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Comparison of tide-gauge data and a saltmarsh-derived reconstruction of mean sea-level for the Mersey Estuary

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ABSTRACT

Using saltmarsh sediment cores, Mills (2011) reconstructed the historic trend of mean sea-level in the Mersey over a period since 1975. The analysis is based on the foraminifera species identified at different levels within the sediment core; each species being associated with a tidal elevation (for example, mean high water neap) identified from present-day vertical distribution of saltmarsh foraminifera at the coring sites. While the reconstruction at Decoy Marsh matched the tide gauge record at Gladstone Dock, the reconstruction at Oglet Bay for the period 1993 and 2003 disagreed. During this period the reconstruction suggested an initial drop in mean tidal level (MTL) of 50 cm followed by a 50 cm rise back to the underlying trend after 2002. Because a local drop in sea-level (SL) is unlikely, and the foraminifera fossils used in the reconstruction are unlikely to have changed their tolerance to inundation, another factor must account for this sea-level anomaly. Here using the 3D hydrodynamic Proudman Oceanographic Laboratory Coastal Ocean modelling System (POLCOMS), the impact of the position of the main estuarine channel and historic sea-level elevations on the tidal dynamics are investigated relative to the conditions in 2008. Changes in the proportion of time that certain elevations at the saltmarsh coring sites are inundated could explain the deviation observed in the reconstruction. Such an effect is hypothesised to occur in response to local changes in the tidal dynamics, i.e. changes in tidal range or asymmetry in tidal elevation. It is found that in response to changes in channel configuration to test the scenario of a northern channel migrating up-estuary through Oglet Bay, a change in inundation characteristics caused by a change in the bank drying phase of the tidal cycle, may well have contributed to the anomalous reconstruction.

KEYWORDS

ISSUING ORGANISATION

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1. Introduction

This investigation explores the impacts of (i) channel migration and (ii) changes in historic sea-levels on the spatial and temporal variability in tidal range and asymmetry within the Mersey Estuary. The differences and asymmetries in tidal elevation have been explored at 6 of the 8 proposed reference locations (Fig. 1), positioned with increasing distance into the estuary, from the long-term tide gauge station at the estuary mouth. Locations 4 and 6 represent sediment core sites that have been analysed to reconstruct historic sea-level trends using an ecological transfer function applied to saltmarsh sediments (see Mills, 2011). The remaining 6 locations were included as points of interest. Figure 1 shows the model bathymetry, with an exaggerated 5 m-deep main channel. This modification was to ensure the upper channels were able to discharge river flow at low water to improve the simulation of the coastal region (see Norman et al., 2014b). The extension of the channel stops close to location 7 and location 8 is frequently cut off from the tidal excursion. These last two sites (7 and 8) were therefore not considered in this analysis because they are not well resolved by the model. The original locations of the reference sites for examining tidal dynamics (yellow triangles, Fig. 1) have also been adjusted (blue triangles Fig.1) at some locations to ensure they are on numerical grid points that are not permanently dry.

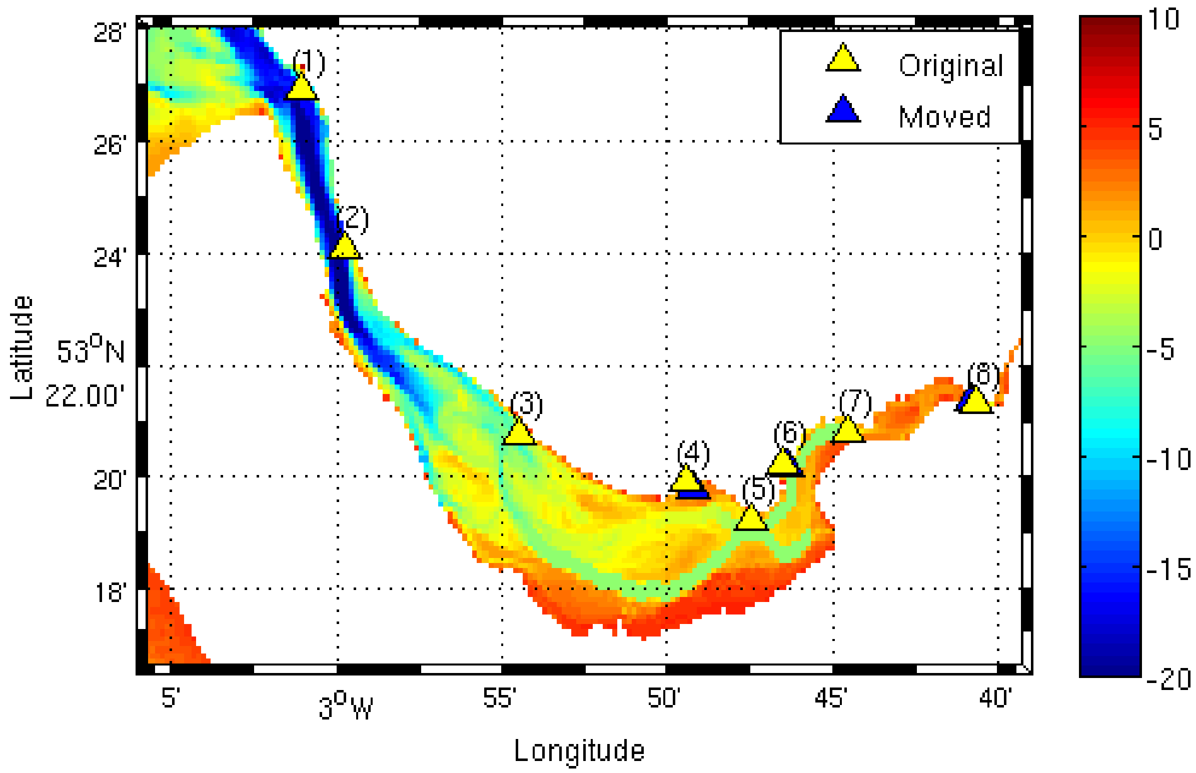

Figure 1: The 8 locations of interest in the Mersey Estuary. (1)=Gladstone Dock tide gauge, (2)=Liverpool, Albert Dock, (3)=Garston Dock, (4)=Oglet Bay, Speke, (5)=Hale Head, (6)=Decoy Marsh, Hale, (7)=Runcorn bridge, (8)=Fiddlers Ferry. This is the bathymetry used for the control model run and has had the main channel artificially deepened to ensure that river flow is discharged at low water. Yellow triangles represent the reference sites for examining tidal characteristics and blue triangles represent the relocation to points of tidal inundation.

Mills (2011) used foraminifera (referred to as forams here after) records within the sediment cores to reconstruct mean sea-level (SL) in the Mersey for the last c.100 years and found that while her reconstructions of mean tidal level (MTL) at Decoy Marsh (location 6, Fig. 1) matched the tide-gauge record at Gladstone Dock well (Fig. 2), the reconstruction at Oglet Bay (location 4, Fig. 1) was noticeably different for the period c.1994 to 2002 (Fig. 3).

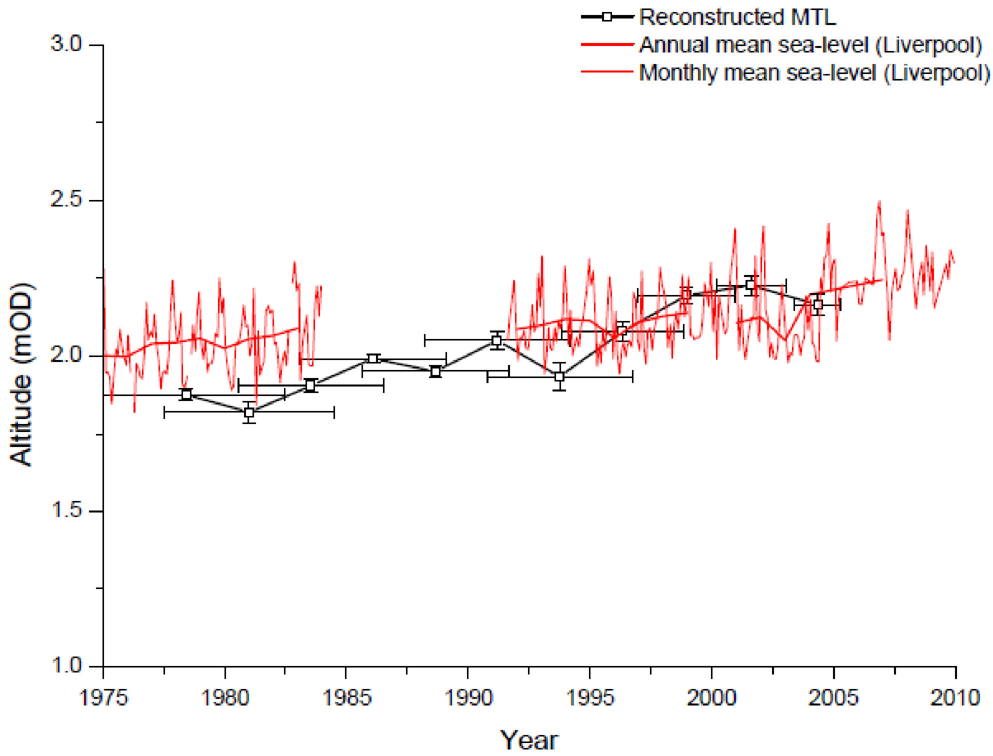

Figure 2: Taken from Mills (2011) p311. The red line(s) shows sea-level (SL) at Gladstone Dock while the black line shows the reconstructed MTL at Decoy Marsh (Location 6, Fig. 1).

