

1 **SHORT COMMUNICATION**

2
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**

16
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.

44

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

47

48 **1. Introduction**

49

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

55

56 Remote sensing has become an established technique for the measurement of topography
57 over tidal flats, due in no small part to its synoptic nature. While ground and ship surveys
58 may be able to achieve high height accuracies, these are laborious and time-consuming to
59 perform over the large areas involved. The remote sensing techniques most commonly
60 employed over tidal flats are airborne LiDAR (Light Detection And Ranging) (Flood and
61 Gutelius, 1997; Stockdon et al., 2002; Deronde et al., 2006), airborne InSAR
62 (Interferometric Synthetic Aperture Radar) (Greidanus et al., 1999; Wimmer et al., 2000)
63 and the waterline method (Collins and Madge, 1981; Koopmans and Wang, 1995; Mason
64 et al., 1995; Niedermeier et al., 2005; Kim et al., 2007; Zhao et al., 2008; Ryu et al.,
65 2008; Heygster et al, in press). Because of the cost over large areas and the logistical
66 difficulties of flying at low tide, airborne methods are normally used to survey narrower
67 beaches. The waterline method applied to satellite images remains of importance for the
68 topographic mapping of large areas of tidal flats, partly because of its relatively low cost
69 (Mason et al., 2000). The term waterline is used to denote the water's edge, which moves
70 to and fro as the tides rise and fall. The method involves finding the geo-coded positions
71 of the waterline in a remotely sensed image using image processing techniques. Predicted
72 water elevations at the waterline are superimposed on these positions. These elevations
73 may be predicted using a hydrodynamic tide-surge model run for the area for the time of
74 acquisition of the image, with the weather conditions pertaining at the time. From
75 multiple images obtained over a range of tidal conditions, a set of heightened waterlines can
76 be assembled in the intertidal zone, and from this a gridded Digital Elevation Model
77 (DEM) can be interpolated.

78

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 (340km²). 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)

99

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 than 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.

151

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)

191

192 **4. Results**

193

194 **4.1 Intertidal sediment budget**

195

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

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 $-11.6\text{cm} \pm 6.7\text{cm}$ 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 $1 \pm 5\text{cm}$. 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

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

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

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 overlaid, 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.

394

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396

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401

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517

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 (km²)	Mean height change (cm)	Volume change (m³ x 10⁶)	Error (m³ x 10⁶)
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**

526

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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