1   **SHORT COMMUNICATION**

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3   **Remote sensing of intertidal morphological change in Morecambe Bay,**

4   **U.K., between 1991 and 2007.**

5

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14

15   **Abstract**

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17   Tidal Flats are important examples of extensive areas of natural environment that remain

18   relatively unaffected by man. Monitoring of tidal flats is required for a variety of

19   purposes. Remote sensing has become an established technique for the measurement of

20   topography over tidal flats. A further requirement is to measure topographic changes in

21   order to measure sediment budgets. To date there have been few attempts to make

22   quantitative estimates of morphological change over tidal flat areas. This paper illustrates

23   the use of remote sensing to measure quantitative and qualitative changes in the tidal flats

24   of Morecambe Bay during the relatively long period 1991 – 2007. An understanding of

25   the patterns of sediment transport within the Bay is of considerable interest for coastal

26   management and defence purposes. Tidal asymmetry is considered to be the dominant

27   cause of morphological change in the Bay, with the higher currents associated with the

28   flood tide being the main agency moulding the channel system. Quantitative changes

29   were measured by comparing a Digital Elevation Model (DEM) of the intertidal zone

30   formed using the waterline technique applied to satellite Synthetic Aperture Radar (SAR)

31   images from 1991-4, to a second DEM constructed from airborne laser altimetry data

32   acquired in 2005. Qualitative changes were studied using additional SAR images

33   acquired since 2003. A significant movement of sediment from below Mean Sea Level

34   (MSL) to above MSL was detected by comparing the two Digital Elevation Models,

35   though the proportion of this change that could be ascribed to seasonal effects was not

36   clear. Between 1991 and 2004 there was a migration of the Ulverston channel of the river

37   Leven north-east by about 5km, followed by the development of a straighter channel to

38   the west, leaving the previous channel decoupled from the river. This is thought to be due

39   to independent tidal and fluvial forcing mechanisms acting on the channel. The results

40   demonstrate the effectiveness of remote sensing for measurement of long-term

41   morphological change in tidal flat areas. An alternative use of waterlines as partial

42   bathymetry for assimilation into a morphodynamic model of the coastal zone is also

43   discussed.

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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.

79   In addition to topographic mapping, a further requirement is to measure topographic

80   changes over tidal flats occurring during a certain period in order to measure sediment

81   budgets. Ryu et al. (2008) point out that as yet there have been few attempts to make

82   quantitative estimates of morphological change over large tidal flat areas (e.g. Mason et

83   al., 1999; Ryu et al., 2008). This paper illustrates the use of remote sensing to measure

84   quantitative and qualitative changes in the tidal flats of Morecambe Bay (fig. 1) during

85   the relatively long period 1991–2007. Morecambe Bay is a macro-tidal embayment in

86   north-west England containing the largest single area of intertidal zone in Britain

87   ($340km^2$). The intertidal area is very dynamic, and changes in the positions of many

88   subtidal channels and sandbanks are apparent even over a single season. An

89   understanding of the patterns of sediment transport within the Bay is of considerable

90   interest. The Cumbria Coastal Study (SMP, 1991) lists a number of areas of concern

91   around the Bay regarding coastal management and defence issues. For example,

92   shoreward movement of the Kent channel near Morecambe can make it easier for waves

93   to travel up the channel and access the coastline, increasing urban flood risk in

94   Morecambe. Whilst many problems appear to be localized, previous studies accept that

95   the cause is unlikely to be purely local and that it is necessary to adopt a more holistic

96   view of processes and sediment movement within the Bay.