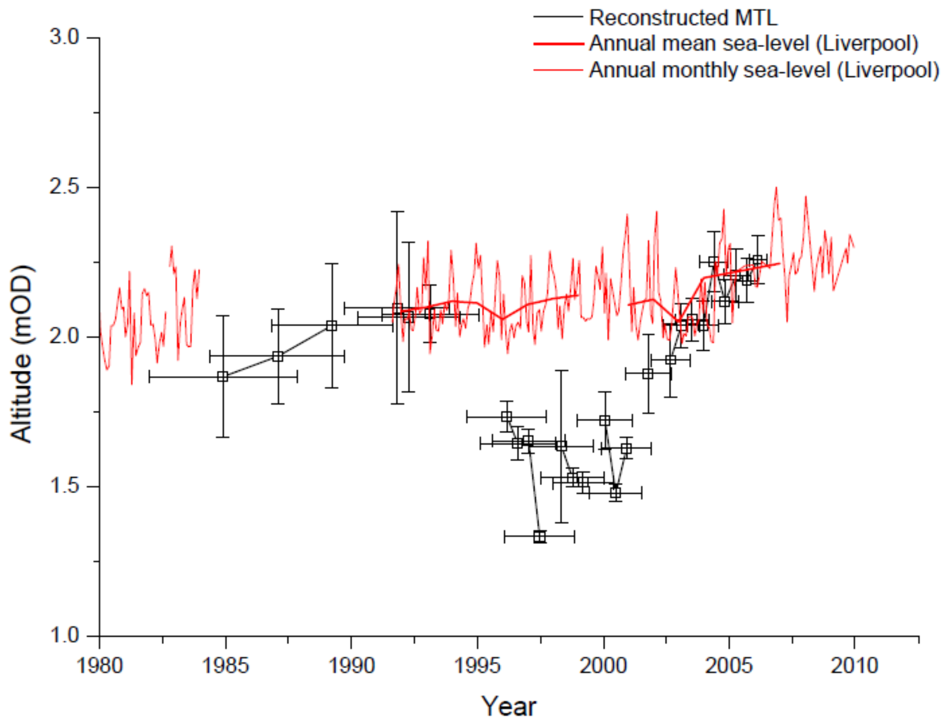

Figure 3: Taken from Mills (2011) p310. As in Figure 2, but for Oglet Bay.

The foram species which were used for the reconstruction live at altitudes on the saltmarsh that experience a certain proportion of time underwater that enables them to thrive. Different species live at different altitudes across the intertidal region (known as vertical zonation). A drop in SL, as suggested in Figure 3, would lead to a widespread relocation of forams on the saltmarsh surface in response to decreased duration of tidal inundation. Within a saltmarsh core, this would be recorded by the presence of a greater abundance of upper saltmarsh foram species temporarily replacing a greater abundance of mid saltmarsh species. However, the tide gauge record and the other sediment core locations indicate a steadily rising sea-level. It is unlikely that a drop in sea-level of the order of 0.5 m would have occurred at such a local scale. This poses the question why does the foram record indicate a short-term drop in SL at Oglet Bay, while all other indicators, e.g. Decoy Marsh, show a continued rise in sea-level?

Our hypothesis is that: *localised changes in the tidal asymmetry (including duration of inundation and tidal range) at Oglet Bay may cause a change in the distributon of forams preventing accurate reconstruction of trends in sea-level.*

Changes in tidal range and/or asymmetry in elevations can lead to consequential changes in the difference in height between mean high water springs (MHWS) and MTL. Hence, reconstructing MTL from foram species from higher tidal levels, e.g. MHWS or highest astronomical tide (HAT), by assuming a constant difference through time, may result in an apparent drop in sea-level if the altitude of MTL became closer to the higher tidal levels (e.g. through a reduction in tidal range). In the case of a saltmarsh that wets and dries during the tidal cycle it may only be possible to determine changes in the shape of the crest of the tidal wave as the troughs/low waters (LW) may have been 'clipped' out of the record. A clipped tidal cycle will also make calculating the mean tidal level (MTL) and tidal range difficult (Evans and Pugh, 1982).

Changes in elevation asymmetry may be caused by variations in the continuously evolving channel configurations, of both the main channel and more minor local channels. This will be investigated using the Proudman Oceanographic Laboratory Coastal Ocean Modelling System (POLCOMS; Holt, 2007) with different estuarine channel configurations and historic sea-level conditions to see if these localised changes can be reproduced.

While the actual position of the main channel throughout the period is not known, the use of numerical scenarios will explore whether bathymetric changes could have the hypothesised impacts, influencing the localised tidal dynamics. These simulations have been repeated for a reduction in sea-level to also see how the tidal dynamics may have behaved historically.

1.1. The study area: The Mersey Estuary

The Mersey is a hyper-tidal, partially mixed estuary located in the north-west of the UK. It has a tidal range of between 4 and 10 m and has experienced an average sea-level rise of around 1.82 mm/yr over the period 1901 to 2004 (Woodworth *et al.*, 2009).

The estuary is approximately 45 km long. The entrance is narrow and deep (15 m below the approximate lowest astronomical tide) with fast tidal currents that can exceed 2 m/s. The inner estuary expands in places to a width of 5 km and has large areas of intertidal mud/sand banks along the shoreline which become exposed at low tide (Lane, 2004; Thomas *et al.*, 2002). The 63-year long record of tidal elevation in the lower estuary shows little change in the main M_2 and S_2 constituents (Lane, 2004).

For further information on sediment transport and geomorphological changes within the Mersey see Lane (2004) and Thomas *et al.* (2002).

1.2. Tidal asymmetry within estuaries

A symmetric tide can be defined as a tide where the duration of the ebb tide and the flood tide are roughly equal, where the peak ebb tide and flood tide currents are roughly equal and where there is no net sediment transport either landwards or seawards. Tidal asymmetry is often associated with a saw-tooth elevation curve, which causes an asymmetric tidal flow to occur when either the flood tide or ebb tide is shorter and has faster velocities than the other.

Flood tide dominance is thought to occur when the tidal wave propagates into an estuary and shallow water interactions generate a strong M_4 tidal constituent that can lead to a strengthening of the flood tide and a weakening of the ebb. As a tide enters a shallow estuarine environment the crest of the tidal wave (high water) is able to catch up with the proceeding trough (because deeper shallow water waves travel faster than shallower ones) and this results in a shorter flood tide and a longer ebb tide. Ebb tide dominance occurs once the estuarine banks have built up to form relatively deep narrow channels. Frictional influence on the flow during higher water elevations when the banks are inundated and flow constraint in the deeper channels at lower water elevations enables faster ebb velocities than during the flood (Pethick, 1994).

Friedrichs and Aubrey (1988) quantify tidal asymmetry using the following 2 measures

1. Tidal distortion factor, TD_iF

$\frac{\mathrm{M_4 Amplitude}}{\mathrm{M_2 Amplitude}}$ >0.01 means a significant distortion of the tide. (1)

2. Tidal dominance factor, TD_oF

$$(2\mathrm{x}\ \mathrm{M_2 Phase}) - \mathrm{M_4\ Phase} \quad (2)$$

where;

0-180deg = flood dominance, and 180-360deg = ebb dominance.

Although the tidal dominance factor indicates the potential for flood or ebb dominance, it is necessary for a large tidal distortion factor to be present in order for a flood or ebb asymmetry to become apparent, e.g. a tidal dominance factor of 90 degrees and distortion factor of 0 will still appear as a symmetrical sine wave. The greater the M_4 constituent's amplitude the greater the distortion of the tidal wave and the greater the departure of the tidal cycle from a sine wave (see Pugh and Woodworth, 2014, p136-137).

Moore *et al*. (2009) applied these 2 quantities to the Dee Estuary and found the continually inundated deepest sections of both of the main channels of the Dee to be weakly ebb-dominant and the intertidal banks to be strongly flood-dominant with most of the tidal distortion occurring on the intertidal banks.

Two further parameters used to quantify tidal asymmetry are:

$$\frac{a}{h} \qquad (3)$$

to quantify flood asymmetry, and:

$$\frac{v_s}{v_c} \qquad (4)$$

to quantify ebb-dominant tidal asymmetry, where a = amplitude (half of the offshore tidal range), h = depth (specifically mean channel depth), v_s = volume of intertidal storage and v_c = volume of the channel (Environment Agency, 2008; Spear & Aubrey, 1985). Typically a is taken at the mouth of the estuary to represent the tidal forcing. Here we calculate a (mean HW depth minus mean wet depth) at each site of interest (see Fig. 1) and h takes the value of the mean estuarine depth. This allows the comparison of the tidal attenuation across the estuary.

For flood dominant asymmetry Friedrichs and Aubrey found values of less than 0.2 in Equation 3 indicated ebb dominance, and values of greater than 0.3 indicated flood dominance. Values between 0.2 and 0.3 were either flood or ebb dominant depending on Equation 4.

As the tide enters the estuary, friction with the shallow bed causes the tidal range to attenuate. In the case of the Mersey the mean tidal range at Gladstone Dock (location 1, Fig. 1) is of the order of 8.2 m but has fallen to 2.9 m by the time it gets to Fiddler's Ferry (location 8, Fig. 1). The largest tidal range in the Mersey is at Eastham on the south bank, reaching 8.9 m (Ridgway *et al.*, 2012). We use Equation 3 as a way of quantifying attenuation of the tidal range with distance up estuary if applied to the local value of a.

As the feedbacks between tidal asymmetry and estuary morphology are complex, these different measures (Eqs. 1-4) are best used together to gain a qualitative idea of the general trend within the estuary (Environment Agency, 2008).

Tidal asymmetry can also refer to an asymmetry in the shape of the tidal elevation wave, for example, the shape of the HW crest being different to that of the LW trough. This is an important distinction as a flood tide could be referred to as an asymmetric tide due to the fact that the flood tide is faster than the ebb tide, but could also be considered symmetric as the HW crest is a similar shape to the LW trough. In this report the asymmetry in the tidal elevation shape rather than the flood/ebb tide speed asymmetry will be the main focus. In the case of a drying bank, tidal asymmetry may be difficult to identify as the LW crests are effectively masked by the banks.

