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SHORT COMMUNICATION

Remote sensing of intertidal morphological change in Morecambe Bay, U.K., between 1991 and 2007.

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Abstract

Tidal Flats are important examples of extensive areas of natural environment that remain relatively unaffected by man. Monitoring of tidal flats is required for a variety of purposes. Remote sensing has become an established technique for the measurement of topography over tidal flats. A further requirement is to measure topographic changes in order to measure sediment budgets. To date there have been few attempts to make quantitative estimates of morphological change over tidal flat areas. This paper illustrates the use of remote sensing to measure quantitative and qualitative changes in the tidal flats of Morecambe Bay during the relatively long period 1991 – 2007. An understanding of the patterns of sediment transport within the Bay is of considerable interest for coastal management and defence purposes. Tidal asymmetry is considered to be the dominant cause of morphological change in the Bay, with the higher currents associated with the flood tide being the main agency moulding the channel system. Quantitative changes were measured by comparing a Digital Elevation Model (DEM) of the intertidal zone formed using the waterline technique applied to satellite Synthetic Aperture Radar (SAR) images from 1991-4, to a second DEM constructed from airborne laser altimetry data acquired in 2005. Qualitative changes were studied using additional SAR images acquired since 2003. A significant movement of sediment from below Mean Sea Level (MSL) to above MSL was detected by comparing the two Digital Elevation Models, though the proportion of this change that could be ascribed to seasonal effects was not clear. Between 1991 and 2004 there was a migration of the Ulverston channel of the river Leven north-east by about 5km, followed by the development of a straighter channel to the west, leaving the previous channel decoupled from the river. This is thought to be due to independent tidal and fluvial forcing mechanisms acting on the channel. The results demonstrate the effectiveness of remote sensing for measurement of long-term morphological change in tidal flat areas. An alternative use of waterlines as partial bathymetry for assimilation into a morphodynamic model of the coastal zone is also discussed.

Keywords: remote sensing, hydrodynamic equations, temporal variations, water level measurement, U.K., Morecambe Bay.

1. Introduction

Tidal Flats such as those of the European Wadden Sea are present at various locations around the world, and are important examples of extensive areas of natural environment that remain relatively unaffected by man. Monitoring of tidal flats is required for a variety of purposes, including coastal defence, navigation, fishing, survey of wildfowl habitats and salt marshes, and tourism.

Remote sensing has become an established technique for the measurement of topography over tidal flats, due in no small part to its synoptic nature. While ground and ship surveys may be able to achieve high height accuracies, these are laborious and time-consuming to perform over the large areas involved. The remote sensing techniques most commonly employed over tidal flats are airborne LiDAR (Light Detection And Ranging) (Flood and Gutelius, 1997; Stockdon et al., 2002; Deronde et al., 2006), airborne InSAR (Interferometric Synthetic Aperture Radar) (Greidanus et al., 1999; Wimmer et al., 2000) and the waterline method (Collins and Madge, 1981; Koopmans and Wang, 1995; Mason et al., 1995; Niedermeier et al., 2005; Kim et al., 2007; Zhao et al., 2008; Ryu et al., 2008; Heygster et al, in press). Because of the cost over large areas and the logistical difficulties of flying at low tide, airborne methods are normally used to survey narrower beaches. The waterline method applied to satellite images remains of importance for the topographic mapping of large areas of tidal flats, partly because of its relatively low cost (Mason et al., 2000). The term waterline is used to denote the water's edge, which moves to and fro as the tides rise and fall. The method involves finding the geo-coded positions of the waterline in a remotely sensed image using image processing techniques. Predicted water elevations at the waterline are superimposed on these positions. These elevations may be predicted using a hydrodynamic tide-surge model run for the area for the time of acquisition of the image, with the weather conditions pertaining at the time. From multiple images obtained over a range of tidal conditions, a set of heighted waterlines can be assembled in the intertidal zone, and from this a gridded Digital Elevation Model (DEM) can be interpolated.