97

98   (Fig. 1 about here)

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100   Mason et al. (1999) studied intertidal sediment transport in Morecambe Bay over the

101   period 1992-7 using the waterline method. It was apparent that there was substantial

102   intertidal sediment transport over this period. This led on to attempts to model the

103   sediment transport (Mason and Garg, 2001; Scott and Mason, 2007), in the latter paper by

104   assimilating partial bathymetry from waterlines into the morphodynamic model run to

105   keep the model 'on track' and improve its ability to predict future sediment transport. The

106   advantages of performing data assimilation within a morphodynamic model run are

107   currently being studied further, and this has led to the acquisition of a good deal of

108   modern-day intertidal bathymetry. Whilst the separation in time is too large and the

109   intermediate data too sparse for the two periods to be linked by morphodynamic

110 modelling using assimilation, it was felt that useful information could be obtained by

111 comparing the modern intertidal bathymetry with that from the early 1990s. The

112 evolution of the low-water channels could be studied over a 16-year period, perhaps

113 allowing the detection of discernable patterns. The intertidal sediment budget over the

114 period could also be estimated quantitatively. These are the objectives of this short

115 communication. In practical terms, at present this is probably almost the longest time

116 period over which intertidal morphological change can be measured quantitatively at this

117 site using remote sensing. The low rate of acquisition of suitable images from visible

118 band sensors due to frequent cloud cover over the Bay, coupled with the rapidity with

119 which morphological change can occur, mean that it is unlikely that an accurate DEM of

120 the intertidal zone could be produced using the waterline method prior to the launch of

121 the ERS-1 SAR sensor in 1991.

122

123 **2. Study area**

124

125 Morecambe Bay is an estuary which serves as an interface between the open sea and its

126 four primary feeder rivers, the Kent and Leven in the north and the smaller Lune and

127 Wyre in the south. Intertidal sand and mud banks form the dominant coastal landforms in

128 the Bay, representing 68% of its total area, with the remainder being composed of large

129 subtidal channels and saltmarsh. A detailed description of the Bay, including its tide and

130 wave climates and sediment composition, has been given in (Mason et al., 1999), and

131 only a summary is presented here.

132

133 The Bay has a large ordinary spring tidal range of about 8.2m at Morecambe. The

134 duration of the semi-diurnal ebb and flood tides are unequal, with the ebb running for

135 about 40 minutes longer that the flood at Heysham (Coomber and Hansom, 1994). In the

136 large subtidal channels, the spring tide attains a maximum velocity of about $1.5ms^{-1}$, with

137 currents being higher on the flood than the ebb. The wave climate of the area is

138 dominated by smaller waves, as wave sizes are limited by the restricted fetch due to the

139 sheltering landmasses of Ireland, the Isle of Man and spits at the mouth of the Bay. The

140 sediments in the intertidal zone are predominantly composed of very fine and fine sand

141   (0.06-0.2mm), with coarser sand and fine gravel at the mouth of the Bay and silts in the

142   inner Bay (SMP, 1996). Tidal asymmetry is considered to be the dominant cause of

143   morphological change in the Bay, with the higher currents associated with the flood tide

144   being the main agency moulding the channel system (Pringle, 1987). Sediment transport

145   in the Bay has been investigated in a number of studies (e.g. McClaren, 1989; Kestner,

146   1970). Coomber and Hanson (1994) point out the importance of quantifying the sediment

147   budget in order to formulate effective management policies for the Bay. On the basis of

148   limited evidence from past patterns of erosion and deposition, it appears that the sediment

149   budget for the inner Bay is essentially positive, while that for the outer Bay is negative,

150   with net import of sediment into the Bay being small.

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152   **3. Data sets**

153

154   The study compared an older data set of SAR images acquired between 1991 and 1994

155   with a modern data set comprised of further SAR images acquired since 2003 together

156   with scanning airborne laser altimetry (LiDAR) data. In order to estimate the intertidal

157   sediment budget over the period, two Digital Elevation Models (DEMs) were constructed

158   from these data.

159

160   A DEM for 1992-4 (fig. 2a) was constructed using the waterline method. The DEM was

161   constructed from 18 ERS SAR images acquired between late 1991 and 1994. SAR

162   images were used because of their all-weather, day-night capability, allowing a set of

163   images at various stages of the tidal cycle to be acquired in a reasonably short time.

164   Details of the method of construction are given in (Mason et al., 1999), and only a

165   summary is presented here. DEM construction involved waterline delineation and

166   registration, determination of waterline elevations and interpolation of a set of waterlines.