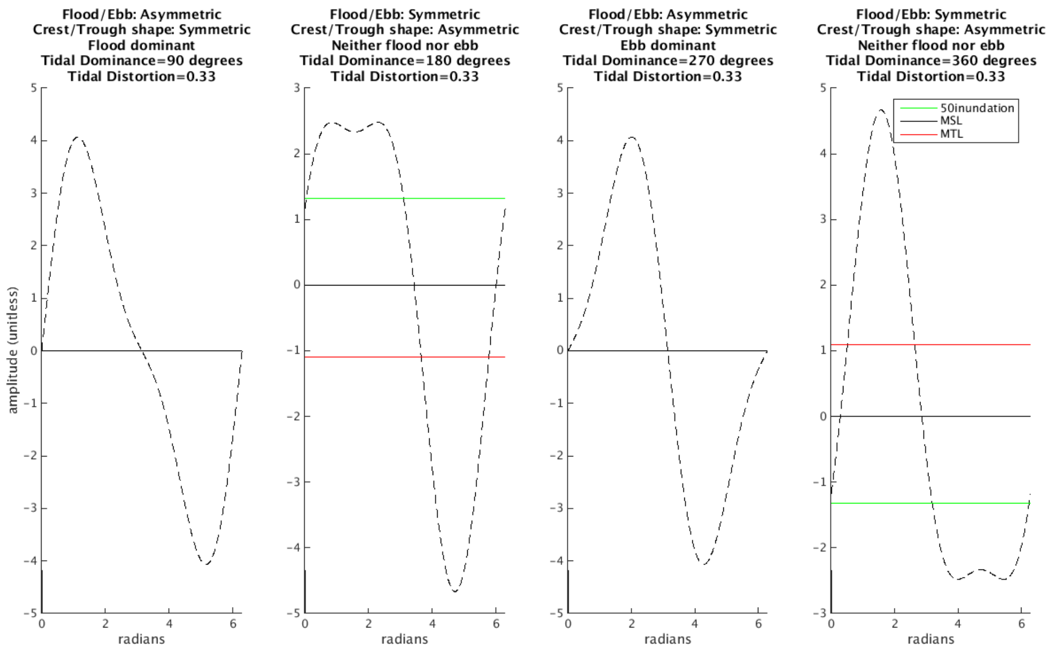

Figure 4: The 4 panels show 4 different resultant tidal curves produced by the interaction of the M2 tidal constituent with the M4 tidal constituent of varying phase lags (M2 and M4 constituents not shown). When the resultant tidal curve is either flood or ebb dominant (panels 1 & 3) the MTL level is equivalent to MSL and the 50% inundation level. When the tide is neither flood nor ebb dominant (panels 2 & 4) these levels diverge from one another. While the curves represent tidal curves they were produced by combining sine waves and not real tidal data. The y-axis is equivalent to elevation on a real tidal curve and the x-axis is equivalent to time.

1.3. The POLCOMS Model Application

In order to investigate the spatial variation of the tide in the Mersey the 3D Proudman Oceanographic Coastal Ocean Modelling System (POLCOMS) was applied to Liverpool Bay (which includes the Mersey) with a resolution of 180 m and 20 levels in the vertical. The Liverpool Bay model is nested inside an Irish Sea model which has a 1.8 km resolution and 32 vertical levels. The number of vertical levels in the Liverpool Bay is fewer than in the Irish Sea setup, which has a minimum depth of 5 m in Liverpool Bay. This is to minimize the possibility of errors occurring in very shallow locations due to the vertical resolution becoming less than the bed roughness, 0.003 m. In this case the number of vertical coordinates was chosen to ensure the vertical spacing did not become less than the bottom roughness length. For further detail of the numerical setup, see Holt and James (2001) and the POLCOMS user guide (Holt, 2007).

POLCOMS uses terrain following sigma coordinates in the vertical and incorporates:

1. Bathymetry files from hydrographic and LiDAR surveys,

2. Meteorological data from the UK Met Office numerical weather predictions (Wind, pressure, cloud cover, humidity and air temperature),

3. Data from the National Oceanography Centre's Coastal Observatory pre-operational modelling system to provide large scale circulation, temperature and salinity fields. These are used as boundary conditions for the Irish Sea model and initial conditions for both the Irish Sea and Liverpool Bay simulations.

4. Daily mean river flow data from the UK national river flow archive at locations where weighting factors to account for the downstream catchment contribution from the gauging station is available (Marsh and Sanderson, 2003).

The model is fully baroclinic and incorporates algorithms to simulate the wetting and drying of intertidal banks in the shallow regions. In this investigation the model has been run for the year 2008 following a model spin up period for the month of December 2007. Data is output from the model every 30 minutes at the 8 locations of interest (Fig. 1). Each annual simulation for Liverpool Bay took around 6 days using 128 processors of the local NOC cluster. The model has been validated at 2 offshore moorings in Liverpool Bay and has been found to perform well during the year 2008 (see Norman *et al.* (2014a) for further details).

To allow a realistic simulation of annual conditions to provide the control scenario to assess alternative channel configurations and sea-levels, the year 2008 was chosen to represent typical current dominant, wave dominant and wave-current conditions that can occur within the bay. Norman *et al.* (2014b) have compared 2008 to long-term data sets of Metocean parameters finding this is a typical year. Here, we have continued to use the same realistic forcing (as in Norman et al., 2014a) to repeat simulations of this year under different sea-level and bathymetric conditions. The full year was simulated to enable a suitably long data set to be used in the tidal analysis. In order to investigate the effect of sea-level and estuary bathymetry on tidal elevation asymmetry, all other parameters have been maintained for this representative year.

2.Methods

To observe what effect an alteration in sea-level or channel configuration might have on the tidal asymmetry and range at the 6 reference locations (Fig.1), and thus on the duration certain thresholds are exceeded, the following 3 main steps were followed.

1. Altering the Mersey bathymetry input files[1] and running POLCOMS.

2. Validating the model output[2] and the tidal analysis method for the control run at Gladstone Dock (See section 3: Validation)

3. Analysing the model output using Matlab scripts and functions[3] to investigate changes in tidal asymmetry and range.

2.1. Altering the bathymetry input files.

Due to a slight differences between the model's bathymetry and the actual bathymetry at the time of the sediment sampling, in addition to the 180 m horizontal resolution, some of the 8 locations were positioned on continually dry banks when the nearest grid point was considered. To ensure the points were inundated appropriately, adjustments to their geographical coordinates towards the channels were made (See Table 1). Locations 7 and 8 were later omitted from the analysis as the reliability of the model could not be guaranteed this far up estuary.

[1] Bathymetry input files can be found at /projectsa/intertidal/Mersey.
[2] Model output files can be found at /projectsa/intertidal/Mersey.
[3] Matlab scripts and functions can all be found at /projectsa/intertidal/Mersey/matlab

Table 1: Site location information

Location Number	Location Name	Original Coordinates (Decimal Degrees)	Moved Coordinates (Decimal Degrees)
1	Gladstone Dock	(53.4483, -3.0178)	
2	Liverpool, Albert Dock	(53.4014, -2.9958)	
3	Garston Dock	(53.3464, -2.9078)	
4	Oglet Bay, Speke	(53.3319, -2.8239)	(53.33, -2.82)
5	Hale Head	(53.3208, -2.7906)	
6	Decoy Marsh, Hale	(53.3372, -2.775)	(53.3208, -2.7725)
7	Runcorn Bridge	(53.3469, -2.7417)	
8	Fiddlers Ferry	(53.3553, -2.6778)	(53.3565, -2.68)

In POLCOMS the Mersey Estuary bathymetry originates from LiDAR data collected between 2002 and 2008. For the purposes of running a control run a 'best setup' bathymetry was used (see Norman et al. (2014a) for further details).

A total of nine POLCOMS simulations were carried out (Table 2 and Figs. 5-8).

In order to investigate differences caused by a change in sea-level, sea-level was reduced in 3 of the simulations by 5.46 cm, the equivalent of 30 years of sea-level rise in the Mersey (equivalent to sea-level in the 1970s) averaging 1.82 mm per year (Woodworth et al., 2009).

Table 2: Model scenarios.

Model simulation	Description
Control	No changes to bathymetry or sea-level (using the ‘best setup’ which involved using atmospheric temperature as a proxy for river temperature, includes surface heat flux calculations, sets river salinity to 0 psu but excludes waves in this study for computational efficiency.)
Mindepth5	Estuary bathymetry set to a minimum depth of 5 m relative to the MTL at Gladstone Dock removing the shallowest parts of channel-bank structure.
Northonly	The main channel in the estuary was imposed with a 5 m depth and orientated to run northwards while still at a distance from the north coast (see Fig. 5).
Northoglet	The main channel in the estuary was imposed with a 5 m depth and orientated to run along the coast between Oglet Bay and Hale Head (see Fig. 6).
Southonly	The main channel in the estuary was imposed with a depth of 5 m positioned in the south (see Fig. 7).
Northogletsouth	Both the north channel in the ‘Northoglet’ and the south channel in the ‘Southonly’ positions were imposed to investigate the impact of multiple channels (see Fig. 8).
Northoglet546F	Same as ‘Northoglet’ except the bathymetry across the full Liverpool Bay domain has been raised to represent a historic sea-level of 5.46 cm lower than the present day.
Southonly546F	Same as ‘Southonly’ with the same -5.46 cm sea-level adjustment as in ‘Northoglet546F’
Northogletsouth546F	Same as ‘Northogletsouth’ with the same -5.46 cm sea-level adjustment as in ‘Northoglet546F’

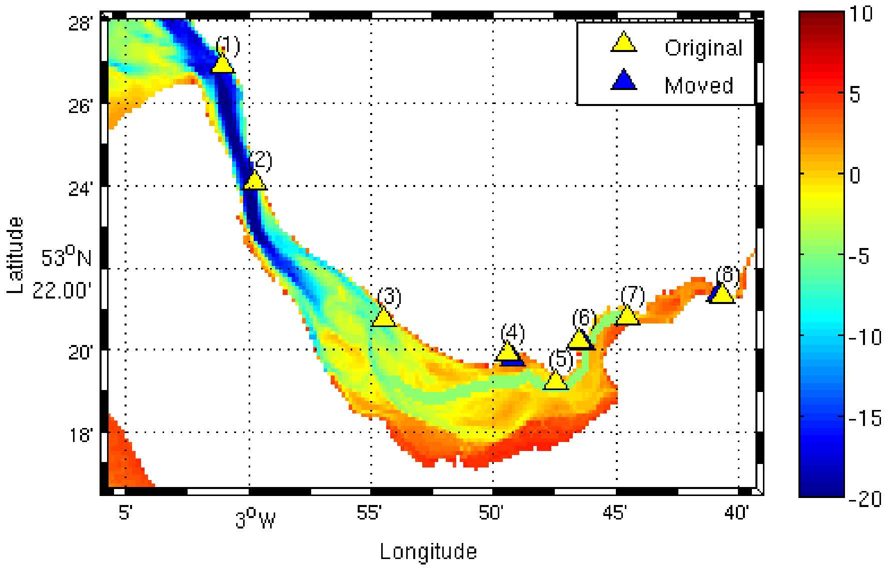

Figure 5: The north channel (in green) configuration applied in the Northonly and Northonly546F simulations, see Table 2.

