sea beach consists of sediment with a bimodal distribution with 88% gravel 12% sand. Selection of a single shape parameter for beaches with large cross-shore sediment variability is sub-optimal (Pilkey, 1993). However, despite potential differences between wave energy dissipation on the steep Milford-on-Sea beach and on a gentle slope associated with Dean's profile shape parameter, the overall agreement between mean subaqueous profile shape of Milford-on-Sea beach and the Dean's profile shape is very encouraging.

In Fig. 6c, a comparison of Hasaki Coast mean beach profile with Dean's Equilibrium profile is shown. D_{50} of 0.18 mm (Kuriyama et al. 2008) was used to determine profile shape parameter, which is found to be 0.092. Dean's equilibrium profile model closely resembles the mean subaqueous beach profile of Hasaki Coast above −2 m depth (RMSE 6%) but underestimates below −2 m depth (RMSE ~25%). It may be possible that the sediment grain size in the deeper areas of the beach is smaller than the median grain size thus resulting in profile depths larger than that produced by the Dean's model. The significant differences between the mean profile and Dean's profile in areas deeper than 2 m (maximum of 25%) suggest that the use of Dean's profile to determine long term morphology of the cross-shore profiles at Hasaki Coast should be done with caution, in the absence of a further study on cross shore sediment distribution. However, it should be noted that the local scour around Hasaki Pier from which profile measurememts are taken, may have contributed to profile measurements deeper than 2 m.

The comparison of mean subaqueous profile with the Dean's profile at Joetsu-Ogata Coast is shown in Fig. 6d. $D_{50} = 1.6$ mm is used to determine the profile shape parameters of the Dean's profile, which is found to be 0.26. The overall RMSE between measured a mean profile and Dean's equilibrium profile is around 20% and there are some significant localised differences between the two. Dean's profile underestimates the upper part of the subaqueous profile depth while over-estimate the lower region. This is similar to that found it Milford-on-Sea and may be attributed to the selection of single grain size to calculate the Dean's profile while Joetsu-Ogata Coast has a complex sediment grain size variability across the profile. As a result, Dean's equilibrium profile with single grain size may not be a suitable model to determine long term morphology of Joetsu-Ogata Coast.

The above results indicate that despite its simplicity Dean's equilibrium profile model is suitable to characterise long term subaqueous cross shore morphology when cross-shore sediment distribution is well known and that the model should be used with caution if sediment details are sparse. However, it should be noted that the extent of the surveyed beach widths in all study sites do not cover the entire active beach profile and therefore, the results cannot be verified for the entire active beach profile. It should also be noted that the Dean's model is used here with single grain size and that some discrepancies between measured and Dean's equilibrium profile should be expected.

5. Empirical Orthogonal Function analysis

In this section, beach profiles are analysed using Empirical Orthogonal Functions to investigate spatial and temporal variation of profiles at the four selected study sites. The characteristic variability of profile shape at the four sites are then compared and contrasted through EOFs.

EOF analysis is widely used to investigate patterns in beach variability (e.g. Winant et al., 1975 and Wijnberg and Terwindt, 1995) and other coastal features (e.g. Reeve et al., 2001, 2008; Kroon et al., 2008). The method maps the observed coastal morphological data into a set of shape functions known as eigenfunctions that are determined from the data itself, analogues to Fourier Transformation. For example, the first eigenfunction is equivalent to the time mean computed directly from the data (e.g., Aranuvachapun and Johnson, 1979). The second eigenfunction represents the first 'mode of variation' about the time mean, and so on. When applied to cross-shore beach profiles, it can reveal patterns of variation about the mean profile shape, such as bars and troughs (Reeve et al., 2001; Larson et al., 2003). The cross-shore profile shape is represented as a linear summation of the products of the relevant time and space varying functions:

$$h_{xt} = \sum_{i=1}^{nx} c_i(t).e_i(x) \tag{2}$$

$$c_i(t) = \sum_{j=1}^{n_t} h_{xt}.e_i(x) \tag{3}$$

where h = profile depth and x = distance measured offshore from a reference point on the profile. e_i are spatial orthogonal functions and c_j are corresponding temporal functions respectively, where $i = 1\ldots n_x$ and $j = 1\ldots n_t$. n_x is the number of measurement points in the cross-shore profile. n_t is the number of cross-shore profile surveys.

Each eigenfunction corresponds to a statistical description of the data with respect to how the data variance is concentrated in that function. The functions are usually ranked according to the magnitude of their corresponding eigenvalues which are proportional to the data variance. Typically, a large proportion of the data variance is contained within a small number of eigenvalues and hence, only a limited number of eigenfunctions is needed to explain most of the variation in the measurements (Reeve et al., 2001; Larson et al., 2003, Reeve et al., 2016).

The EOF analysis of beach profiles at all four sites reveals that more than 90% of the data variation is captured by the first five eigenfunctions. Therefore, only the first five eigenfunctions will be used to describe the beach profile change phenomena. We will first investigate spatial empirical orthogonal functions (SEOF). The first spatial eigenfunction (SEOF1) at all sites reflect the mean profile (thick black line in Fig. 7). The primary vertical axis in Fig. 7 corresponds to second and subsequent eigenfunctions while secondary vertical axis corresponds to the first eigenfunction.

In Fig. 7(a), the first five spatial eigenfunctions derived from Narrabeen Beach profiles at Profile 4 are shown. The second eigenfunction (SEOF2) reflects an intertidal beach trough and terrace which distinctly deforms the profile from its mean profile shape. The third eigenfunction (SEOF3) reflects the presence of a sub-tidal bar and a trough. The fourth eigenfunction (SEOF4) implies sediment exchange across the profile, which reflects erosion of the intertidal zone (Wijnberg and Terwindt, 1995). The fifth eigenfunction (SEOF5) may be related to other small scale accumulative-erosive features of the profile which may contribute to deform the profile shape in time. The largest variability of the spatial Eigenfunctions at the Narrabeen Beach is found after 60 m cross-shore location, which covers the lower intertidal and subtidal zones of the profile ($x > 70$ m). Variability of eigenfunctions in the upper shore face (swash region; $x < 60$ m) is significantly smaller than that of the rest of the profile. The bar crest, which is submerged at all times tide is located in the sub-tidal zone. SEOF4, which implies sediment exchange cross the profile, shows offshore sediment transport, which typically happens during storms. As SEOF4 implies, sediment moves from the inter-tidal zone to sub-tidal zone, which may lower the sub-tidal beach at Narrabeen.