167   Waterlines were delineated using a semi-automatic technique in which sea regions were

168   first detected as regions of low edge density in a low resolution version of a SAR image,

169   then image edges along the waterline were extracted using more elaborate processing at

170   high resolution based on an active contour model. Waterline elevations were determined

171   using the Proudman Oceanographic Laboratory's Morecambe Bay tide-surge model

172 having a 240m grid size. Modelled water elevations were corrected using readings from

173 the tide gauge at Heysham measured relative to Ordnance Datum Newlyn (ODN).

174 Interpolation in space and time was carried out using block kriging to produce a

175 continuous spatiotemporal DEM of the intertidal zone having a spatial resolution of 50m

176 and height accuracy of about 40cm. Strong temporal decorrelation of heights in the Bay

177 limited the height accuracy achievable. The DEM was constructed from SAR images

178 acquired prior to the introduction of height measurement using scanning airborne

179 LiDARs.

180

181 The LiDAR DEM (fig. 2b) was constructed from data provided by Lancaster City

182 Council that were obtained by over-flying the Bay at low tide during November 2005.

183 The area covered included almost the complete intertidal zone. The data had a spatial

184 resolution of 2m, and the complete data set included almost 200 million samples. To

185 match the resolution of the waterline DEM, the data were averaged to blocks of side 50m.

186 Because of the high cost of acquiring and processing the data for the large area involved,

187 and the logistical difficulty of overflying the Bay at low tide, such a large LiDAR dataset

188 of a region of tidal flats remains a rarity.

189

190 (Fig. 2 about here)

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192 **4. Results**

193

194 **4.1 Intertidal sediment budget**

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196 An attempt was made to estimate the absolute intertidal sediment budget of the Bay over

197 a 12-year period by comparing the two DEMs of the intertidal zone. Fig. 2c shows the

198 height changes that have occurred over the 12-year period at each grid cell of the

199 intertidal zone for which a height exists in both DEMs. Areas of erosion are indicated by

200 blue/purple colours and areas of accretion by orange/red. From fig. 2c, the mean height

201 change in the intertidal zone over this time was estimated to be 1.1cm. A considerable

202 error is associated with this figure. In (Mason et al., 1999), the waterline heights at

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203   Heysham predicted by the tide-surge model were regressed against the heights of the

204   Heysham tide gauge at the times of the image acquisitions, and found to have a mean

205   height difference of -11.6cm ± 6.7cm and a standard deviation of 15.8cm. The random

206   component of the error is subsumed into the block kriging height error (see below), but,

207   while the mean height difference is corrected for in the waterline height calculation, its

208   error is an additional component that must be taken into account in the sediment budget

209   calculation. For the LiDAR data, the LiDAR height standard deviation was estimated to

210   be 6cm by sampling heights from flat surfaces. The error in the mean LiDAR height was

211   estimated by comparing LiDAR heights with independently-surveyed heights at a number

212   of positions in flat urban areas around the Bay, and was found to be 1 ± 5cm. Given the

213   magnitudes of the errors on the mean heights together with the block kriging errors on the

214   waterline DEM, no significant change could be detected in the absolute intertidal

215   sediment budget.

216

217   However, it was possible to estimate the relative change in intertidal sediment volume

218   from below MSL to above MSL by normalising the 2005 LiDAR heights to have the

219   same mean height as the 1992-4 DEM, thus eliminating the errors on the biases of the

220   two data sets. Table 1 gives the relative change in sediment volume above MSL after

221   normalisation, obtained by subtracting the 1992-4 DEM heights from the normalised

222   2005 LiDAR heights in the area above MSL in the 1992-4 DEM. The relative change in

223   sediment volume below MSL in table 1 was calculated in similar fashion.

224

225   The table also gives the random errors on these volumes calculated by the method given

226   in the Appendix of (Mason et al., 1999). These errors are based on the block kriging

227   errors on the individual 50m blocks resulting from the waterline interpolation procedure.