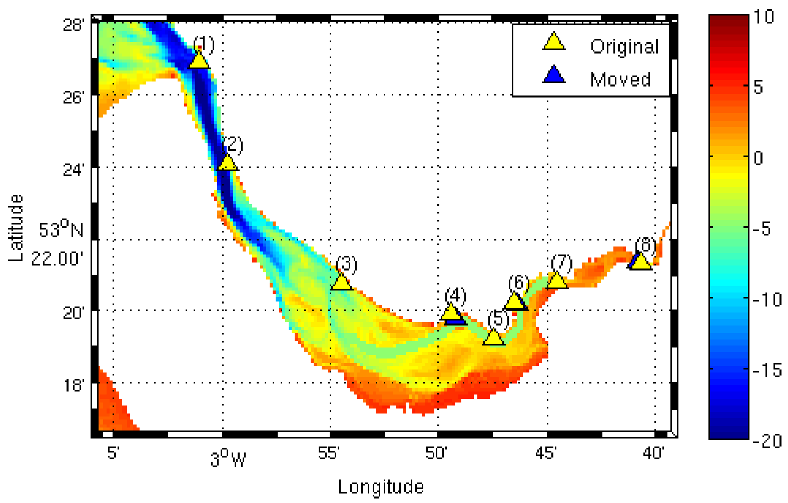

Figure 6: The north channel (in green) configuration in Oglet Bay applied in the Northoglet and Northoglet546F simulations, see Table 2. Note the further penetration of the channel into Oglet Bay (4).

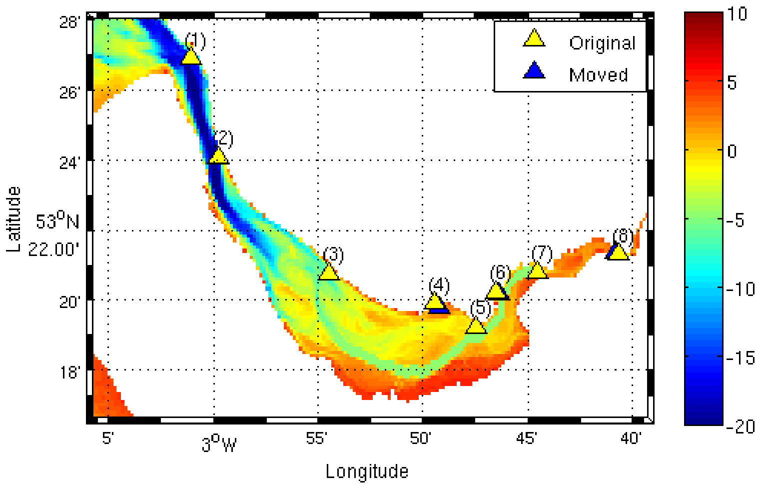

Figure 7: The south channel (in green) configuration applied in the Southonly and Southonly546F simulations, see Table 2.

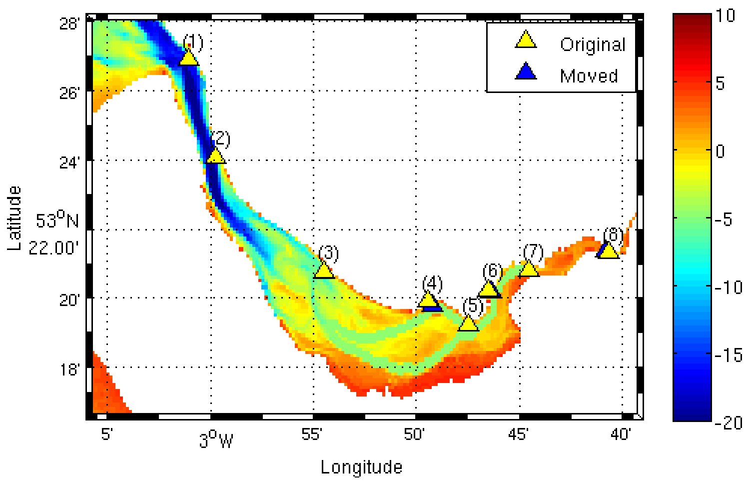

Figure 8: The combined north and south channel (in green) configuration applied in the Northogletsouth and Northogletsouth546F simulations, see Table 2.

The 'modify_bathymetry'[4] script was used to alter the bathymetry (from the control setup, Fig. 1, to the scenario setups, Figs. 5-8), and also adjust the sea-level by modifying the bathymetry reference level (the bathymetry is imposed as m below MTL at Gladstone Dock). The 'bathymetry'[5] script was used as a check to ensure the bathymetry modifications were correct before application within the model.

The positions of the modified 5 m deepened north and south channel routes were decided based on the existing morphology of the estuary, i.e. where there was evidence a minor channel presently

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[4] This script can be found at /projectsa/intertidal/mersey/matlab/modify_bathymetry.m
[5] This script can be found at /projectsa/intertidal/mersey/matlab/bathymetry.m

existed that had probably been a major channel in the past. The only constraint was that the channel configuration had to remain constant in the upper estuary (east of Hale Head, location 5, Fig. 1) so that the river inflows remained unmodified. The south route was positioned to be at some distance from Hale Head whereas the north route passed close to the coring site. The Northoglet channel follows the coast from Oglet Bay to Hale Head and the Northonly route was made to pass south of Oglet Bay before following the coast at Hale Head. These configurations enable the testing of likely historic channel locations to represent what might happen if a channel migrated into Oglet Bay and proceeded to travel past the coring site before migrating out. Such channel migration could be the result of an intense storm in the area.

The majority of the tidal reference sites are permanently situated next to less mobile channels (that are fixed in the model), thus reconstructing sea-level trends in accordance with those observed at the tide gauge location. Oglet Bay and Hale Head are influenced by local channel migrations which potentially cause their sea-level reconstructions to be complicated by changes in the local tidal dynamics. In the simulations the main channel distance from Oglet Bay was varied greatly, while to a lesser extent from Hale Head. These appreciable changes in this local area have been observed in historic bathymetric surveys presented by Mills (2011), which suggest a minor channel meander migrated into Oglet Bay during the period 1971-2000 with a time-varying configuration.

2.2. Model Analysis.

The Matlab package T-tide[6] (Pawlowicz *et al*., 2002) has been applied to extract the tidal signal (tidal constituent amplitudes and phases) from the modelled total water elevation for 2008. A 48-hour period during both a spring and neap tidal phase was selected at each of the 6 locations considered to assess the degree of flood/ebb current asymmetry throughout the estuary.

The attenuation ratio (Eq. 3) has been calculated to quantify the degree of tidal elevation asymmetry within the estuary. The method to calculate this ratio has been modified due to 3 of the 6 considered locations being situated on drying banks (making it difficult to calculate the mean depth locally in a consistent manor). h was taken to be the mean depth of the Mersey Estuary. a was defined as the difference between the mean HW depth and the mean water depth (MD). For locations that remain wet throughout the tidal cycle, the MD becomes equivalent to MTL, while at points that dry this depth is influenced by periods of drying so is above the MTL.

The first step in analysing the attenuation was to use the 'extract_model'[7] Matlab function to extract the modelled SL time series at each location for each model simulation. Second, in order to calculate

[6] T-tide can be downloaded from the SEA-MAT website (http://woodshole.er.usgs.gov/operations/sea-mat/)
[7] This script can be found at /projectsa/intertidal/mersey/matlab/extract_model.m

the mean HW depth, the HWs at each location were identified. This was achieved by creating a Matlab function 'springneapID' [8]that:

1. Extracted the total elevation for Gladstone Dock from the control simulation.

2. Cut the time series so that it has both an integer number of spring-neap cycles and integer number of tidal cycles. (The latter prioritised over the former.)

3. Reconstructed the M_2 and S_2 tidal components from tidal analysis (using T-tide) to create a spring-neap cycle.

4. Identified both the HWs and LWs of this M_2 & S_2 tidal cycle.

5. Calculated the range in meters between every HW and following LW.

6. Calculated the median of this range.

7. Then used the median value of this range to classify 50% of the HWs as spring HWs and 50% as neap HWs over the studied period.

8. The tidal classification for each tidal cycle over the full period was then saved.

Once the springneapID function identified the times at which the HWs of the $M_2 + S_2$ cycle occurred at Gladstone Dock, another function 'meanlevel'[9] used this information to locate the HWs at all other locations. Meanlevel contained a loop that:

1. Extracted the tidal elevation (at each location) both 250 minutes before and after the time that each HW occurred in the $M_2 + S_2$ cycle at Gladstone Dock.

2. Within each of these ranges, all maxima in the total elevation were identified

3. From these maxima the largest was identified as the true HW.

[8] This script can be found at /projectsa/intertidal/mersey/matlab/springneapID.m
[9] This script can be found at /projectsa/intertidal/mersey/matlab/meanlevel.m

4. Any range that had either no maxima (due to fully dry tidal cycles) or had a maximum that was within 5 cm of the bed was disregarded (Set to NaN). This was done to eliminate false maxima that would be detected in the dried out part of the tidal cycle.

