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Understanding and predicting the temporal variability of sediment grain size characteristics on high-energy beaches

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ABSTRACT

Despite representing a key parameter when modelling morphology or sediment transport, surface sediments are often assumed homogenous, with grain size temporally constant. This contribution uses a 6-year data set of monthly sediment samples to quantify the observed variability in intertidal beach sands at four energetic, macrotidal locations (North Cornwall, UK). Changes in grain size and sorting were related to periods of high-steepness storm waves promoting a relatively rapid coarsening and an improvement in sorting and low-steepness swell waves, a fining and a reduction in sorting. These temporal changes in intertidal grain size were coherently linked to the disequilibrium in wave steepness, with peak coarsening occurring when the instantaneous wave steepness conditions vastly exceeded a temporally evolving antecedent time series. Using this concept, a simple model is proposed that provides skilful predictions of the unseen variability in sediment grain size (average $r^2 = 0.86$, $p < 0.01$) and sorting (average $r^2 = 0.75$, $p < 0.05$), at all four sites.

1. Introduction

Sandy beaches are abundant worldwide; they provide a natural coastal defence by dissipating high-energy storm waves and are an important socio-economic resource. The coastal zone represents a highly energetic and dynamic environment, where the beach slope and morphology continually attempt to reach equilibrium with the changing hydrodynamic conditions. Grain size and sediment sorting are two key textural parameters used to describe beach sands (Folk, 1966). There have been many studies relating these parameters to beach slope (Dean, 1973; Mclean and Kirk, 1969), morphology (Masselink and Short, 1993; Scott et al., 2011) and sediment transport (Masselink et al., 2005; Mclaren and Bowles, 1985). Beach morphology (Baptista et al., 2014; Masselink and Pattiaratchi, 2001), sandbar location (De Santiago et al., 2013; Stokes et al., 2015), aeolian sand dune accumulation (Sherman and Bauer, 1993; Wal and Mcmanus, 1993) and sediment transport pathways (Curran et al., 2015; Larson and Kraus, 1995) have all been shown to be highly variable across a variety of temporal scales. However, studies of the long-term temporal evolution of the sediment characteristics associated with these changes are lacking. Instead, sediments are often assumed to be well sorted and homogenous in both size and composition, with grain sizes remaining fixed in space and time. Additionally, characterisation of sediments is generally based on physical samples that are limited in terms of temporal coverage (Hanson and Kraus, 1989; Nielsen, 2002; Turki et al., 2013).

A number of recent studies have shown there to be significant variations in sediment characteristics across a number of temporal and spatial scales. Holland and Elmore (2008) showed that generalising complexity in terms of simplified descriptions (e.g. a single D_{50} value, where D_{50} is the median particle size by mass) was insufficient in capturing the influence of many coastal sediments. Gallagher et al. (2011), presented evidence that large spatial variations in beach face grain size of the order of 0.2–0.7 mm were possible over 10–100 m and Gujar et al. (2011) found that local and seasonal environmental conditions both produced substantial changes in beach morphology and sediment characteristics. There have also been recent advances in the sediment transport modules of models such as Delft3D (Yang et al., 2013) and XBeach (Roelvink et al., 2010), which can simulate some limited short-term temporal changes in sediment properties (Villaret et al., 2013). However, the capability to capture such variations consistently over seasonal/annual time-scales is not currently possible.

This paper investigates the magnitude of the observed temporal variability in sediment characteristics, whether this variability is significant in terms of nearshore morphodynamics and sediment transport and whether the variability is predictable.

2. Site descriptions and data collection

Monthly sediment samples have been collected at four (Perranporth, Porthtowan, Chapel Porth and Gwithian) (Fig. 1) energetic, macrotidal (mean spring range 6.5 m) beaches on the north coast of Cornwall, UK (Scott et al., 2009) since 2008. These beaches all face west/northwest towards the Atlantic Ocean and are exposed to the prevailing westerly winds. Like many beaches that face the open ocean, they