228   Although block kriging errors are calculated using only the geometric relationship

229   between an interpolated block and its sample points (Journel, 1989), their sizes correlated

230   reasonably well with errors between the kriged estimates and the validation data used in

231   (Mason et al., 1999). In the latter paper, the variances of a set of 50m blocks were

232   combined by taking into account the spatial correlations between the blocks estimated

233   using their variogram. Thus the error on the relative change in sediment volume above

234   MSL in table 1, for example, is the square root of the combined variance of all the 50m

235   blocks in the area above MSL.

236

237   The relative volume change above MSL in table 1 was compared to its error to test

238   whether the change was significantly non-zero. Assuming a normally distributed variable,

239   the change was consistent with being zero at the 95% confidence level, so that no

240   significant change was found. The same was true for the relative volume change below

241   MSL. However, if the total relative volume change from below to above MSL was

242   calculated by subtracting the relative volume change below MSL from that above MSL,

243   there was a significant positive change at the 95% confidence level (table 1). Thus a

244   significant movement of sediment from below MSL to above MSL appears to have

245   occurred over the 12-year period. It is not clear how much of this movement may be

246   ascribed to the fact that a seasonal effect may have been present in the LiDAR DEM

247   acquired in November 2005, whereas this could have been averaged out in the waterline

248   DEM. The slope of the intertidal zone may be higher in summer than in winter due to

249   gentler wave action in summer (Komar, 1998), and the LiDAR DEM was acquired before

250   the winter storm season had begun.

251

252   **4.2 Tidal channel migration**

253

254   A number of significant morphological changes in the Bay are apparent in the SAR

255   images over the period. Fig. 2c shows that the most significant change in terms of

256   sediment volume is that of the Ulverston channel in the Leven estuary. Fig. 3 shows a

257   sequence of SAR images of the Bay acquired at low-water between August 1991 and

258   February 2007, which depicts the evolution of this channel over a 16-year period.

259   Between 1991 and 2004 there is a gradual but substantial migration of the channel north-

260   east by about 5km, cutting into Cartmel Wharf. This movement appears to have been

261   ongoing since at least 1970, since fig. 1 (based on O.S. maps revised in 1968-71) shows

262   the channel lying even further to the west than in August 1991. An intermediate

263   observation shows that the channel migrated 2km to the north-east between 1991 (fig. 3a)

264   and 1996 (fig. 3b) (Mason et al., 1999). A change in this pattern occurred between May

265   2004 (fig. 3d) and November 2005 (fig. 3e). By November 2005, a straighter Ulverston

266   channel had developed to the west, leaving the previous curved channel decoupled from

267   the river Leven. Higher land on Cartmel Wharf now formed a barrier between the end of

268   this cul-de-sac and the new channel of the Leven (the proximity of the higher land to the

269   channel can be clearly seen at A in fig. 2b). Two transects sampled across the curved

270   section of the cul-de-sac channel from the LiDAR data of November 2005 are shown in

271   fig. 2b. For both transects, the slope of the outer bank of the curve is higher than that of

272   the inner bank, which is consistent with the outer bank being eroded, even though the

273   slopes involved are very low (0.1°- 2.7°). It is not known if this pattern of migration is

274   cyclical, but if it is, the period of the cycle must be greater than 16 years, since Cartmel

275   Wharf in 2007 (fig. 3f) exhibited three main intrusions, the new Ulverston channel, the

276   cul-de-sac channel and the Kent channel, whereas in 1991 (fig. 3a) only the Kent and old

277   Ulverston channels were present. This example of tidal channel migration is discussed

278   further in the following section.

279

280   (Fig.3 about here)

281

282   The other main morphological changes that have occurred relate to the Kent and Lune

283   estuaries. In the Kent estuary, accretion has occurred on the west bank near Grange-over-

284   Sands during the period, together with erosion of the Silverdale Marsh on the east

285   (though some accretion south-west of Jenny Brown's Point is apparent) (fig. 2c). This can

286   be explained by a net migration of the Kent low-water channels to the east over the

287   period, continuing a trend that was apparent between 1991 and 1996 (Mason et al., 1999).