Fig. 7(b) shows spatial eigenfunctions determined from Milford-on-Sea beach profiles measured at location 5f00107. SEOF2 reflects the presence of an upper beach ridge while SEOF3 reflects the presence of a sub-tidal bar and a trough. SEOF4 implies sediment exchange between the upper beach and the intertidal zone ($x < 50$ m). SEOF5 corresponds to small scale changes that contribute to deform beach profile shape, similar to that at Narrabeen Beach. The spatial variability of all eigenfunctions at Milford-on-Sea Beach is strongest between 18 m and 40 m cross-shore section of the profile, which covers the entire swash zone and the upper half of the inter-tidal zone. This confirms that the subaqueous (above MWL) beach undergoes the strongest morphodynamic variability. As seen in SEOF3, the bar crest at Milford-on-Sea is located in the inter-tidal zone and therefore can be exposed at low tide. SEOF4, which reflects sediment exchange across the profile,

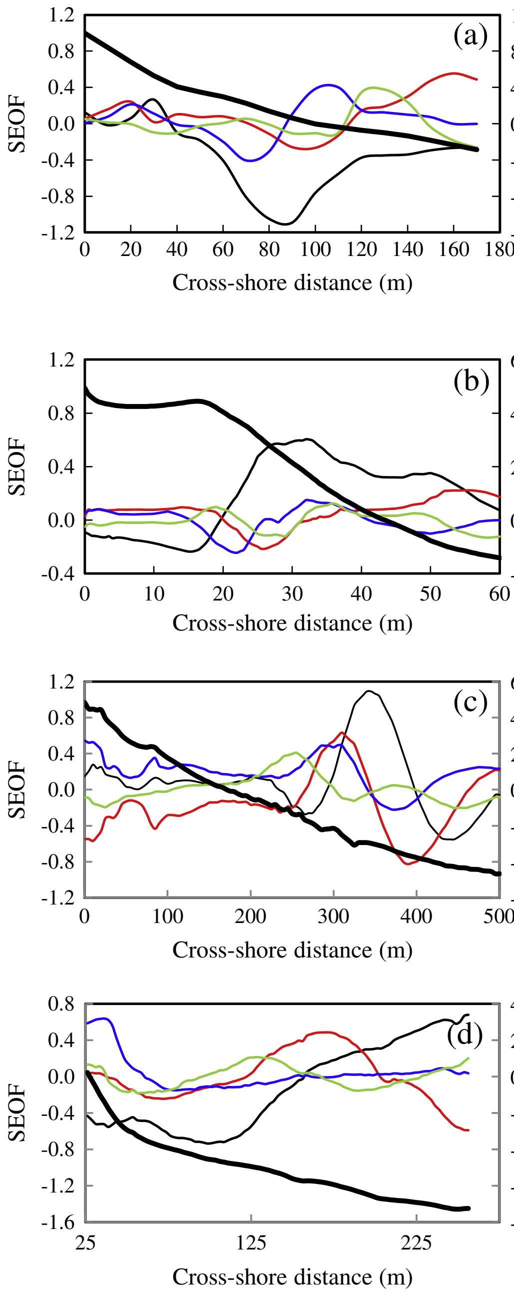


Fig. 7. First five spatial eigenfuntions of beach profiles at four study sites. (a) Narrabeen Beach; (b) Milford-on-Sea beach; (c) Hasaki coast; and (d) Joetsu-Ogata coast. Primary axis corresponds to SEOF2 to SEOF5. Secondary axis corresponds to SEOF1. Dark black line resembles mean profile. Black line SEOF2, red line SEOF3, blue line SEOF4 and green line SEOF5.

shows that in Milford, sediment moves from foreshore to the inter-tidal zone thus eroding the upper beach.

Fig. 7(c) corresponds to spatial eigenfunctions of Hasaki Coast profiles. In this figure, SEOF2 reflects a distinct inter-tidal bar and a trough, which dominates the profile variability. SEOF3, together with SEOF2 indicates sediment exchange, bar migration and erosion of the foreshore area. SEOF4 is also related to the bar however the variability of profile gradient at the upper beach is more prominent in SEOF4. SEOF3 and SEOF4 collectively show bar movement and sediment exchange between different parts of the profile. SEOF5 corresponds to small scale features that change the profile shape. Unlike in the other three beaches, morphodynamics of the bar and trough dominate profile variability where bar movement takes place between 300 m and 400 m cross-shore distance. The bar is mainly confined to the subtidal region. The inter-tidal zone is relatively stable. As EOFs 3 and 4 indicate, the gradient of the shoreface varies with strongest changes seen closer to the beach crest.

In Fig. 7(d), spatial eigenfunctions for Ogata-Joetsu profiles are given. SEOF2 reflects the change in profile gradient at both shore face and intertidal zone of the profile and possibly the development of a sub-tidal ridge. A subtidal bar/berm is reflected in SEOF3. SEOF4 implies sediment exchange across the profile between upper shore face/intertidal zone and subtidal area of the beach. SEOF5 indicates small localised erosion and accretion of the profile, which is not very significant. According to these results, it can be confirmed that the primary causes of beach profile change at Joetsu-Ogata Coast are variability of profile gradient, berm formation and shoreface steepening are. Similar to the observations made at Narrabeen Beach, the spatial eigenfunctions at Joetsu-Ogata Coast are largest in the subtidal zone ($x > 125$ m). The swash and upper surf zones of the profile (25 m $< x <$ 75 m) also show significant amount of profile variability. The shape of SEOF3 suggests that there may be a subtidal bar, which remains submerged at all times. This is similar to that observed at Narrabeen Beach. Cross-shore sediment exchange shown in SEOF4 reveals shoreward sediment movement and steepening of beach face but, seaward advance of the intertidal beach, which is a unique an interesting feature of this beach.

In order to investigate the morphodynamic change of beach profiles in time, we then investigated temporal eigenfunctions (TEOF). TEOFs show how the corresponding spatial eigenfunctions vary in time thus indicating temporal trends of morphodynamic change. The results are shown in Fig. 8. It should be noted that the first temporal EOF (TEOF1) is approximately constant at all sites as it corresponds to the time-averaged cross-shore beach profile. Furthermore, TEOF5 at all four sites does not show any structure. Therefore, both TEOF1 and TEOF5 are not shown in Fig. 8.

Fig. 8a shows TEOFs at Narrabeen Beach. In TEOF2, which corresponds to inter-tidal trough and terrace a clear 3–5 year cyclic signal is visible. However, a weak, high frequency (~3–6 months) variability can also be seen. In TEOF3, which corresponds to subtidal bar and trough, a dominant 3–6 monthly cyclic signal and a long term upward trend which indicates a long term accretion of the bar, can also be seen. TEOF4, which corresponds to intertidal-subtidal sediment exchange, also shows a 3–6 months cyclic variability however, an underlying strong1–1.5 year cyclic signal can also be seen in some sections of the time series. Subsequent TEOFs do not show any significant structure apart from the high frequency signal at the timescale of the data resolution.