In addition to topographic mapping, a further requirement is to measure topographic changes over tidal flats occurring during a certain period in order to measure sediment budgets. Ryu et al. (2008) point out that as yet there have been few attempts to make quantitative estimates of morphological change over large tidal flat areas (e.g. Mason et al., 1999; Ryu et al., 2008). This paper illustrates the use of remote sensing to measure quantitative and qualitative changes in the tidal flats of Morecambe Bay (fig. 1) during the relatively long period 1991–2007. Morecambe Bay is a macro-tidal embayment in north-west England containing the largest single area of intertidal zone in Britain (340km^2). The intertidal area is very dynamic, and changes in the positions of many subtidal channels and sandbanks are apparent even over a single season. An understanding of the patterns of sediment transport within the Bay is of considerable interest. The Cumbria Coastal Study (SMP, 1991) lists a number of areas of concern around the Bay regarding coastal management and defence issues. For example, shoreward movement of the Kent channel near Morecambe can make it easier for waves to travel up the channel and access the coastline, increasing urban flood risk in Morecambe. Whilst many problems appear to be localized, previous studies accept that the cause is unlikely to be purely local and that it is necessary to adopt a more holistic view of processes and sediment movement within the Bay.

(Fig. 1 about here)

Mason et al. (1999) studied intertidal sediment transport in Morecambe Bay over the period 1992-7 using the waterline method. It was apparent that there was substantial intertidal sediment transport over this period. This led on to attempts to model the sediment transport (Mason and Garg, 2001; Scott and Mason, 2007), in the latter paper by assimilating partial bathymetry from waterlines into the morphodynamic model run to keep the model 'on track' and improve its ability to predict future sediment transport. The advantages of performing data assimilation within a morphodynamic model run are currently being studied further, and this has led to the acquisition of a good deal of modern-day intertidal bathymetry. Whilst the separation in time is too large and the intermediate data too sparse for the two periods to be linked by morphodynamic modelling using assimilation, it was felt that useful information could be obtained by comparing the modern intertidal bathymetry with that from the early 1990s. The evolution of the low-water channels could be studied over a 16-year period, perhaps allowing the detection of discernable patterns. The intertidal sediment budget over the period could also be estimated quantitatively. These are the objectives of this short communication. In practical terms, at present this is probably almost the longest time period over which intertidal morphological change can be measured quantitatively at this site using remote sensing. The low rate of acquisition of suitable images from visible band sensors due to frequent cloud cover over the Bay, coupled with the rapidity with which morphological change can occur, mean that it is unlikely that an accurate DEM of the intertidal zone could be produced using the waterline method prior to the launch of the ERS-1 SAR sensor in 1991.

2. Study area

Morecambe Bay is an estuary which serves as an interface between the open sea and its four primary feeder rivers, the Kent and Leven in the north and the smaller Lune and Wyre in the south. Intertidal sand and mud banks form the dominant coastal landforms in the Bay, representing 68% of its total area, with the remainder being composed of large subtidal channels and saltmarsh. A detailed description of the Bay, including its tide and wave climates and sediment composition, has been given in (Mason et al., 1999), and only a summary is presented here.

The Bay has a large ordinary spring tidal range of about 8.2m at Morecambe. The duration of the semi-diurnal ebb and flood tides are unequal, with the ebb running for about 40 minutes longer that the flood at Heysham (Coomber and Hansom, 1994). In the large subtidal channels, the spring tide attains a maximum velocity of about 1.5ms^{-1}, with currents being higher on the flood than the ebb. The wave climate of the area is dominated by smaller waves, as wave sizes are limited by the restricted fetch due to the sheltering landmasses of Ireland, the Isle of Man and spits at the mouth of the Bay. The sediments in the intertidal zone are predominantly composed of very fine and fine sand

(0.06-0.2mm), with coarser sand and fine gravel at the mouth of the Bay and silts in the inner Bay (SMP, 1996). Tidal asymmetry is considered to be the dominant cause of morphological change in the Bay, with the higher currents associated with the flood tide being the main agency moulding the channel system (Pringle, 1987). Sediment transport in the Bay has been investigated in a number of studies (e.g. McClaren, 1989; Kestner, 1970). Coomber and Hanson (1994) point out the importance of quantifying the sediment budget in order to formulate effective management policies for the Bay. On the basis of limited evidence from past patterns of erosion and deposition, it appears that the sediment budget for the inner Bay is essentially positive, while that for the outer Bay is negative, with net import of sediment into the Bay being small.