Having identified the HWs at each location, the mean and median HW elevation at that location could then be calculated using the meanlevel function. Meanlevel also calculates the mean and median high water spring (HWS) and high water neap (HWN) mean and median levels (or thresholds) using the spring and neap identity tags from the function springneapID. In addition the script calculates the MD by first eliminating depths that are within 5 cm of the bed from the SL elevation time-series before calculating the mean and median values.

Finally the attenuation script was created to calculate Equation 3 using both mean and median values for a at each location for each simulation. The attenuation script also plots the relationship between bathymetry and the attenuation ratio (a/h)

The TD_iF and TD_oF have been calculated to further quantify changes in the shape and asymmetry of the tide at the 6 locations up estuary.

Model data was first extracted (using the extract_model function) at each location for each model simulation. T-tide was then applied to derive the M_2 and M_4 amplitudes and phases before finally calculating the TD_iF and TD_oF for each location and model simulation using the 'AssymAnalysis'[10] Matlab script.

The foram abundance is controlled to a large extent by the proportion of time that a certain saltmarsh altitude is inundated for. Six water level thresholds were chosen in order to compare how changes in the tidal elevation have impacted the 'duration of exceedance' of these thresholds at these locations. The extent to which duration of exceedance of any given saltmarsh altitude changes between location and simulation provides direct evidence of changing tidal characteristics in space through the period of time modelled.

The 6 chosen water level thresholds were:

Mean depth

Median depth

[10] This script can be found at /projectsa/intertidal/mersey/matlab/AssymAnalysis.m

Mean high water springs (HWS mean)

Median high water springs (HWS median)

Mean high water neaps (HWN mean)

Median high water neaps (HWN median)

Duration analysis identifies (for each location and simulation, using 'DuratAnalys'[11])

1. The (absolute) percentage of 2008 that each of the 6 water level thresholds were exceeded for, i.e. 263520 minutes would be 50% of 2008.

2. The duration that each of the 6 thresholds were exceeded over the year expressed as a percentage change relative to the duration of threshold exceedance for the control simulation at that location.

These steps identify if a change in the channel position and/or sea-level results in a change of exceedance duration above a certain threshold at Oglet Bay (and at the other core sites) without affecting other locations for that same threshold.

In order to calculate duration of threshold exceedance, the percentage of time in 2008 that a chosen threshold at a certain location was inundated for, a script was created ('Duration'[12]) that counted the amount of time each water level threshold was met or exceeded (for each location and each model run) during the tidal cycle. The duration script achieves this by calling the function 'CutBeginCutEnd'[13], which provides each time-series cut over the same period as that of the Gladstone Dock control run to consider only complete tidal cycles, and calling the function meanlevel to provide the elevation above the MTL at Gladstone Dock of the 6 thresholds for each location and model simulation. The HWS and HWN thresholds were calculated using the springneapID function which reconstructs the M_2 and S_2 tide only water elevation and then classifies half of the HWs as springs and half as neaps. The meanlevel function then uses the times of these HWSs and HWNs at Gladstone to identify the HWSs and HWNs at other locations and from this calculates the water level thresholds.

[11] This script can be found at /projectsa/intertidal/mersey/matlab/DuratAnalys.m
[12] This script can be found at /projectsa/intertidal/mersey/matlab/Duration.m
[13] This script can be found at /projectsa/intertidal/mersey/matlab/CutBeginCutEnd.m

3. Validating the model output and the application of T-tide.

In order to have confidence in the model simulation, tide gauge observations at Gladstone Dock (location 1, Fig. 1) are used. Tide gauge records for the year 2008 were downloaded from the BODC website[14] for this purpose. Although validation is limited to a single point, other studies (Brown *et al*., 2015; Brown *et al*., 2014a; Brown *et al*., 2014b; Bolanos-Sanchez *et al*., 2014; Bolanos-Sanchez *et al*., 2013) have shown POLCOMS to perform well in Liverpool Bay and within the Dee Estuary. The validation applied here provides a measure of the model's ability to reproduce time-varying sea-level at Gladstone Dock during 2008 to give confidence in the results across the estuary.

In order to validate the model, the following steps were taken:

1. The modelled total elevation was plotted against the observed elevation to examine the model's ability at predicting SL variability (Fig. 9a).

2. Harmonic analysis using T-tide was applied to the observed total water elevation for the year 2008 to extract the tidal constituent amplitudes and phases from total elevation. These constituents were then used to reconstruct the tide and then compared with the tidal elevation provided from tide gauge data, which is based on much longer record thus more accurate, to validate T-tide's ability to extract accurate tides and phases from sea-level time series. In this reconstruction 67 constituents were considered including the shallow water components (Fig. 9b).

3. Harmonic analysis using T-tide[7] was applied to the modelled total water elevation for the year 2008 and compared with the observed tide obtained in point 2 above (Fig. 9b).

The validation comparisons were made using a set of Matlab scripts. Functions were initially made to extract the model data ('extract_model')[15] and observational data ('extract_gauge'[16]) into a format that could be used in multiple analysis scripts. The 'quality_cont[17]' script quality controls the observational data removing erroneous data (exceeding defined thresholds) before calculating the *RMSE*, *D* and *bias* (defined below, Eqs. 5-8) to quantify the skill of both the model and the T-tide analysis over the study period.

[14] https://www.bodc.ac.uk/data/online_delivery/ntslf/
[15] All subsequent Matlab scripts and functions can be found at: /projectsa/intertidal/mersey/matlab/
[16] This script can be found at /projectsa/intertidal/mersey/matlab/extract_gauge.m
[17] This script can be found at /projectsa/intertidal/mersey/matlab/quality_cont.m

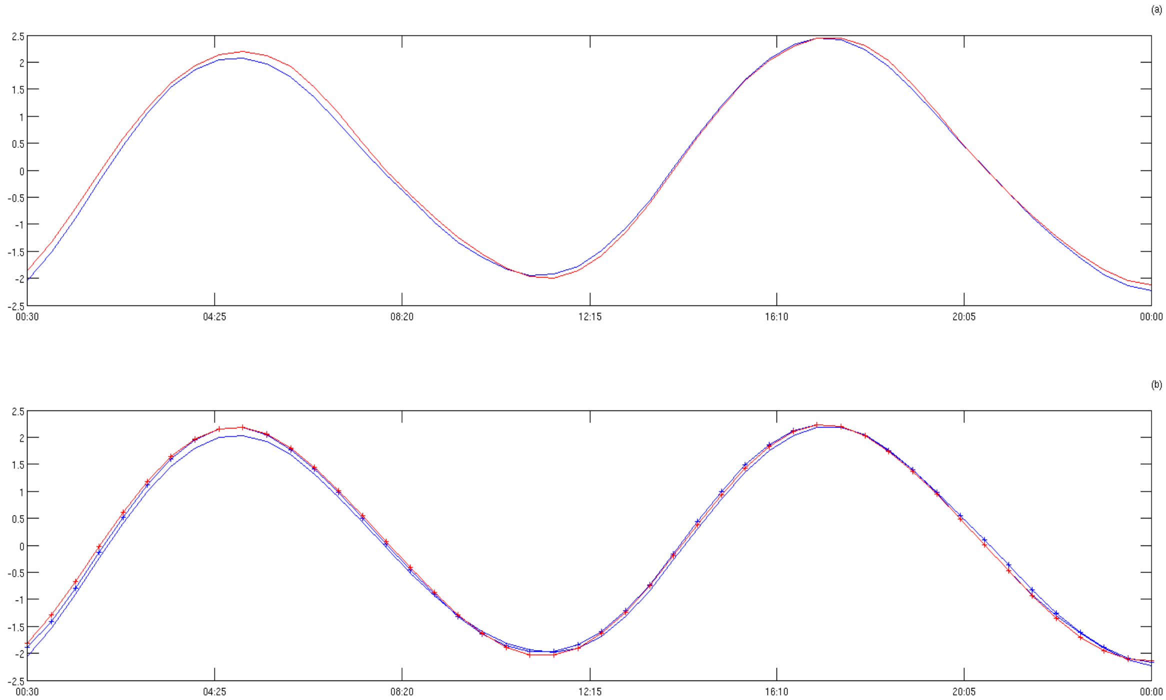

Figure 9: Validation plots for the Gladstone Dock control run over the first 48 hours of 2008. (a) Comparison of the observed SL elevation (blue line) at Gladstone Dock (BODC website) with POLCOMS predicted SL elevation (red line). (b) Comparison of the observed tidal elevation (BODC, blue line) with both the T-tide predicted tide based on the 2008 SL observations (Blue line +) and on the POLCOMS predicted 2008 SL elevation (red line +).

On initial assessment POLCOMS is found to accurately hindcast the time-varying SL (Fig. 9a). A comparison between the T-tide analyses of observed SL variability in 2008 with the long-term BODC tide-gauge analysis confirms that T-tide can accurately extract the tidal constituent amplitudes and phases and can therefore accurately reconstruct the tidal signal (Fig. 9b). Application of T-tide to both the observed and modelled 2008 SL demonstrates POLCOMS accurately simulates the tidal component of the total water elevation (Fig. 9b).

In order to quantify the model's ability to predict tidal elevation over the full annual period, 3 statistical measures were applied. The first was the *Bias*:

$$Bias\ of\ the\ mean = \bar{M} - \bar{O} \qquad (5)$$

Where *M* represents the model values and *O* represents the observed values. The mean, depicted by the over bar, of each is calculated using the following formula:

$$\bar{X} = \frac{1}{n}\sum_{k=1}^{n} X_k \tag{6}$$

The *Bias* gives a sense of whether the values from model tend to be too high (positive value) or too low (negative value). A value of 0 suggests an unbiased estimator.