Fig. 8b corresponds to Milford-on-Sea Beach. The second temporal EOF (TEOF2) at Milford-on-Sea, which corresponds to upper beach ridge, exhibits a gradual decline over time. This indicates long term beach recession due to degradation of the upper beach ridge. No seasonal signature is evident, may partly be due to the relatively low temporal resolution of data. The TEOF3, which is related to subtidal bar and trough, shows some evidence of a 5–6 year scale variability. A weak 1 year cyclic signal can be seen in some parts of TEOF3 and TEOF4 however, the low temporal resolution of the dataset does not allow any investigations of beach variability at short term timescales. Subsequent TEOFs do not show any significant structure.

Fig. 8c shows TEOFs derived from beach profiles at Hasaki Coast. TEOF2 shows a cyclic signature of around one year period indicating alternate bar growth and decay and a slight upward trend indicating net accretion. Furthermore, 4–5 month cyclic signal is also apparent in TEOF2. TEOF3, together with TEOF2 corresponding to bar movement, shows a cyclic signal of around the same period as that of TEOF2 indicating cyclic on-offshore bar movement. TEOF3 shift from predominantly positive values between 1987 and 1992 to predominantly negative values between 1993 and 1997, which indicates a shift in net sediment transport direction. Although some evidence of a 1 year cyclic signal is

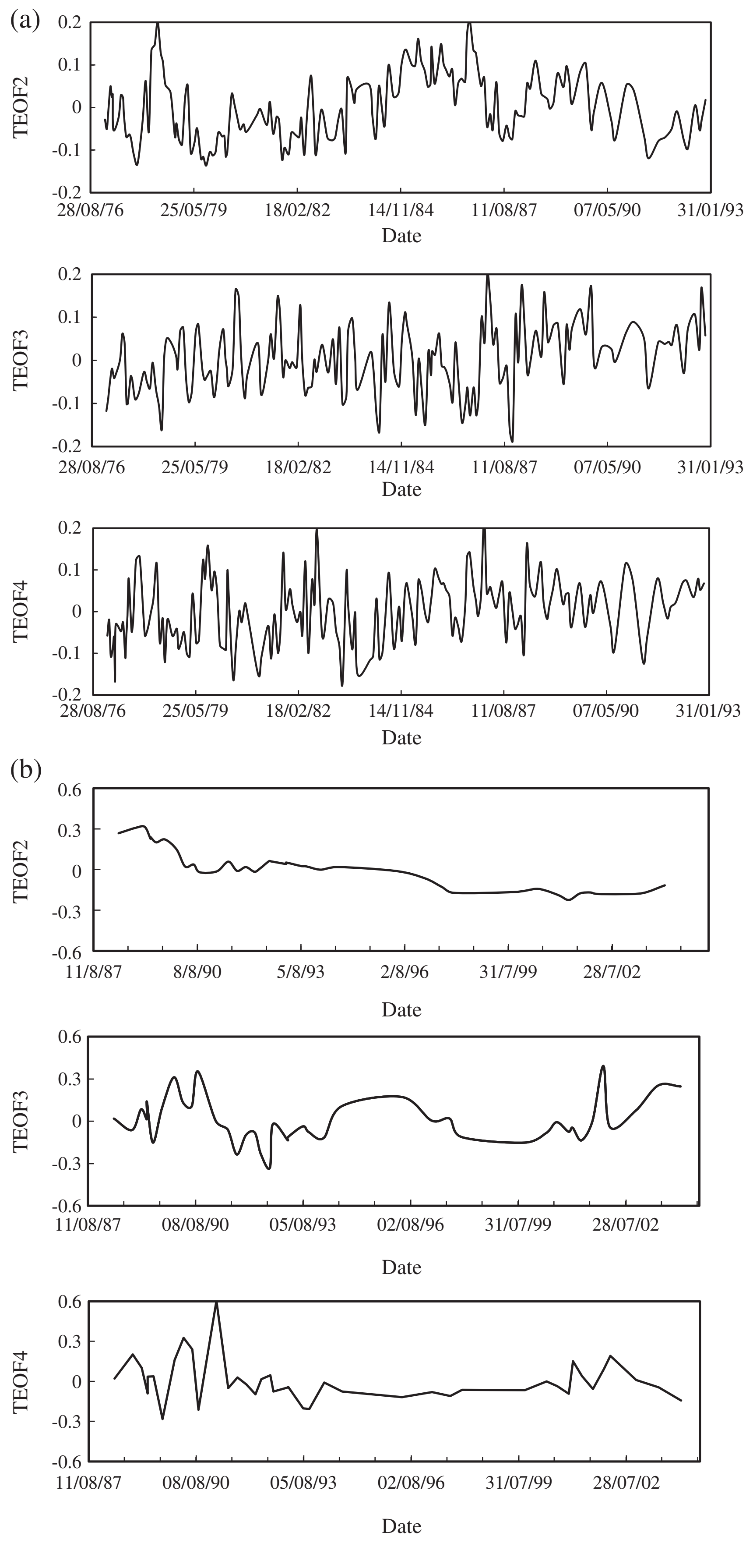
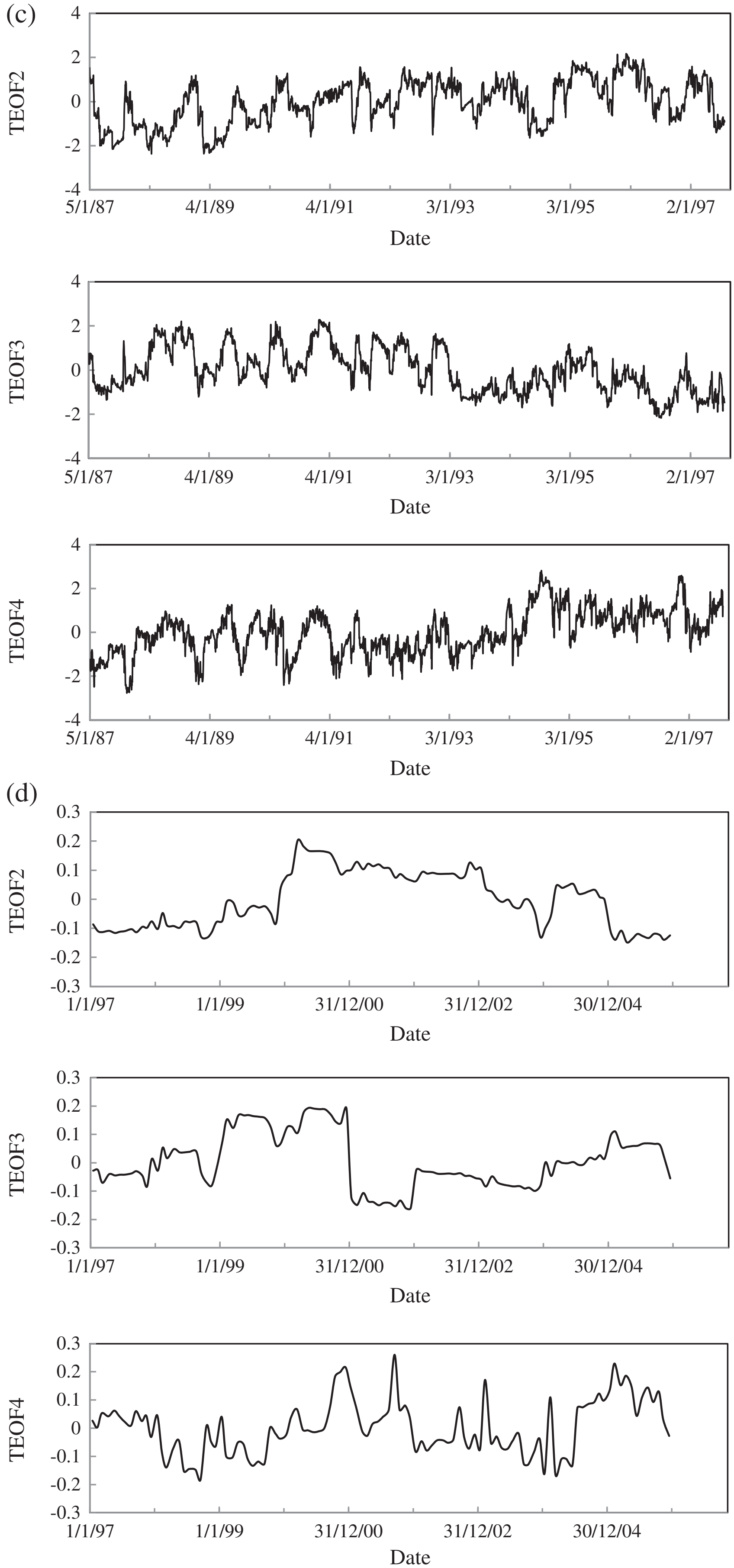