3. Data sets

The study compared an older data set of SAR images acquired between 1991 and 1994 with a modern data set comprised of further SAR images acquired since 2003 together with scanning airborne laser altimetry (LiDAR) data. In order to estimate the intertidal sediment budget over the period, two Digital Elevation Models (DEMs) were constructed from these data.

A DEM for 1992-4 (fig. 2a) was constructed using the waterline method. The DEM was constructed from 18 ERS SAR images acquired between late 1991 and 1994. SAR images were used because of their all-weather, day-night capability, allowing a set of images at various stages of the tidal cycle to be acquired in a reasonably short time. Details of the method of construction are given in (Mason et al., 1999), and only a summary is presented here. DEM construction involved waterline delineation and registration, determination of waterline elevations and interpolation of a set of waterlines. Waterlines were delineated using a semi-automatic technique in which sea regions were first detected as regions of low edge density in a low resolution version of a SAR image, then image edges along the waterline were extracted using more elaborate processing at high resolution based on an active contour model. Waterline elevations were determined using the Proudman Oceanographic Laboratory's Morecambe Bay tide-surge model having a 240m grid size. Modelled water elevations were corrected using readings from the tide gauge at Heysham measured relative to Ordnance Datum Newlyn (ODN). Interpolation in space and time was carried out using block kriging to produce a continuous spatiotemporal DEM of the intertidal zone having a spatial resolution of 50m and height accuracy of about 40cm. Strong temporal decorrelation of heights in the Bay limited the height accuracy achievable. The DEM was constructed from SAR images acquired prior to the introduction of height measurement using scanning airborne LiDARs.

The LiDAR DEM (fig. 2b) was constructed from data provided by Lancaster City Council that were obtained by over-flying the Bay at low tide during November 2005. The area covered included almost the complete intertidal zone. The data had a spatial resolution of 2m, and the complete data set included almost 200 million samples. To match the resolution of the waterline DEM, the data were averaged to blocks of side 50m. Because of the high cost of acquiring and processing the data for the large area involved, and the logistical difficulty of overflying the Bay at low tide, such a large LiDAR dataset of a region of tidal flats remains a rarity.

(Fig. 2 about here)

4. Results

4.1 Intertidal sediment budget

An attempt was made to estimate the absolute intertidal sediment budget of the Bay over a 12-year period by comparing the two DEMs of the intertidal zone. Fig. 2c shows the height changes that have occurred over the 12-year period at each grid cell of the intertidal zone for which a height exists in both DEMs. Areas of erosion are indicated by blue/purple colours and areas of accretion by orange/red. From fig. 2c, the mean height change in the intertidal zone over this time was estimated to be 1.1cm. A considerable error is associated with this figure. In (Mason et al., 1999), the waterline heights at

Heysham predicted by the tide-surge model were regressed against the heights of the Heysham tide gauge at the times of the image acquisitions, and found to have a mean height difference of -11.6cm ± 6.7cm and a standard deviation of 15.8cm. The random component of the error is subsumed into the block kriging height error (see below), but, while the mean height difference is corrected for in the waterline height calculation, its error is an additional component that must be taken into account in the sediment budget calculation. For the LiDAR data, the LiDAR height standard deviation was estimated to be 6cm by sampling heights from flat surfaces. The error in the mean LiDAR height was estimated by comparing LiDAR heights with independently-surveyed heights at a number of positions in flat urban areas around the Bay, and was found to be 1 ± 5cm. Given the magnitudes of the errors on the mean heights together with the block kriging errors on the waterline DEM, no significant change could be detected in the absolute intertidal sediment budget.