The *RMSE* is calculated using the formula below:

$$RMSE = \sqrt{\overline{(M - O)^2}} \tag{7}$$

A smaller value indicates better model performance.

The Willmot (1981) model skill score, *D*, gives a value of 1 for complete agreement between model estimator and 0 for total disagreement.

$$D = 1 - \frac{\overline{(M-O)^2}}{\overline{(|M-\bar{O}|+|O-\bar{O}|)^2}} \tag{8}$$

Table 3: Error metrics for Model vs Observations at Gladstone Dock.

	Bias of the Mean	RMSE	Model Skill
POLCOMS predicted SL elevation against observed SL elevation	0.0874	0.1742	0.9981
T-tide's tidal reconstruction of 2008 against the long-term BODC analysis.	0.1320	0.0976	0.9987
T-tide's tidal reconstruction of 2008 of model hindcast against the observation.	0.1320	0.1712	0.9977

Table 3 shows that POLCOMS accurately simulates time-varying sea-level at Gladstone Dock. The model skill is shown to be good, with a value very close to 1. The *Bias* of the mean is positive, suggesting a slight over-prediction but is nevertheless close to zero. The *RMSE* are shown to be small.

Table 3 also indicates T-tide's ability to accurately reconstruct the tide at Gladstone Dock. While there is a tendency for T-tide to over-estimate the tide this is within acceptable limits. The *RMSE* is small in both cases and the model skill is close to 1.

Figure 9a and Table 3 error metrics give confidence that the model can accurately reproduce the SL variability. In comparison with the large tidal range in the region the *Bias* and *RMSE* are small. A good correlation between the observed tidal level obtained from long-term analysis and the T-tide reconstruction applied to the observed annual SL is found, confirming this analysis method is acceptable. This is important as we will be relying on this process to extract the tidal elevation at the other locations where no observations exist. T-tide was found to give erroneous amplitudes and phases when applied to clipped tidal curves on the drying banks.

4. Results

4.1. Spring-Neap plots of the tide in the estuary

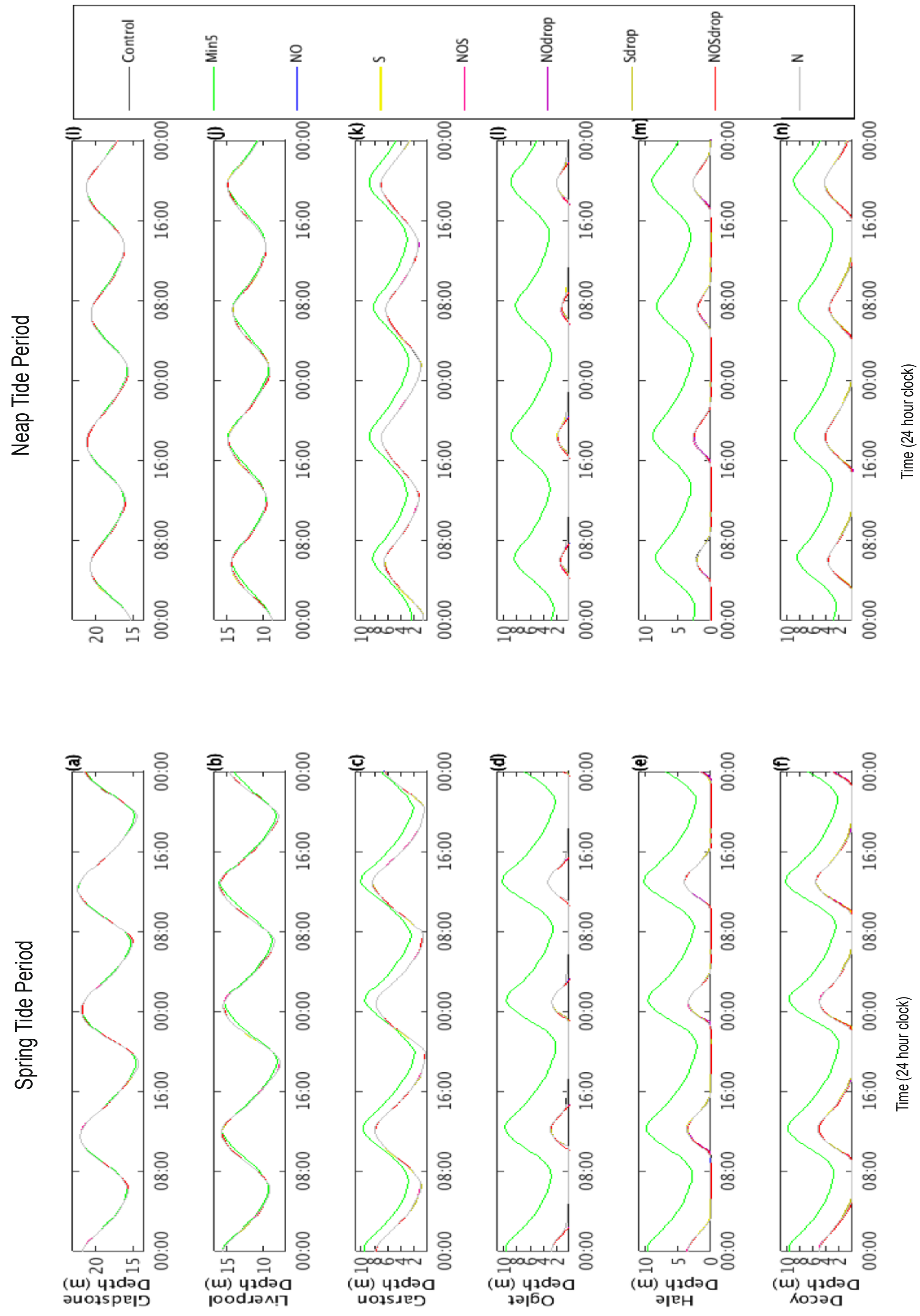

Figure 10: Depth predicted by POLCOMS during a spring (left) and neap (right) phase of the tidal cycle occurring from the 9th to the 11th and the 17th to the 19th of January 2008 respectively. The locations 1-6 are represented by each row sequentially.

The Mindepth5 simulation enables permanent inundation at all locations within the estuary and clearly shows the shape of the tide becoming progressively more saw-toothed with distance into the estuary (Fig. 10).

The deviation of the non-Mindepth5 simulation from the Mindepth5 at locations 4-6 arises due to the shallow banks at these coring sites. The greatest deviation can be seen at Oglet Bay as this has the shallowest site location. Although the Mersey becomes shallower up estuary, Figure 10 does not show a systematic decrease in wetting and increase in drying. This is because the degree of wetting and drying of a location will be influenced by its relative position on the bank and proximity to local channels. The asymmetry in tidal elevation is inferred from Figure 10, but cannot clearly be seen due to the LWs being 'clipped' at locations further up estuary than Garston (location 3).

All of the simulations (apart from Mindepth5, Fig. 10) give similar output for SL depth at the 6 locations except for a slight variation in the tidal cycle at Oglet Bay (this phenomenon is discussed under assumption 2 of Section 5 and an enlarged image of the tidal cycle at Oglet Bay can be seen in Figure 11) where there is a marked difference between the simulations containing the Northoglet channel and those that did not. This difference does not appear at either Hale Head or Decoy Marsh (Fig. 12).

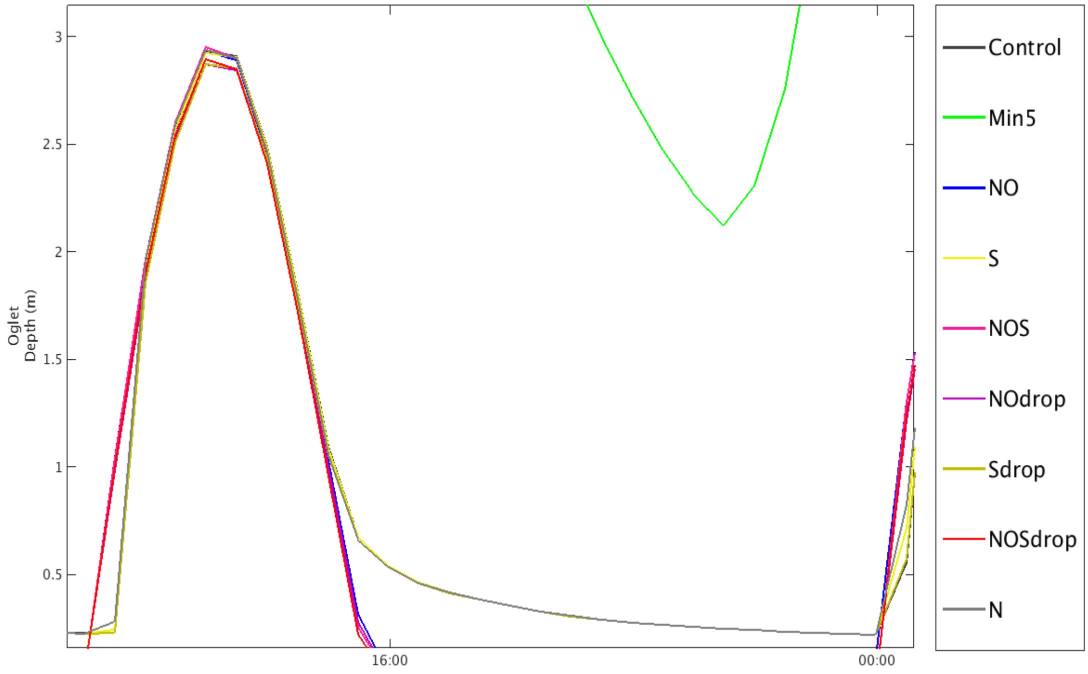

Figure 11: A complete spring tidal cycle at Oglet Bay. The simulations which include the Northoglet channel experience a drying out at low tide whereas the simulations that exclude the Northoglet channel remain wet over the tidal cycle.