Fig. 8. a. Temporal EOFs of Narrabeen Beach profiles at Profile 4. b. Temporal EOFs of Milford-on-Sea Beach profiles at Profile 5F00107. c. Temporal EOFs of Hasaki Coast profiles at Hazaki Pier. d. Temporal EOFs of Joetsu-Ogata Coast profile.


(c)
TEOF2
TEOF3
TEOF4
4
2
0
-2
-4
5/1/87
4/1/89
4/1/91
3/1/93
3/1/95
2/1/97
Date
(d)
TEOF2
TEOF3
TEOF4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
1/1/97
1/1/99
31/12/00
31/12/02
30/12/04
Date

visible in TEOF4, which corresponds to upper beach gradient, an upward trend is more prominent.

In Fig. 8d, TEOFs for Joetsu-Ogata coast are shown. TEOF2, which corresponds to the variability of the profile gradient, shows a positive gradient until 2000 and a negative gradient afterwards. This is an indication of the beach having a gently sloping cross-shore profile until 2000 and steepening of the profile thereafter, which correctly captures the trend observed at the beach. In addition, a high frequency cyclic signal of approximately 4–5 months and 1 year can also be seen. TEOF3, which represents subtidal berm, shows a positive gradient from 1997 to 2000 followed by a steep negative gradient in 2000 and then a positive gradient until 2005 which resembles the gradual subtidal bar growth, sudden erosion and re-growth. An underlying annual cycle can also be seen throughout TEOF3. This behaviour coincides with the profile variability between three different beach states, observed when annual average profiles were analysed (not shown). In TEOF4, which is related to shoreface steepening, an approximately 4 monthly cyclic variability and a longer term periodic signal are clearly visible. However, the profile data set is not long enough to confirm the periodicity of the long term trend. TEOF5 (not shown) primarily shows a high frequency variability.

6. Discussion

Despite the differences in incident wave climate, sediment composition and other local conditions of the four beaches studied, there are some significant similarities as well as differences between beach behaviours. Even though all four beaches characterise one or multiple intertidal/subtidal bars, the mean profiles of all four beaches were fairly uniform. However, Milford-on-Sea and Joetsu-Ogata beaches show distinct reflective composite profile shapes where beach profile variability is dominated by the development and decay of an upper beach ridge while variability of Narrabeen and Hasaki profiles are dominated by a subtidal bar and a trough.

At Narrabeen Beach, bar-trough variability does not show any long term trend and is only a response to short term changes in wave climate. On the other hand in Joetsu-Ogata Coast, a long-term variability is seen underlying the short term variability of the bar. In Hasaki Coast, the bar-trough variability is more prominent at annual scale, a time period shorter than any of the climate variabilities that operate in South-Pacific Ocean. In Milford-on-Sea Beach, 5–6 year scale variability can be seen even though the available data length is not long enough to comment on it further.

All beaches show sediment exchange between different sections of the profile (SEOF4). In Narrabeen Beach and Joetsu-Ogata Coast, sediment exchange takes place predominantly between inter-tidal and subtidal zones. On the other hand in Milford-on-Sea and Hasaki, most sediment exchange takes place between the upper shoreface and the intertidal zones. The dominant timescale of sediment exchange at Narrabeen is short-term. However, changes at timescales shorter than one month cannot be investigated using the monthly measured beach profile surveys. In contrast, in Milford-on-Sea and Joetsu-Ogata, longer term (3–6 years) changes are more prominent. At Hasaki, a long term trend is more prominent even though some evidence of short-term and inter-annual scale processes can also be seen.

To investigate potential relationships between characteristics of beach profile variability shown by EOFs at the four sites and incident wave conditions, spectral analysis of incident wave height time series was carried out. The results are shown in Fig. 9. Spectral peaks of wave heights observed at the four sites are given in Table 2.

In the Narrabeen Beach wave height spectrum, significant peaks are seen at 1 year, 1.6 years and 3.9 years. Wave height spectra at Milford-on-Sea Beach, Hasaki Coast and Joetsu-Ogata Coast are somewhat similar. All of them have the highest spectral peak at 1 year. Two other significant peaks are seen at 4–5.5 years and 4–5 months. 4–5.5 year spectral peaks observed in wave height data in Narrabeen, Hasaki and Joetsu-Ogata sites coinciding with the 4–5 year cycles of El Niño-La Niña Southern Oscillation (ENSO) driven Southern Oscillation Index (SOI) during the corresponding periods of wave measurements (Fig. 10a) (Ranasinghe et al., 2004; Harley et al., 2011). 5.5 year spectral peak observed at Milford-on-Sea wave height data coincided with 5–5.5 year cyclic signal observed in North Atlantic Oscillation (NAO) index during 1989 and 1999 (Visbeck et al., 2001; http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml) which controls the direction and intensity of storms in the Atlantic (Fig. 10b).

