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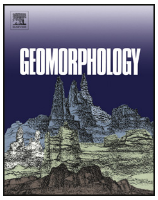

Application of marine radar to monitoring seasonal and event-based changes in intertidal morphology

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ABSTRACT

This paper demonstrates the application of marine radar and a newly developed waterline mapping technique to the continued surveillance and monitoring of inter- and intra-annual intertidal morphological change, thus capturing new detail on coastal system behaviours. Marine radar data from 2006 to 2009 are used to create a sequence of waterline elevation surveys that show clear morphological evolution of two different sites in the Dee estuary, UK. An estimate of volumetric change was made at two locations: West Hoyle sandbank and the NW Wirral beach. Both sites exhibited a similar cyclic pattern of volumetric change, with lowest volumes in autumn and winter, respectively. The average beach elevations above Admiralty Chart Datum clearly reflect the observed change in sediment volume, with reduced elevations in winter and increased elevations in summer, suggesting a trend of high-energy storm waves in autumn and winter that remove sediment and simultaneously moderate the vertical dimension of bedforms in the intertidal area. Data at this temporal and spatial scale are not easily obtainable by other current remote sensing techniques. The use of marine radar as a tool for quantifying coastal change over seasonal and event timescales in complex hydrodynamic settings is illustrated. Specifically, its unique application to monitoring areas with dynamic morphology or that is vulnerable to erosion and/or degradation by storm events is exemplified.

1. Introduction

1.1. Research context and aims

The coast is temporally and spatially dynamic, with the constant action of waves, wind, currents and tides serving to reshape its physical nature over relatively short geological timescales (Mason et al., 2010). The processes and impacts of morphological change across a gamut of spatial and temporal scales have been studied extensively, and many are well documented (Wright and Short, 1984; Cowell and Thom, 1994). Several examples of these studies include sandy beach (e.g., Johnson et al., 2014; Senechal et al., 2015) and gravel beach response to storms (e.g., Ruiz de Alegria-Arzaburu and Masselink, 2010) in addition to long term, extensive area studies of coastal morphological response to natural and anthropogenic forcing (e.g., Hapke et al., 2010). Changes in the physical environment often have considerable consequences for human populations and biota in close proximity to the coastline. The density and concentration of human population and infrastructure assets are increasing continuously (Nicholls et al., 2011). Additionally, resources in these areas are finite and in many places at risk of degradation and overuse. It is vital, therefore, that the overall health and stability of these increasingly vulnerable areas are monitored, along with their morphological response to further human development and natural processes including storm events (Tătui et al., 2014; Castelle et al., 2015; Dissanayake et al., 2015). The research presented here aims to better capture and understand the morphological behaviours of the estuary-beach interface over a multiple season timescale and to examine the sensitivity and recovery of the associated intertidal beach in response to storms. The purpose of this paper is to demonstrate how recent advances in radar-based monitoring techniques can be applied to better constrain coastal system behaviours resulting from complex geomorphic interactions in time and space. The resulting data sets provide an effective evidence base for the prediction and tracking of coastal morphological changes in response to a variety of forcings.

1.2. Modelling and monitoring for assessing the vulnerability of coastal areas

Traditionally, coastal defence construction has focused on damage mitigation and protection of vulnerable, high value assets and infrastructure (including extensive residential areas) from flooding and coastal erosion through extensive hard engineering. Examples of these

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structures negatively affecting the coast and causing increased erosion or undesirable sediment accretion (Kraus, 1988; Gillie, 1997; Phillips and Jones, 2006; Ilić et al., 2007) are numerous, and such developments can act as barriers to natural shoreline adjustments (Dugan et al., 2008; Berry et al., 2014) thus causing intertidal zones to be squeezed out (Doody, 2004; De Vriend et al., 2011). Soft engineering approaches and working with natural processes (European Commission, 1999; McKenna et al., 2008) maintain coastlines through the monitoring and nurturing of dune systems, saltmarshes, tidal flats (Arkema et al., 2013), and dissipative beaches through recharge and nourishment schemes (Hanson et al., 2002; Stive et al., 2013; Wengrove and Henriquez, 2013). Continued pressure on the coastline from erosion and sea level rise (Wahl et al., 2011; Hanley et al., 2014; Kirshen et al., 2014; Wadey et al., 2014) demands that the response of natural and 'engineered' coastal morphological systems to changing forcing factors is modelled and monitored effectively over appropriate timescales.

Coastal engineers and managers often depend on the results of modelling efforts for projecting shoreline response. However, conceptualizing and modelling changes in coastal morphology is particularly challenging over mesoscale (decadal) timescales that lie between the dynamic instantaneous, short-term process and the long-term coastal evolutionary dynamics (Clarke et al., 2014; French et al., 2015; Payo et al., 2015; van Maanen et al., 2016). Nearshore topographic-bathymetric data are required to drive and validate models used at the foreshore, for example, coastal hydrodynamic and morphological models such as Xbeach (Roelvink et al., 2009) and Xbeach-G (Masselink et al., 2014) are capable of modelling sediment transport (McCall et al., 2015) in addition to profile response.