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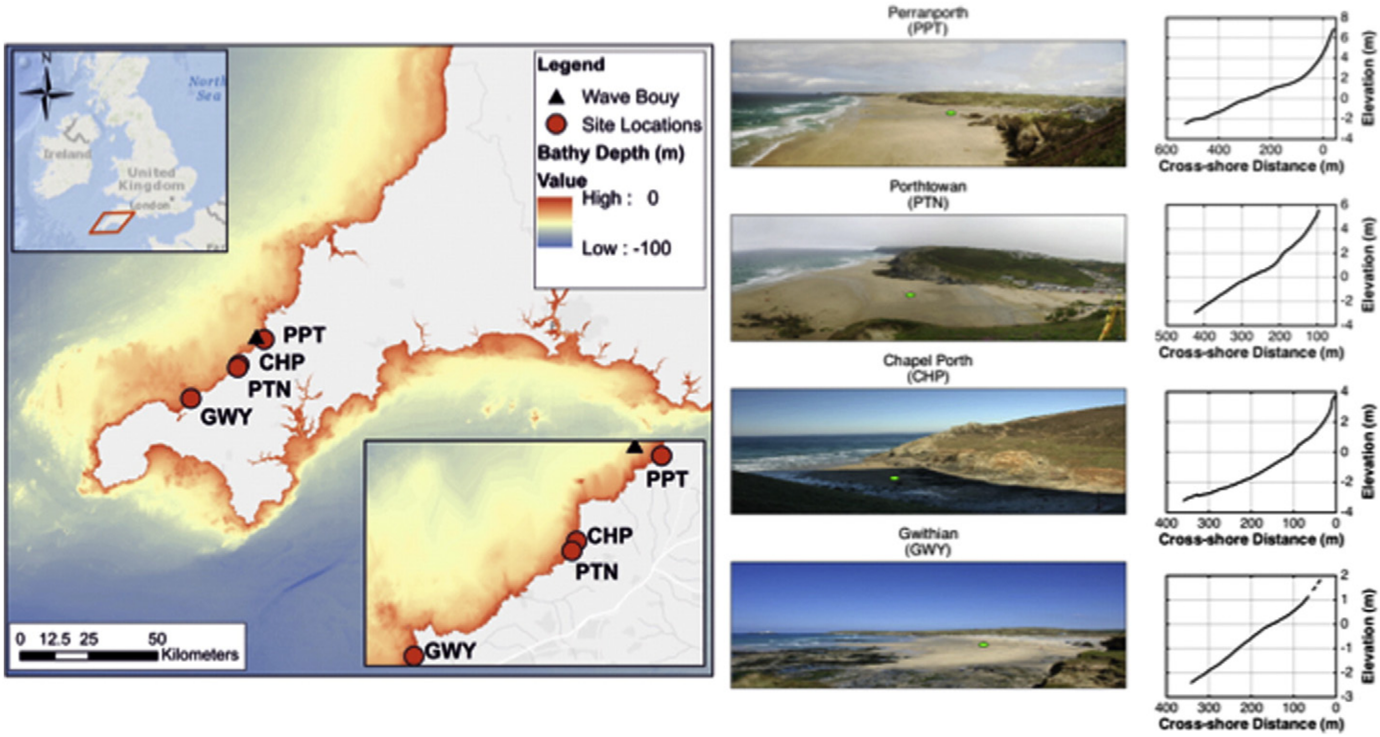

Fig. 1. *Left*) The location of the four study sites on the Northwest coast of Cornwall (UK) and the nearshore wave buoy, 1 Km offshore from Perranporth in ~16 m water depth. A Centre) Panoramic photo of each site taken from the south looking north, green circle denotes the mid-tide sediment sampling point. *Right*) Mean alongshore-averaged profile plots from each site. Cross-shore distance increases in the offshore direction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

therefore receive a wide variety of low steepness swell waves and high steepness wind waves.

With a full spring to neap cycle occurring every two weeks, sampling occurred on the lowest spring low tide for the month, which was deemed sufficient to capture both the short- and long-term variability in sediment grain size. The data presented here are 'surface' samples from the upper 0.02 m of the sediment column collected at consistent mid-tide positions, located by RTK-GPS, on the linear part of the beach profile, away from the three-dimensional rip and bar topography that is sometimes present towards spring low-tide. Spring high-tide positions were similarly avoided as they receive no wave action on neap tides. Simultaneous monthly topographic surveys were also carried out at the beaches. The sites are all comprised of medium quartz sand with time-averaged median grain sizes (D_{50}) over the 6-year study period of 0.33 mm at Perranporth, 0.43 mm at Chapel Porth, 0.37 mm at Porthtowan and 0.30 mm at Gwithian.

The beach morphological classification of each site varies between Low-Tide Bar/Rip and Dissipative (Scott et al., 2011). There is a strong seasonality in incident wave conditions, with average summer and winter significant wave heights of 1.2 m and 2.7 m respectively and maximum wave heights exceeding 9 m. Each site is a natural, open coast beach with a shore normal wave approach, where the storm/swell cycle drives cyclic sediment movement in onshore and offshore directions, with no significant net longshore component to the sediment transport (Masselink and Russell, 2006). Each site is backed by Quaternary aeolian sand dunes, composed of quartz sediment that is slightly finer than the intertidal beach sand.

Statistics from the monthly sediment samples were quantified using the settling tube approach of Folk and Ward (1957), with sediment fall velocity converted to median grain size (D_{50}) using the Ferguson and Church (2004) method. Each sample was passed through the settling tube on five occasions, with a D_{50} resulting from the average of these five tests. If the standard deviation of the five runs exceeded 0.01 mm (0.5% of sample size) then the analysis was repeated until the standard deviation was <0.01 mm.

Monthly data is available from 2008 to 2014 for Perranporth and Porthtowan and 2008 to 2010 for Chapel Porth and Gwithian, with 485 separate grain size samples collected by hand during 207 separate field visits. Sampling frequency was increased to bi-monthly between December 2013 and February 2014 in order to capture the variation caused by a number of extreme storms.

Samples were collected from the same mid-tide position (±0.5 m horizontally) each visit, identified using an RTK-GPS. Significant wave height (H_s), peak period (T_p) and direction were recorded every 30 min from a nearshore wavebouy (50.35379°N, 5.17497°W, in 16 m water depth, 1.4 km west of Perranporth), with all four sites exposed to similar energetic offshore wave conditions (Poate et al., 2009). The breaking wave height (H_b) was estimated using the simple equation proposed by Komar and Gaughan (1972), where:

$$H_b = 0.39\, g^{1/5} \left(T_p H_s^2\right)^{2/5}. \tag{1}$$

Here, g is the acceleration due to gravity (9.82 ms^{-2}). T_p is the peak wave period (s) and H_s the significant wave height (m), which both came from the wave buoy.

3. Results

3.1. Observed temporal variations in surface grain characteristics (size, sorting and distributions)

In order to investigate the overall temporal variation in grain size, the D_{50} values from the same month at each site were averaged together to give the typical annual variation in grain size at each site (Fig. 2). There is a clear seasonal cycle with the finest sediments typically present in the summer months (June to September) and the coarsest in the winter months (January to February), commensurate with persistent periods of low steepness swell waves and high-steepness storm waves respectively.

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