However, it was possible to estimate the relative change in intertidal sediment volume from below MSL to above MSL by normalising the 2005 LiDAR heights to have the same mean height as the 1992-4 DEM, thus eliminating the errors on the biases of the two data sets. Table 1 gives the relative change in sediment volume above MSL after normalisation, obtained by subtracting the 1992-4 DEM heights from the normalised 2005 LiDAR heights in the area above MSL in the 1992-4 DEM. The relative change in sediment volume below MSL in table 1 was calculated in similar fashion.

The table also gives the random errors on these volumes calculated by the method given in the Appendix of (Mason et al., 1999). These errors are based on the block kriging errors on the individual 50m blocks resulting from the waterline interpolation procedure. Although block kriging errors are calculated using only the geometric relationship between an interpolated block and its sample points (Journel, 1989), their sizes correlated reasonably well with errors between the kriged estimates and the validation data used in (Mason et al., 1999). In the latter paper, the variances of a set of 50m blocks were combined by taking into account the spatial correlations between the blocks estimated using their variogram. Thus the error on the relative change in sediment volume above

MSL in table 1, for example, is the square root of the combined variance of all the 50m blocks in the area above MSL.

The relative volume change above MSL in table 1 was compared to its error to test whether the change was significantly non-zero. Assuming a normally distributed variable, the change was consistent with being zero at the 95% confidence level, so that no significant change was found. The same was true for the relative volume change below MSL. However, if the total relative volume change from below to above MSL was calculated by subtracting the relative volume change below MSL from that above MSL, there was a significant positive change at the 95% confidence level (table 1). Thus a significant movement of sediment from below MSL to above MSL appears to have occurred over the 12-year period. It is not clear how much of this movement may be ascribed to the fact that a seasonal effect may have been present in the LiDAR DEM acquired in November 2005, whereas this could have been averaged out in the waterline DEM. The slope of the intertidal zone may be higher in summer than in winter due to gentler wave action in summer (Komar, 1998), and the LiDAR DEM was acquired before the winter storm season had begun.

4.2 Tidal channel migration

A number of significant morphological changes in the Bay are apparent in the SAR images over the period. Fig. 2c shows that the most significant change in terms of sediment volume is that of the Ulverston channel in the Leven estuary. Fig. 3 shows a sequence of SAR images of the Bay acquired at low-water between August 1991 and February 2007, which depicts the evolution of this channel over a 16-year period. Between 1991 and 2004 there is a gradual but substantial migration of the channel north-east by about 5km, cutting into Cartmel Wharf. This movement appears to have been ongoing since at least 1970, since fig. 1 (based on O.S. maps revised in 1968-71) shows the channel lying even further to the west than in August 1991. An intermediate observation shows that the channel migrated 2km to the north-east between 1991 (fig. 3a) and 1996 (fig. 3b) (Mason et al., 1999). A change in this pattern occurred between May

2004 (fig. 3d) and November 2005 (fig. 3e). By November 2005, a straighter Ulverston channel had developed to the west, leaving the previous curved channel decoupled from the river Leven. Higher land on Cartmel Wharf now formed a barrier between the end of this cul-de-sac and the new channel of the Leven (the proximity of the higher land to the channel can be clearly seen at A in fig. 2b). Two transects sampled across the curved section of the cul-de-sac channel from the LiDAR data of November 2005 are shown in fig. 2b. For both transects, the slope of the outer bank of the curve is higher than that of the inner bank, which is consistent with the outer bank being eroded, even though the slopes involved are very low (0.1°- 2.7°). It is not known if this pattern of migration is cyclical, but if it is, the period of the cycle must be greater than 16 years, since Cartmel Wharf in 2007 (fig. 3f) exhibited three main intrusions, the new Ulverston channel, the cul-de-sac channel and the Kent channel, whereas in 1991 (fig. 3a) only the Kent and old Ulverston channels were present. This example of tidal channel migration is discussed further in the following section.