In addition to modelling, various methods of in situ and remote sensing are utilised to monitor the nearshore zone. Remote sensing techniques are increasing in popularitiy because of their many advatanges over insitu methods (Holman and Haller, 2013). Synthetic Aperture Radar (SAR) and multispectral and optical satellite images can be used to map coastal change on large scales using sequential images and tidal models (Koopmans and Wang, 1994; Mason et al., 1995, 1999; Annan, 2001; Mason and Garg, 2001; Ryu et al., 2002, 2008; Heygster et al., 2010; Liu et al., 2013). Site-specific survey platforms include manual DGPS and TLS surveys (Blenkinsopp et al., 2010; Brodie et al., 2012; Almeida et al., 2013; Almeida et al., 2015) and, more recently UAV/drone systems (Mancini et al., 2013; Rovere et al., 2014). Video camera analysis is widely used in the observation of nearshore processes, including the derivation of hydrodynamics and topography (Holman and Guza, 1984; Holman et al., 1993; Holland et al., 1997; Aarninkhof et al., 2003, 2005; Davidson et al., 2007; Holman and Stanley, 2007; Uunk et al., 2010; Sobral et al., 2013; Santiago et al., 2013); and infrared cameras are able to operate in low light conditions to observe hydrodynamics in the nearshore zone (Jessup et al., 1997; Watanabe and Mori, 2008).

Standard marine navigation radar can be used to create image data appropriate for use in coastal monitoring. The fine spatial resolution (3–10 m depending on range setting) and unique interaction between radar-emitted EM waves and a rough sea surface (Valenzuela, 1978) allow numerous critical nearshore hydrodynamic phenomena to be observed and measured. Marine radar is ideally suited to observing wave fields and has been used extensively to derive wave spectra (Reichert et al., 1999; Nieto-Borge and Guedes Soares, 2000) based on techniques pioneered by Young et al. (1985). There are a number of approaches to determining and filtering these wave spectra to extract wave and current statistics (Nieto-Borge et al., 2004, 2008; Senet et al., 2001, 2008; Hessner et al., 2008; Serafino et al., 2010, 2012). In this respect, Bell et al. (2012) successfully determined and mapped surface currents around the island of Eday off the north-eastern coast of Scotland. Subtidal water depths can also be estimated based on the observed wave behaviour, which allows nearshore bathymetric maps to be created (Bell, 1999, 2008; Bell et al., 2006; Flampouris et al., 2009; Bell and Osler, 2011). Previous researchers have mapped shoreline positions using marine radar by imaging the waterline in the spatial domain and describing beach contour levels using time-stamped time exposure images and a record of tidal elevation (e.g., Takewaka, 2005). This technique was also used to observe morphological change at a river mouth (Takewaka et al., 2009). The ability to robustly map intertidal zone elevations on a pixel-by-pixel basis without the need to consistently observe wave fields (Bell et al., 2016) adds to the capability of marine radar in coastal monitoring. This paper expands on previous research by demonstrating its application to monitoring changing intertidal morphology over the multiseasonal timescale.

2. Methodology

2.1. Data collection and study site description

Data used in this contribution were gathered for the *Liverpool Bay Coastal Observatory* over 2005–2009 (Bell, 2008) using a *Kelvin Hughes* marine radar operating at X-band, 9.4 GHz located in an elevated position (~25 m aMSL) on Hilbre Island, at the mouth of the Dee estuary, UK (Fig. 1). The radar waterline survey method used to generate results shown in this paper will be briefly described in the following section along with a description of its application to the observation of seasonal trends in morphology along the Wirral coastline and within the sandbanks of the Dee estuary.

The morphology of the Dee and nearby Mersey estuaries have changed significantly over the last few centuries (e.g., Marker, 1967), and regular dredging is required to maintain the deepwater navigation channel that cuts through Salisbury Bank to the southwest into Mostyn port and out into the Irish Sea via the Welsh Channel or 'Wild Road' as it is known locally.

The Dee estuary exhibits flood-dominated tidal asymmetry and is a mature, infilled estuary approaching morphological equilibrium (Moore et al., 2009). The Dee has long been a sediment sink and has experienced continued expansion of saltmarsh since at least 1900 (cf. Rahman and Plater, 2014). In addition, mobile sedimentary bedforms within the outer estuary and mouth may still be encroaching on channels and tidal inlets, with the potential to cause a navigation hazard (e.g., Demirbilek and Sargent, 1999) and change the topographical distribution of the estuary significantly. This is of particular concern within the Dee estuary where critical wing components for the Airbus A380 "Superjumbo" passenger jet are ferried to Mostyn port before being shipped to mainland Europe for final assembly.

Hydrodynamics in the Dee estuary are extremely varied; waves in the eastern Irish Sea are fetch limited with significant wave heights of <5.5 m and mean periods of <8 s. However, the very high tidal range of >10 m on high spring tides exposes a large expanse of intertidal area that is influenced by the actions of waves and tides across an area of several square kilometres at low tide in the estuary mouth. More detailed analysis of the Dee estuary and Liverpool Bay hydrodynamics can be found in Bolaños and Souza (2010), Bolaños et al. (2011), Wolf et al. (2011), and in Thomas et al. (2002) for an assessment of historical morphological change and resulting hydrodynamic regime change.

2.2. Radar-based intertidal topographical survey methodology

Marine radar "snapshot" images (generated every 2.4 s) are temporally averaged over 10 min, creating a series of time exposure images (Fig. 2) taken every hour throughout 2006–2008. These images are analysed in 2-week blocks such that the full spring-neap period is observed.

When these images are viewed in sequence, the spatial location of the waterline can clearly be seen migrating across the image space according to the rise and fall of the tide. The higher pixel intensity results from greater amounts of microwave energy being reflected from the breaking waves in the surf zone. Surface roughness, and therefore image pixel intensity, is determined by wind speed (Valenzuela, 1978), direction (Dankert et al., 2003; Dankert and Horstmann, 2006),