Variabilities observed in TEOFs at 4–5 year timescales and wave height spectral directly peaks corresponding to that time period show notable correlations where some features of the beach profiles followed the variability of incident wave climate at different timescales related to local weather patterns and inter-annual scale climatic variations. For example, the long term cyclic variability of growth and decay of intertidal terrace in Narrabeen Beach profile (TEOF2) had similar period to that of the wave spectral peak at 4 years. The 1–1.5 year cycles of inter-tidal sediment exchange (TEOF4) corresponds to the peak of the wave height spectra at 1.6 years which may be determined by local weather patterns operates in the Narrabeen region. The 4–5 year variability is likely to be associated with the long term changes in the incident wave climate driven by ENSO related climatic variations in the South Pacific Ocean (You and Lord, 2006). Therefore, we conclude that some specific features of the Narrabeen Beach profile follow climatic variability of the incident wave climate whereas some follow local, shorter-term variations associated with local weather fronts.

Similar observations are made at other three beaches too. In Milford-on-Sea, TEOF3 and TEOF4 (Fig. 8b) of the profiles which relate to subtidal bar-trough and sediment exchange respectively show a weak 1 year cyclic signal. The highest wave height spectral peak at Milford-on-Sea also occurred at 1 year, which may correspond to intense winter waves. Therefore, enough evidence is seen to conclude that variability of beach profile features other than upper beach ridge (TEOF2) correlates with winter-summer variability of the incident wave climate. However, limited data availability and resolution restricts further investigations of these features. In TEOF3, the 5–6 year variability coincides with the wave height spectral peak observed at 5.5 years and hence with the NAO periodicity. Therefore, the bar-trough movement at Milford-on-Sea may be related to the incident wave climate variability driven by NAO.

A cyclic signal with approximately 1 year period is seen in all TEOFs of the Hasaki beach profiles. The highest wave height spectral peak is also at 1 year period. Therefore, it is apparent that most significant profile features of Hasaki change as a result of annual scale incident wave climate variability. However, TEOF2 and TEOF4, which are related to bar-trough and upper beach gradient, show long term upward trends indicating gradual long term bar growth and steepening of the upper beach respectively. Even though the length of the data used in this study is not sufficient to conclude the nature of sediment exchange in this beach, the negative (1987–1992)/positive (1993–1998) shift of TEOF3 which is linked to sediment transport direction may be linked with the SOI as well (mostly positive between 1987 and 1992 and mostly negative between 1993 and 1998).

In Joetsu-Ogata Coast, 4–5 year variability of TEOF2 (beach profile gradient), TEOF3 (sub tidal berm) and TEOF4 (intertidal-subtidal sediment exchange) closely matches with 5 year wave spectral peak, which is associated with the SOI. In addition, TEOF4 shows 1 year cycles, which may be related to annual change in wave climate.

Profile shape of coarse grain or composite beaches (Milford-on-Sea and Joetsu-Ogata) is governed by the changes in the upper beach whereas the profile shape of sandy beaches is dominated by bar-trough variability. Sediment exchange is common to all beaches. However, the magnitudes and the locations of exchange is very site specific. No obvious relationships between sediment exchange and beach type or wave climate were found. Timescales of variability of different profile features depend on the incident wave climate. When the incident wave climate is driven by local climatic variabilities, profile response is strongly linked

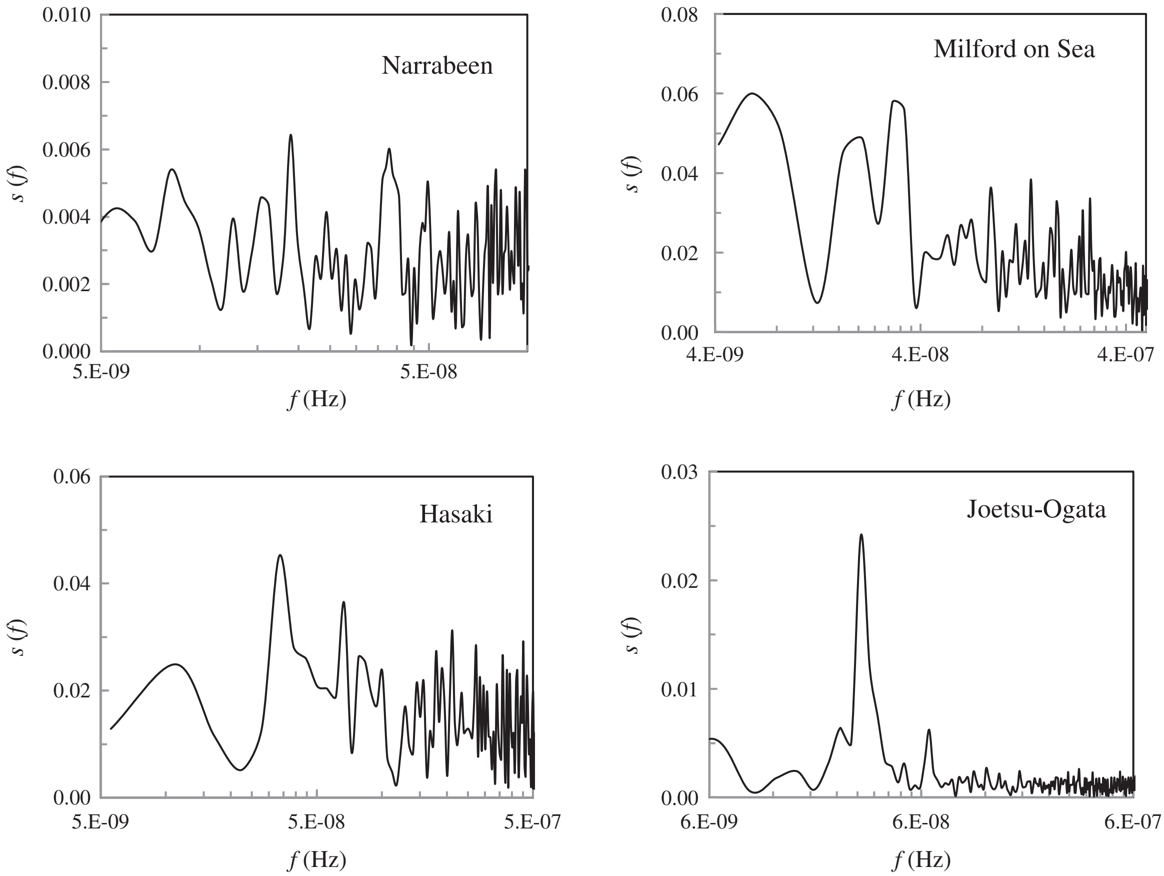


Fig. 9. Spectra of incident wave heights at four study sites.

to the timescale of the climatic variability (Milford-on-Sea, Hasaki and Joetsu-Ogata) However, if local weather fronts dominate the incident wave climate then more short term profile shape changes can be seen (Narrabeen). Different profile zones respond differently to incident waves in all beaches. In steeper beaches supratidal zone of the beach is most active (Milford-on-Sea, Joetsu-Ogata) while in sandy beaches inter-tidal zone found to be the most active part of the profile (Narrabeen, Hasaki). Overall, cross-shore profile change is determined by the profile shape and sediment characteristics however, a significant amount of site-specific variation was found in all study sites.