(Fig.3 about here)

The other main morphological changes that have occurred relate to the Kent and Lune estuaries. In the Kent estuary, accretion has occurred on the west bank near Grange-over-Sands during the period, together with erosion of the Silverdale Marsh on the east (though some accretion south-west of Jenny Brown's Point is apparent) (fig. 2c). This can be explained by a net migration of the Kent low-water channels to the east over the period, continuing a trend that was apparent between 1991 and 1996 (Mason et al., 1999). Movements of the Kent channel over the last century and their consequent effects have been discussed in (Mason et al., 1999). In the Lune estuary, the appearance of a significant north-westerly channel and the decline of the westerly channel occurred between 1991 (fig. 3a) and 1996 (fig. 3b), and has been discussed in (Mason et al., 1999). This change appears to have been largely maintained until 2007 (fig. 3f).

A point of technical interest regarding the SAR images of fig. 3 is the wide variation in backscatter that they display in the intertidal zone. The sequence consists of three ERS and three ASAR images having the same VV polarization, with three descending and three ascending pass images, and with the ASAR images having slightly different look angles to the ERS images. However, this phenomenon can also be seen in different images of the ERS sensor on the same pass direction (Mason et al., 1999). All the images were obtained near low water, so that the differences are unlikely to be due to acquisitions being at different stages of the tidal cycle. Low backscatter from tidal flats is symptomatic of smooth wet surfaces acting largely as specular reflectors. High backscatter can occur if there are ripples on the surface aligned parallel with the satellite track (as these provide scattering surfaces more perpendicular to the incident radiation), or if the sand is dry due to wind and lack of rain.

5. Discussion

The movement of the Ulverston channel over the 16-year period is an interesting example of tidal channel migration. Tidal channel migration in tidal flat areas has been investigated in several studies (Ginsberg et al., 2004; Oost and de Boer, 1994; Asp, 2006). Ginsberg et al. (2004) found that tidal channels in the Bahia Blanca Estuary migrated laterally at a rate of about 25m per year, though the sediment involved was more cohesive than in Morecambe Bay. Oost and de Boer (1994) measured migration rates of 100m per year in areas of the Dutch Wadden Sea. In this case, the Ulverston channel migrated about 5km in 13 years, a rate of about 400m per year. A possible cause of the channel becoming sinuous in the first instance may be that the general direction of the high currents on the flood tide is south-west to north-east (Mason et al., 1999), whereas the Ulverston channel is oriented south-east to north-west, thus creating a component of helical flow in the water entering the channel. Once sinuosity had been established, the helical flow would result in further erosion on the outer bank and deposition on the inner bank, resulting in increased channel curvature and increased helical flow (Hickin, 2003). After May 2004, the channel cut into higher land on Cartmel Wharf forming a barrier between it and the river Leven. The high currents of the flood tide would have gradually reduced as they cut into the higher land. In addition, Lanzoni and Seminara (2002) have shown that tidal asymmetry characterised by higher currents on the flood tide (as is present in Morecambe Bay) induces a land-directed sediment transport, which may have led to increased sedimentation on Cartmel Wharf. Unable to breach the higher land, the river Leven reverted to its older straighter channel. The underlying cause of this pattern of migration is probably that there are two independent forcing mechanisms, the greater tidal forces and the lesser fluvial flow, which act independently of each other. Rinaldo et al. (1999), in their study of tidal channel networks, found that parts of a network may be flood-dominated and others ebb-dominated.

As noted previously, the waterline method applied to satellite images remains of importance for the topographic mapping of tidal flats**.** A difficulty with the method is that it assumes that changes in the intertidal zone are small over the time taken to acquire the image sequence used to construct the intertidal DEM. Given the rapidity with which changes can occur in the Bay, and the fact that in 1991 only the SAR sensor on board ERS-1 was available, there was considerable temporal decorrelation between waterlines over the 3-year period during which SAR images were selected, and this limited the vertical accuracy of the Morecambe Bay DEM for 1992-4 to 40cm. This can be compared with the 10cm accuracy achieved by Ryu et al. (2008) in their study of more stable Korean tidal flats. These authors also achieved a higher accuracy of waterline heighting than that reported by Mason et al. (1999) by using direct levelling of waterlines and assuming each waterline was a contour of uniform height, rather than using a hydrodynamic model to height waterlines. In Morecambe Bay, waterlines were heighted using a hydrodynamic model and tide gauge data because significant height differences could occur along a waterline between the inner and outer parts of the Bay.