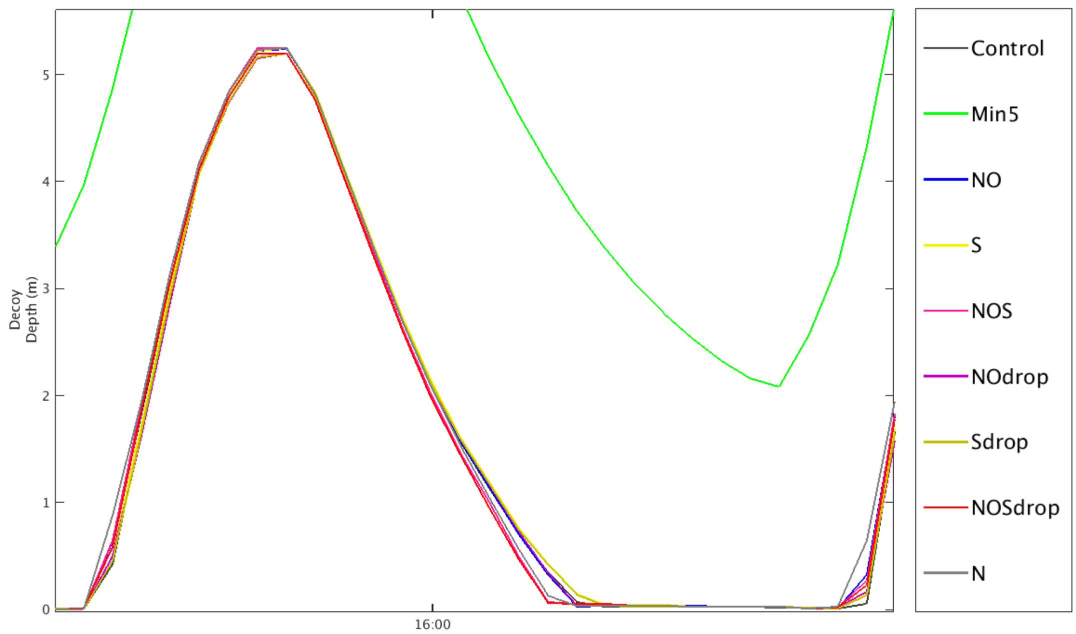

Figure 12: A complete spring tidal cycle at Decoy Marsh. All model simulations result in similar tidal curve.

4.2. Attenuation Analysis Results

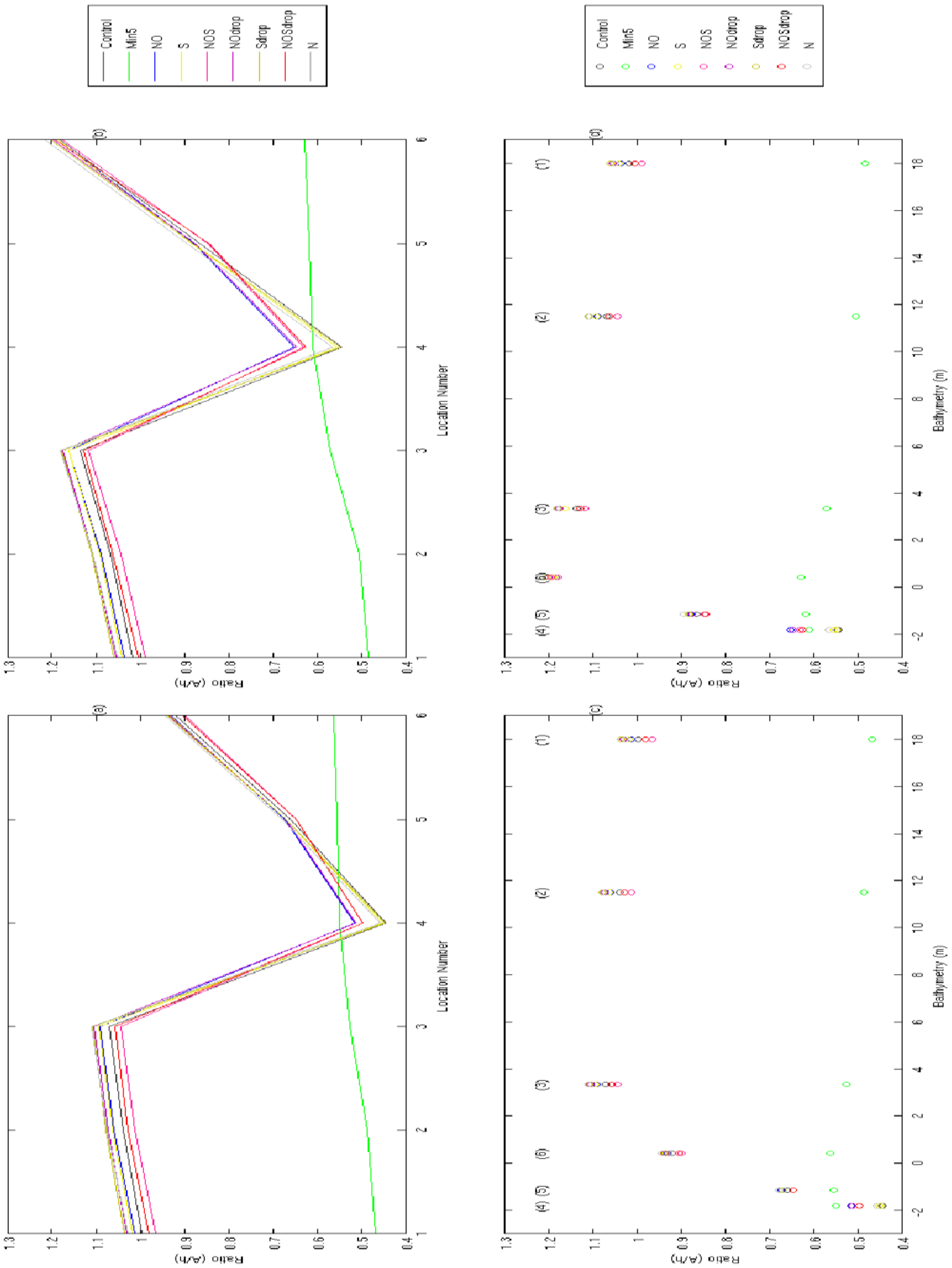

Figure 13: Attenuation plots. (a) and (b) show how the parameter (*a/h*, Eq. 3) varies with distance into the estuary for each model simulation. (c) and (d) show the relationship between bathymetry (m below MTL) and *a/h*. The left-hand panels use the mean *a* whereas the right column uses the median *a*. In the lower row the location is identified by its number in brackets, as in Fig. 1.

'*h*' is defined as the average depth of the Mersey for a given simulation and *'a'* is defined as the mean HW depth minus the mean wet depth at each location. The range in the values of *a*/*h* (Fig. 13) and its value at the mouth of the estuary indicate that the Mersey is strongly flood dominant (Eq.3 >0.3).

The variability in this metric also show channel configuration, whether single or multi-channel, has an influence on the local tidal amplitude, *a*. Even though the channel modifications are implemented mid–estuary, the tides are influenced to some degree across the domain, while changes in sea-level have much less an impact. Unlike the other locations there is a noticeable divergence between the simulations with a Northoglet channel and those without suggesting a change in value of *a* as defined above (Fig. 13a and b). Towards the mouth (Locations 1-3) there is a more uniform response between locations, due to an increasing '*a*' as a result of an increase in the mean wet depth. There is a sudden change at location 4 followed by a rapidly increasing trend for location 5 and 6. The fact locations 4 and 5 have low values can be explained by the reduced HW depth at these sites (Fig. 10) relative to the other locations. Location 6 has a low HW depth, but the greater duration of wetting relative to locations 4 and 5 also reduces the mean wet depth comparatively restoring the ratio back to similar values as locations 1-3.

The nearer the channel to Oglet Bay the less attenuated the tide becomes (greater *a* due to a reduced mean wet depth in response to a greater duration of bank drying). When both the Northoglet and South channel are considered together this also modifies the tidal dynamics, slightly reducing *a* at Oglet Bay compared with the Northoglet only simulation.

Figure 13 (c) and (d) show clear attenuation of the tide in response to local depth. The ratio *a*/*h* rapidly increases (suggesting reduced attenuation) with increased depth up to approximately 4 m. This is due to an increase in *a* which results from the balance between an increased mean HW depths and reduced mean wet depths. The ratio then slowly decreases (attenuates) for increasing depth greater than approximately 4 m. This is when wetting and drying is no longer complicating the mean wet depth and *a* becomes more attenuated with greater water depth.

The Mindepth5 simulation (Fig. 13) shows little variation as the smoothed estuarine bathymetry removes much of the channel-bank configuration. There is a general trend of greater *a* values with distance into the estuary, the locations with depth < 5 m now have a 5 m depth imposed. The shallower locations clearly have an increased ratio due to a reduced mean wet depth relative to the deeper locations out weighing the reduced HW elevations. For all other simulations the spread in data at Oglet Bay, which is the shallowest point of interest (location 4), is greatest in response to the imposed local channel configurations. These results also support the findings of Ridgway *et al*. (2012), showing an initial increase in *a* up until Eastham with distance into the estuary before decreasing further into the estuary.