7. Conclusions

This study aimed to compare and contrast cross-shore morphodynamic behaviour of four distinctly different beaches at a range of timescales and investigating potential relationships between their variability and incident wave climate. The selected sites span a wide parameter range in relation to sediment size, incident wave climate and tidal variations. A range of analysis methods are used to analyse long term measurements of cross-shore beach profiles and wave measurement at the four sites. The main conclusions arising from the analysis are listed below:

- Despite complex site specific morphological features present at the individual sites, the time-averaged profile at all four sites fall into either reflective, intermediate or dissipative states defined by Short et al. (2006).
- In general, Dean (1991)'s equilibrium profile model is able to describe the long term average profile at all four sites. However, deviations were found in certain sections of the profiles. This may be due to variability of sediment characteristics across the profile, which is not taken into account when determining Dean's profile.
- Spatial variability of profile features at the four sites shows some similarities and distinct differences. Although Milford-on-Sea Beach and Joetu-Ogata Coast have distinctly different tidal regimes and sediment characteristics, the profile shape variability of both beaches is dominated by morphodynamics of the upper beach ridge. Similarly, irrespective of the differences in mean beach slope and sediment size, the profile change at Narrabeen Beach and Hasaki Coast is dominated by the movement of inter-tidal/sub-tidal bar.
- The dominant timescale of profile change at Narrabeen Beach is short term (several months). At Hasaki Coast, inter-annual scale dominates profile change. At Milford-on-Sea Beach and Joetsu-Ogata Coast, annual scale changes dominate morphodynamic variability while some long term trends are also seen.
- The timescales of profile change at all four beaches show some correlations with the variability of incident wave climate which in turn may be linked to regional climatic variations such as SOI and NAO.
- All four beaches show evidence of cross shore sediment exchange. At Milford-on-Sea Beach and Hasaki Coast, primary sediment exchange takes place between upper shore face and inter tidal zone. At

Table 2
Significant spectral peak of the wave height spectra at four study sites.

Site	Spectral peaks
Narrabeen Beach	4.6 years, 1.6 years, 1 year
Milford-on-Sea Beach	5.5 years, 1 year, 4 months
Hasaki Beach	3.9 years, 1 year, 5 months
Joetsu-Ogata Coast	5 years, 1 year, 4 months

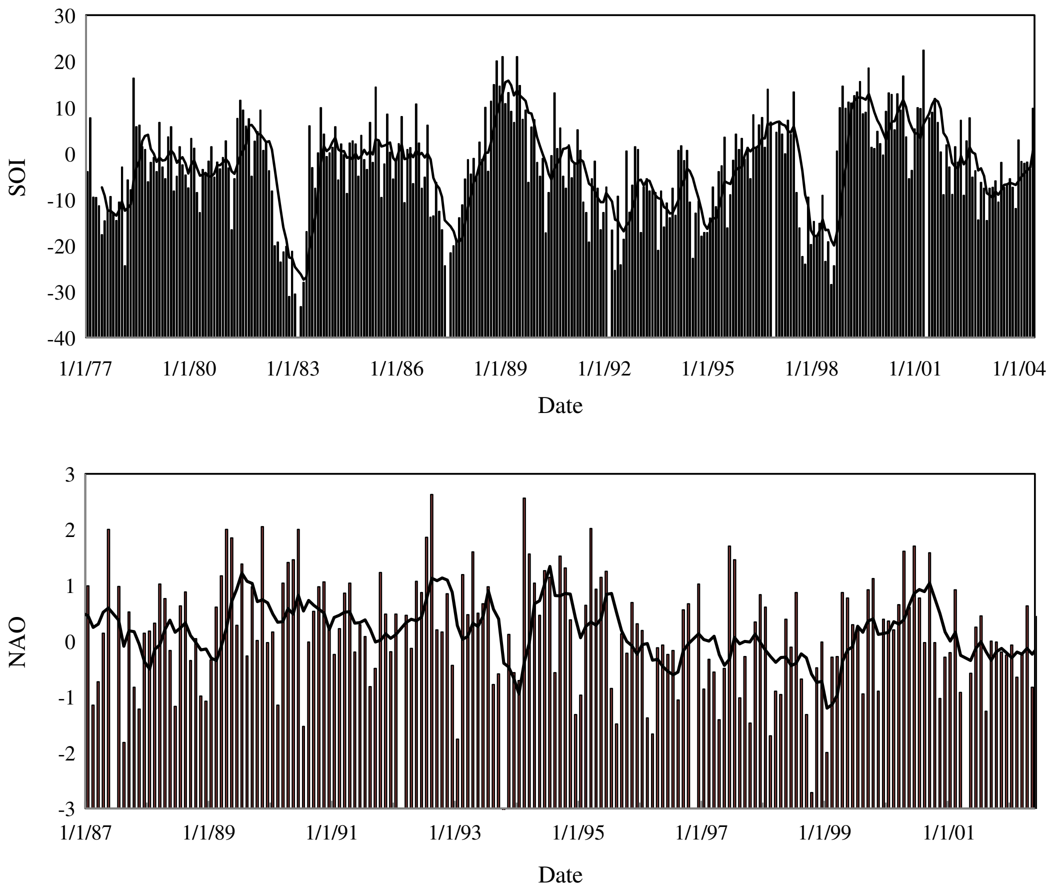


Fig. 10. (a) ENSO driven monthly Southern Oscillation Index during 1977 and 2004 (http://www.bom.gov.au/climate/current/soihtm1.shtml) (top). North Atlantic Oscillation (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao_index.html) (bottom). (Black line- 6 monthly moving average).

Narrabeen Beach and Joetsu-Ogata Coast it is between inter tidal and sub tidal zones.

The beach measurement frequency and the length of the data set at some study sites do not allow reinforcement of certain observations. This highlights the importance of frequent and long term field measurements programmes which will significantly contribute to better understanding of beach behaviour.