288   Movements of the Kent channel over the last century and their consequent effects have

289   been discussed in (Mason et al., 1999). In the Lune estuary, the appearance of a

290   significant north-westerly channel and the decline of the westerly channel occurred

291   between 1991 (fig. 3a) and 1996 (fig. 3b), and has been discussed in (Mason et al., 1999).

292   This change appears to have been largely maintained until 2007 (fig. 3f).

293

294   A point of technical interest regarding the SAR images of fig. 3 is the wide variation in

295   backscatter that they display in the intertidal zone. The sequence consists of three ERS

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296   and three ASAR images having the same VV polarization, with three descending and

297   three ascending pass images, and with the ASAR images having slightly different look

298   angles to the ERS images. However, this phenomenon can also be seen in different

299   images of the ERS sensor on the same pass direction (Mason et al., 1999). All the images

300   were obtained near low water, so that the differences are unlikely to be due to

301   acquisitions being at different stages of the tidal cycle. Low backscatter from tidal flats is

302   symptomatic of smooth wet surfaces acting largely as specular reflectors. High

303   backscatter can occur if there are ripples on the surface aligned parallel with the satellite

304   track (as these provide scattering surfaces more perpendicular to the incident radiation),

305   or if the sand is dry due to wind and lack of rain.

306

307   **5. Discussion**

308

309   The movement of the Ulverston channel over the 16-year period is an interesting example

310   of tidal channel migration. Tidal channel migration in tidal flat areas has been

311   investigated in several studies (Ginsberg et al., 2004; Oost and de Boer, 1994; Asp,

312   2006). Ginsberg et al. (2004) found that tidal channels in the Bahia Blanca Estuary

313   migrated laterally at a rate of about 25m per year, though the sediment involved was

314   more cohesive than in Morecambe Bay. Oost and de Boer (1994) measured migration

315   rates of 100m per year in areas of the Dutch Wadden Sea. In this case, the Ulverston

316   channel migrated about 5km in 13 years, a rate of about 400m per year. A possible cause

317   of the channel becoming sinuous in the first instance may be that the general direction of

318   the high currents on the flood tide is south-west to north-east (Mason et al., 1999),

319   whereas the Ulverston channel is oriented south-east to north-west, thus creating a

320   component of helical flow in the water entering the channel. Once sinuosity had been

321   established, the helical flow would result in further erosion on the outer bank and

322   deposition on the inner bank, resulting in increased channel curvature and increased

323   helical flow (Hickin, 2003). After May 2004, the channel cut into higher land on Cartmel

324   Wharf forming a barrier between it and the river Leven. The high currents of the flood

325   tide would have gradually reduced as they cut into the higher land. In addition, Lanzoni

326   and Seminara (2002) have shown that tidal asymmetry characterised by higher currents

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327 on the flood tide (as is present in Morecambe Bay) induces a land-directed sediment

328 transport, which may have led to increased sedimentation on Cartmel Wharf. Unable to

329 breach the higher land, the river Leven reverted to its older straighter channel. The

330 underlying cause of this pattern of migration is probably that there are two independent

331 forcing mechanisms, the greater tidal forces and the lesser fluvial flow, which act

332 independently of each other. Rinaldo et al. (1999), in their study of tidal channel

333 networks, found that parts of a network may be flood-dominated and others ebb-

334 dominated.

335

336 As noted previously, the waterline method applied to satellite images remains of

337 importance for the topographic mapping of tidal flats. A difficulty with the method is that

338 it assumes that changes in the intertidal zone are small over the time taken to acquire the

339 image sequence used to construct the intertidal DEM. Given the rapidity with which

340 changes can occur in the Bay, and the fact that in 1991 only the SAR sensor on board

341 ERS-1 was available, there was considerable temporal decorrelation between waterlines

342 over the 3-year period during which SAR images were selected, and this limited the

343 vertical accuracy of the Morecambe Bay DEM for 1992-4 to 40cm. This can be compared

344 with the 10cm accuracy achieved by Ryu et al. (2008) in their study of more stable

345 Korean tidal flats. These authors also achieved a higher accuracy of waterline heighting

346 than that reported by Mason et al. (1999) by using direct levelling of waterlines and

347 assuming each waterline was a contour of uniform height, rather than using a

348 hydrodynamic model to height waterlines. In Morecambe Bay, waterlines were heighted

349 using a hydrodynamic model and tide gauge data because significant height differences

350 could occur along a waterline between the inner and outer parts of the Bay.