An alternative method of using the information from waterlines that does not suffer from this disadvantage and does not involve constructing a DEM is to use the waterlines as a source of partial bathymetry that can be assimilated into a coastal area morphodynamic model. Such models can provide information on how the morphology of the coast is evolving in response to natural or man-made causes. Morphodynamic models often perform poorly in detail, partly because the physical processes (tides, waves, etc) that drive morphological change occur on much shorter timescales than the changes themselves (de Vriend, 1993). One approach to improving model performance is to use data assimilation to combine the modelled bathymetry with observations of bathymetry, and waterlines are one type of observation that can be used. Scott and Mason (2007) developed a morphodynamic model of Morecambe Bay that was enhanced by using optimal interpolation to assimilate waterline heights to better predict large-scale bathymetric changes in the Bay over a 3-year period (fig. 4). Waterlines were assimilated into the model run sequentially at the times at which they were acquired. Whilst each SAR image only contains bathymetric information along its waterline, the latter's heights influenced the modelled heights not only of the model grid cells that it overlayed, but also those of neighbouring cells, thus spreading its information over a larger area. Fig. 4a shows the observed changes in intertidal bathymetry over the period 1994-7. Fig. 4b shows the modelled changes in bathymetry over the same period without using data assimilation, showing that the main areas of accretion were predicted but not the area of erosion along the Ulverston channel. Fig. 4c shows the modelled changes in bathymetry using assimilation of waterlines, when the erosion along the Ulverston channel was correctly predicted. A further advantage of using waterlines in this way is that any seasonal effects present in the waterline heights are automatically taken into account. If a DEM is constructed from waterlines, ideally images should be acquired during a single season to reduce seasonal variations, but this may be difficult to achieve in practice (Ryu et al., 2008).

6. Conclusions

The study has demonstrated the effectiveness of remote sensing for qualitative and quantitative measurement of long-term morphological change in tidal flats areas, using as example the intertidal zone of Morecambe Bay. A significant movement of sediment from below MSL to above was detected by comparing DEMs for 1992-4 and 2005, though the proportion of this increase that could be ascribed to seasonal effects was not clear. Between 1991 and 2004 there was a migration of the Ulverston channel north-east by about 5km, followed in 2004 by the development of a straighter Ulverston channel to the west, leaving the previous curved channel decoupled from the river Leven. This is thought to be due to two independent forcing mechanisms acting on the channel. An alternative use of waterlines is as partial bathymetry for assimilation into a morphodynamic model, instead of simply being used for construction of an intertidal DEM.

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Table 1. Relative sediment volume changes in the intertidal zone between 1992-4 and November 2005.

Intertidal region	**Area (km^2)**	**Mean height change (cm)**	**Volume change (m^3 x 10^6)**	**Error (m^3 x 10^6)**
Above MSL	192	1.8	3.5	2.1
Below MSL	117	-3.1	-3.7	1.9
Total			7.1	2.9

Figure captions

1. Morecambe Bay (based on O.S. 1:25,000 maps (revised 1968-71) (after Mason et al., 1999).
2. Morecambe Bay DEMs for (a) 1992-4, (b) November 2005, and (c) height changes between 1992-4 and November 2005.
3. ERS and ASAR sub-images showing the low water channels in Morecambe Bay from (a) August 1991 (-2.1m ODN), (b) November 1996 (-2.3m ODN), (c) June 2003 (-2.3m ODN), (d) May 2004 (-2.6m ODN), (e) November 2005 (-1.3m ODN), and (f) February 2007 (-2.5m ODN).
4. Change in Morecambe Bay intertidal bathymetry over the period 1994-7, (a) observed change, (b) modelled change without data assimilation, (c) modelled change with assimilation of waterlines (after Scott and Mason, 2007).