Acknowledgements

HK wishes to acknowledge UK Channel Coastal Observatory and Prof. Andrew Short at University of Sydney for providing beach profile measurements for Milford-on-Sea and Narrabeen Beaches respectively, EPSRC funded FloodMEMORY project (EP/K013513/1) and Disaster Prevention Research Institute of Kyoto University for providing financial support. HK and DER also acknowledge NERC funded iCOASST project (NE/J005428) for partially funding this research. HM wishes to thank Mr. Kiyoshi Uchiyama, who was responsible for profile measurements at Joetsu-Ogata coast. The Ministry of Land, Infrastructure, Transport and Tourism measured the offshore waves at Hasaki and the Marine Information Group of the Port and Airport Research Institute analysed the raw beach profile data. RR is supported by the AXA Research Fund and the Deltares Harbour, Coastal and Offshore Engineering Research Programme *'Bouwen aan de Kust'*.

References

Aranuvachapun, S., Johnson, J.A., 1979. Beach profile at Gorleston and Great Yarmouth. Coast. Eng. 2, 201–213.
Baba, Y., Uchiyama, K., 2001. Temporal Variations of Bottom Profile and Sediment Along An Observation Pier, 34th IAHR World Congress. Brisbane, Australia.
Banno, M., Kuriyama, Y., 2014. Prediction of Future Shoreline Change with Sea Level Rise and Wave Climate Change at Hasaki, Japan. Proc. Int. Conf. In Coastal Eng, Seoul, South Korea.
Bodge, K.R., 1992. Representing equilibrium beach profiles with an exponential expression. J. Coast. Res. 8, 47–55.
Bruun, P., 1954. Coast Erosion and Development of Beach Profiles Technical Memorandum No. 44 Beach Erosion Board.
Bruun, P., 1962. Sea level rise as a cause of shore erosion. J. Waterw. Harb. Div., ASCE 88, 117–130.
Callaghan, D.P., Nielsen, P., Short, A.D., Ranasinghe, R., 2008. Statistical simulation of wave climate and extreme beach erosion. Coast. Eng. 55 (5), 375–390.
Callaghan, D.P., Ranasinghe, R., Roelvink, D., 2013. Probabilistic estimation of storm erosion using analytical, semi-empirical, and process based storm erosion models. Coast. Eng. 82, 64–75. http://dx.doi.org/10.1016/j.coastaleng.2013.08.007.
Carter, J.D., 1986. Discussion: gravel beach profile characterisation and discrimination. J. Coast. Res. 1 (2), 129–139.
Carter, R.W.G., Orford, J.D., 1993. The morphodynamics of coarse clastic barriers and beaches: a short and long term perspective. J. Coastal Res. 15, 158–179.
Coco, G., Senechal, N., Rejas, A., MacMahan, J.H.M., 2014. Beach response to sequence of Extreme storm. Geomorphology 204, 493–501.
de Algeria-Arzaburu, R., Williams, J.J., Masselink, G., 2011. Application of XBeach to model storm response on a macrotidal gravel barrier. In: Smith, J.K., Lynnet, P. (Eds.), Proceedings of 32nd International Conference in Coastal Engineering, Shanghai, China.
Dean, R.G., 1977. Equilibrium Beach Profiles, US, Atlantic and Gulf Coasts, Department of Civil Engineering Ocean Engineering Report No. 12. University of Delaware, Delaware.
Dean, R.G., 1991. Equilibrium beach profiles: characteristics and applications. J. Coast. Res. 7 (1), 53–84.
Ferreira, O., 2005. Storm groups versus extreme single storms: predicted erosion and management consequences. J. Coast. Res. Spec. Issue 42, 221–227.
Hallermeier, R.J., 1981. A profile zonation for seasonal sand beaches from wave climate. Coast. Eng. 4, 253–277.
Harley, M.D., Turner, I.L., Short, A.D., Ranasinghe, R., 2011. A re-evaluation of coastal embayment rotation: the dominance of cross-shore versus alongshore sediment transport processes, Collaroy-Narrabeen Beach, SE Australia. Journal of Geophysical Research, Atmospheres. http://dx.doi.org/10.1029/2011JF001989.