351

352 An alternative method of using the information from waterlines that does not suffer from

353 this disadvantage and does not involve constructing a DEM is to use the waterlines as a

354 source of partial bathymetry that can be assimilated into a coastal area morphodynamic

355 model. Such models can provide information on how the morphology of the coast is

356 evolving in response to natural or man-made causes. Morphodynamic models often

357 perform poorly in detail, partly because the physical processes (tides, waves, etc) that

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358 drive morphological change occur on much shorter timescales than the changes

359 themselves (de Vriend, 1993). One approach to improving model performance is to use

360 data assimilation to combine the modelled bathymetry with observations of bathymetry,

361 and waterlines are one type of observation that can be used. Scott and Mason (2007)

362 developed a morphodynamic model of Morecambe Bay that was enhanced by using

363 optimal interpolation to assimilate waterline heights to better predict large-scale

364 bathymetric changes in the Bay over a 3-year period (fig. 4). Waterlines were assimilated

365 into the model run sequentially at the times at which they were acquired. Whilst each

366 SAR image only contains bathymetric information along its waterline, the latter's heights

367 influenced the modelled heights not only of the model grid cells that it overlayed, but also

368 those of neighbouring cells, thus spreading its information over a larger area. Fig. 4a

369 shows the observed changes in intertidal bathymetry over the period 1994-7. Fig. 4b

370 shows the modelled changes in bathymetry over the same period without using data

371 assimilation, showing that the main areas of accretion were predicted but not the area of

372 erosion along the Ulverston channel. Fig. 4c shows the modelled changes in bathymetry

373 using assimilation of waterlines, when the erosion along the Ulverston channel was

374 correctly predicted. A further advantage of using waterlines in this way is that any

375 seasonal effects present in the waterline heights are automatically taken into account. If a

376 DEM is constructed from waterlines, ideally images should be acquired during a single

377 season to reduce seasonal variations, but this may be difficult to achieve in practice (Ryu

378 et al., 2008).

379

380 **6. Conclusions**

381

382 The study has demonstrated the effectiveness of remote sensing for qualitative and

383 quantitative measurement of long-term morphological change in tidal flats areas, using as

384 example the intertidal zone of Morecambe Bay. A significant movement of sediment

385 from below MSL to above was detected by comparing DEMs for 1992-4 and 2005,

386 though the proportion of this increase that could be ascribed to seasonal effects was not

387 clear. Between 1991 and 2004 there was a migration of the Ulverston channel north-east

388 by about 5km, followed in 2004 by the development of a straighter Ulverston channel to

389   the west, leaving the previous curved channel decoupled from the river Leven. This is

390   thought to be due to two independent forcing mechanisms acting on the channel. An

391   alternative use of waterlines is as partial bathymetry for assimilation into a

392   morphodynamic model, instead of simply being used for construction of an intertidal

393   DEM.

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

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525 **Figure captions**

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527 1. Morecambe Bay (based on O.S. 1:25,000 maps (revised 1968-71) (after Mason et
528   al., 1999).

529 2. Morecambe Bay DEMs for (a) 1992-4, (b) November 2005, and (c) height
530   changes between 1992-4 and November 2005.

531 3. ERS and ASAR sub-images showing the low water channels in Morecambe Bay
532   from (a) August 1991 (-2.1m ODN), (b) November 1996 (-2.3m ODN), (c) June
533   2003 (-2.3m ODN), (d) May 2004 (-2.6m ODN), (e) November 2005 (-1.3m
534   ODN), and (f) February 2007 (-2.5m ODN).

535 4. Change in Morecambe Bay intertidal bathymetry over the period 1994-7, (a)
536   observed change, (b) modelled change without data assimilation, (c) modelled
537   change with assimilation of waterlines (after Scott and Mason, 2007).

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