Horrillo-Caraballo, J.M., Reeve, D.E., 2008. An investigation of the link between beach morphology and wave climate at Duck, North Carolina, USA. Journal of Flood Risk Management 1 (2), 110–122.
Horrillo-Caraballo, J.M., Reeve, D.E., 2010. An investigation of the performance of a data-driven model on sand and shingle beaches. Mar. Geol. 274, 120–134.
Inman, D.L., Elwany, M.H.S., Jenkins, S.A., 1993. Shorerise and barberm profiles on ocean beaches. J. Geophys. Res. 98 (n. C 10), 18181–18199.
Karunarathna, H., Horrillo-Caraballo, J.M., Ranasinghe, R., Short, A.D., Reeve, D.E., 2012. An analysis of the Cross-Shore Beach morphodynamics of a Sandy and a composite Gravel Beach. Mar. Geol. 299–302. http://dx.doi.org/10.1016/j.margeo.2011.12.011 pp. 33-42.
Karunarathna, H., Pender, D., Ranasinghe, R., Short, A.D., Reeve, D.E., 2014. The effects of storm clustering on beach profile variability. Mar. Geol. 348, 103–112.
Karunarathna, H., Ranasinghe, R., Reeve, D.E., 2015. A Hybrid Beach morphology model applied to a high energy Sandy Beach. Ocean Dyn. 65, 1411–1422. http://dx.doi.org/10.1007/s10236-015-0884-0.
Kroon, A., Larson, M., Moller, I., Yokoki, H., Rozynski, G., Cox, J., Larroude, P., 2008. Statistical analysis of coastal morphological datasets over seasonal to decadal timescales. Coast. Eng. 55, 581–600.
Kuriyama, Y., 2002. Medium-term bar behaviour and associated sediment transport at Hasaki, Japan. J. Geophysical Res. 107 (C9), 3132. http://dx.doi.org/10.1029/2001JC000899.
Kuriyama, Y., Mochizuku, N., Nakashima, T., 2005. Influence of vegetation on aeolian sand transport rate from a backshore to a foredune at Hasaki, Japan. Sedimentology 52, 1123–1132.
Kuriyama, Y., Ito, Y., Yanagishima, S., 2008. Medium-term variations of bar properties and their linkages with environmental factors at Hasaki, Japan. Mar. Geol. 248, 1–10. http://dx.doi.org/10.1016/j.margeo.2007.10.006.
Kuriyama, Y., Banno, M., Suzuki, T., 2012. Linkages among interannual variations of shoreline, wave and climate at Hasaki, Japan. Geophys. Res. Lett. 39, L06604. http://dx.doi.org/10.1029/2011GL050704.
Larson, M., Kraus, N.C., 1989. SBEACH: Numerical model for simulating storm-induced beach change, Report 1: Empirical foundation and model development. Technical Report CERC-89-9, US Army Engineer Waterways Experiment Station. Coastal Engineering Research Center, Vicksburg, MS.
Larson, M., Kraus, N.C., 1994. Temporal and spatial scales of beach profile change, Duck, North Carolina. Mar. Geol. 117, 75–94.
Larson, M., Kraus, N.C., Wise, R.A., 1999. Equilibrium beach profiles under breaking and non-breaking waves. Coast. Eng. 36, 59–85.
Larson, M., Capobianco, M., Hanson, H., 2000. Relationship between beach profiles and waves at Duck, North Carolina, determined by Canonical Correlation Analysis. Mar. Geol. 163, 275–288.
Larson, M., Capobianco, M., Jensen, H., Rozynski, G., Southgate, H.N., Stive, M., Wijnberg, K.M., Hulscher, S., 2003. Analysis and modelling of field data on coastal morphological evolution over yearly and decadal time scales, part 1: background and linear techniques. J. Coast. Res. 19 (4), 760–775.
Lee, G.-H., Nicholls, R.J., Birkemeier, W.A., 1998. Storm driven variability of the beach-nearshore profile at Duck, North Carolina, USA, 1981-1991. Mar. Geol. 148, 163–177.
Martin Grandes, I., Hughes, J.P., Simmonds, D.J., Reeve, D.E., 2009. Novel methodology for one line model calibration using impoundment on a mixed beach. Coastal Dynamics 2009, Tokyo, Japan.
Mase, H., Yamashita, T., Hayashi, K., 1990. Wave Group Properties of Coastal Waves, 22nd Int. Conf. in Coastal Eng, Delft, The Netherlands.
McCall, R.T., Masselink, G., Poate, T.G., Rolevink, J.A., Almeida, L.P., 2015. Modelling morphodynamics of gravel beaches during storms with XBeach-G. Coast. Eng. 103, 52–66.
Moore, B.D., 1982. Beach Profile Evolution in Response to Change in Water Level and Wave Height MSc Thesis Department of Civil Engineering, University of Delaware.
Niodoroda, A.W., Reed, C.W., Swift, D.J.P., Arato, H., Hoyanagi, K., 1995. Modelling shore-normal large scale coastal evolution. Mar. Geol. 126, 181–199.
Pedrozo-Acuna, A., Simmonds, D.J., Otta, A., 2006. On the cross-shore profile change of gravel beaches. Coast. Eng. 53 (4), 335–347.
Pender, D., Karunarathna, H., 2013. A statistical-process based approach for modelling beach profile variability. Coast. Eng. 81, 19–29.
Pilkey, O.H., Young, R.S., Riggs, S.R., Smith, A.W., Pilkey, W.D., 1993. The concept of shore profile of equilibrium: a critical review. J. Coastal Research 9 (1), 255–278.
Pontee, N.I., Pye, K., Blott, S.J., 2004. Morphodynamic behaviour and sedimentary variation of mixed sand and gravel beaches, Suffolk, UK. J. Coast. Res. 20 (1), 256–276.
Ranasinghe, R., McLoughlin, R., Short, A., Symonds, G., 2004. The southern oscillation index, wave climate and beach rotation. Mar. Geol. 204, 273–287.
Reeve, D.E., Li, B., Thurston, N., 2001. Eigenfunction analysis of decadal fluctuations in sandbank morphology at Great Yarmouth. J. Coast. Res. 17 (2), 371–382.
Reeve, D.E., Horrillo-Caraballo, J.M., Magar, V., 2008. Statistical analysis and forecasts of long-term sandbank evolution at Great Yarmouth, UK. Estuar. Coast. Shelf Sci. 79, 387–399.
Reeve, D., Karunarathna, H., Pan, S., Horrillo-Caraballo, J.M., Różyński, G., Ranasinghe, R., 2016. Data-driven and hybrid coastal morphological prediction methods for meso-scale forecasting. Geomorphology 256, 49–67.
Roelvink, D., Reniers, A., van Dongeren, A., de Vries, J.T., McCall, R., Lescinski, J., 2009. Modelling storm impacts on beaches, dunes and barrier islands. Coast. Eng. 56, 1133–1152.
Short, A.D., 1985. Rip current type, spacing and persistence, Narrabeen Beach, Australia. Mar. Geol. 65, 47–71.
Short, A.D., 2006. Australian beach systems – nature and distribution. J. Coast. Res. 22 (1), 11–27.
Short, A.D., Trembanis, A.C., 2004. Decadal scale patterns in beach oscillation and rotation Narrabeen beach, Australia-time series, PCA and wavelet analysis. J. Coast. Res. 20 (2), 523–532.
Short, A.D., Wright, L.D., 1981. Beach systems of the Sydney region. Aust. Geogr. 15, 8–16.
Standing Conference on Problems Associated with the Coastline – SCOPAC, 2003i. Sediment transport study. Hengistbury Head to Hurst Spit. http://www.Scopac.org.uk/scopac%20sediment%20db/chrst/chrsttxt.pdf (Accessed March 2010).
Stive, M.J.F., de Vriend, H.J., 1995. Modelling shoreface profile evolution. Mar. Geol. 126, 235–248.
Vellinga, P., 1983. Predictive computational model for beach and dune erosion during storm surges. Proc. Coastal Structures, ASCE, Washington D.C.
Vellinga, P., 1984. A tentative description of a universal erosion profile for sandy beaches and rock beaches. Coast. Eng. 8 (Issue 2), 177–188.
Visbeck, M.H., Hurrel, J.W., Polvani, L., Cullen, H.M., 2001. The North Atlantic Oscillation: past, present and future. Proc. Natl. Acad. Sci. U. S. A. http://dx.doi.org/10.1073/pnas.231391598.
Wijnberg, K.M., Terwindt, J.H.J., 1995. Extracting decadal morphological behaviour from high-resolution, long-term bathymetric surveys along the Holland coast using eigenfunction analysis. Mar. Geol. 126, 301–330.
Williams, J.J., de Alegría-Arzaburu, A.R., McCall, R.T., van Dongeren, A., 2012. Modelling gravel barrier profile response to combined waves and tides using XBeach laboratory and field results. Coast. Eng. 63, 62–80.
Winant, C.D., Inman, D., Nordstrom, C.E., 1975. Description of seasonal beach changes using empirical eigenfunctions. J. Geophys. Res. 80 (15), 1979–1986.
You, Z.-J., Lord, D., 2006. Influence of El Nino-Southern Oscillation on NSW coastal storm severity. J. Coast. Res. http://dx.doi.org/10.2112/06-0690.1.