4.3. Asymmetry Analysis Results

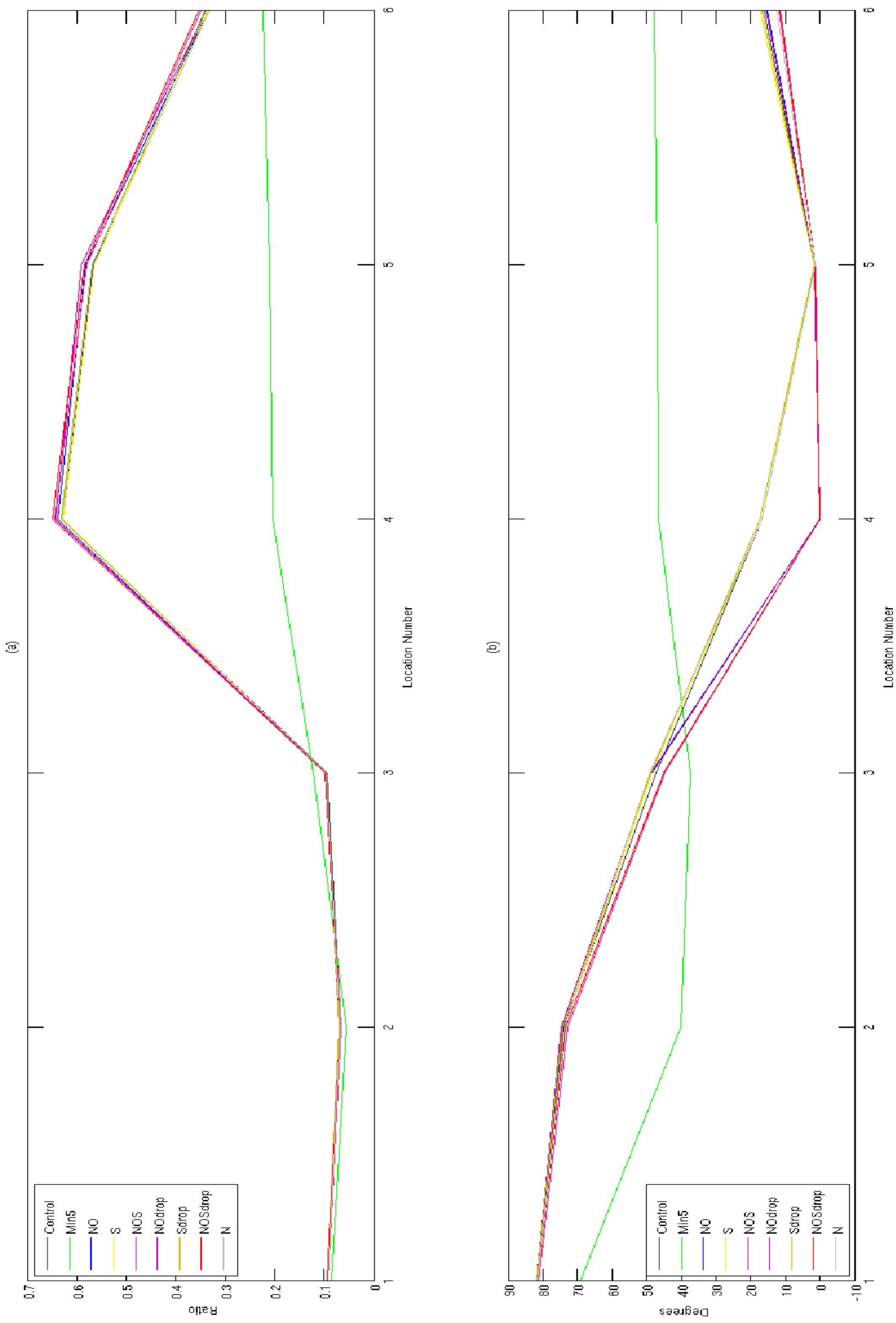

Figure 14: Asymmetry Analysis. a) Tidal Distortion Factor (*TD_iF* Eq.1) and b) Tidal Dominance Factor (*TD_oF* Eq. 2) for each location (up to Decoy Marsh) with increasing distance into the Mersey.

According to Friedrichs and Aubrey (1988) a *TD_iF* (Eq. 1) of greater than 0.01 indicated significant tidal distortion. Here although the *TD_iF* is higher than this for the 3 outermost locations, a large increase occurs at Oglet Bay (the shallowest location) before decreasing at Hale Head and Decoy Marsh. Figure 14(a) shows the same trends as Figure 13 (a and b) only inverted. Generally the Mindepth5 simulation shows a gradual increase in the *TDiF* up estuary.

The *TD_oF* gives an indication of flood/ebb dominance in the tidal currents with 0-180 degrees being flood dominant and 180-360 being ebb dominant. Presuming a value of 90 degrees indicates a maximum in the flood dominance, Figure 14(b) suggests that flood dominance was at a maximum at the mouth of the estuary and decreased with distance into the estuary. This could be the result of the established estuarine banks having greater local frictional influence on the currents at higher water elevations and a constraining influence at lower elevations causing a change from strong flood to neither flood nor ebb dominance in the tidal currents at shallow locations where wetting and drying becomes important locally.

There is a clear large decrease in flood dominance at Oglet Bay (location 4, Fig 14(b)) compared with the other locations for the simulations that included the Northoglet channel. This is the consequence of the presence of a deep channel within established saltmarsh banks modifying the tidal flow.

4.4. Duration Analysis Results

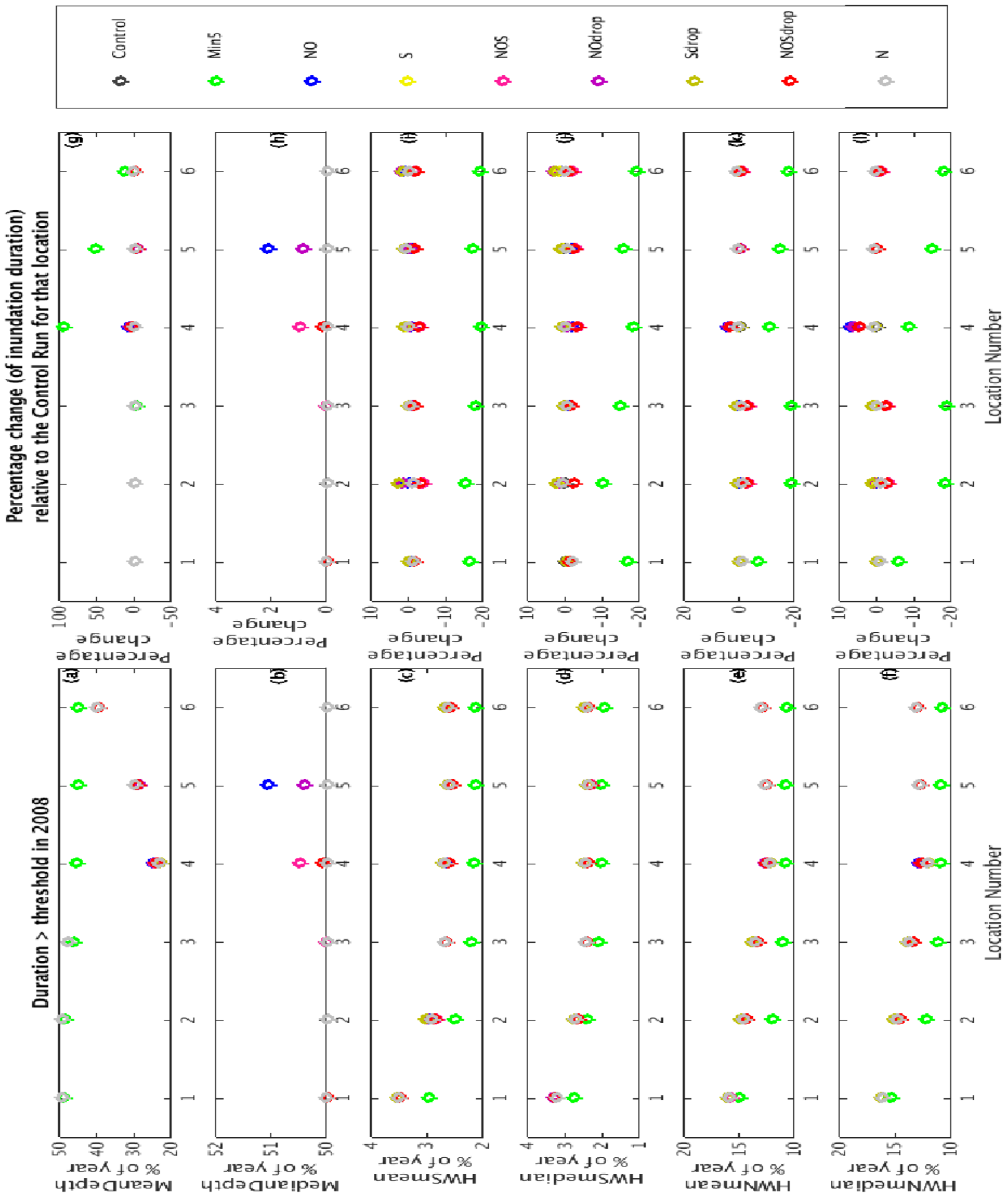

Figure 15: Duration of threshold exceedance for locations 1-6 with increasing distance into the estuary. The rows represent the 6 different threshold levels (section 2.2). The left-hand panels show the percentage of the year that the 6 threshold levels are exceeded. The right-hand panes give the duration of exceedance of each threshold relative to the control simulation at that location calculated using equation 9. Note the y-axis limits vary, but the scale is constant in the first column to clearly show the results for each threshold.

$$\frac{Duration\ of\ simulation\ at\ location - Duration\ of\ simulation\ at\ Gladstone\ Dock}{Duration\ \ of\ simulation\ at\ Gladstone\ Dock} * 100 \quad (9)$$

Figure 15 (a-f) shows that for the first 3 locations, which never dry out, the SL mean and median levels are exceeded for roughly 50% of the time during all the simulations. At locations 4 to 6 (where the banks can wet and dry) the percentage falls noticeably.

Across the HWS and HWN thresholds on Figure 15 (c-f,i-l) there is a general reduction in the threshold exceedance duration between Gladstone Dock (Location 1) and Oglet Bay (Location 4). We focus here on the changes in exceedance time (spread in data) at each location in response to channel and SL changes. Up-estuary of Oglet Bay, the threshold exceedance duration shows little variability, due to channel variation applied in the mid-estuary having limited impact in the upper reaches of the estuary.

For most threshold levels and locations a change in channel position does not result in a significant variation in the duration of threshold exceedance (low spread in data points). Locations 2 & 4 show the greatest sensitivity. At location 2 no discernible pattern between simulations containing the Northoglet channel and those that did not could be found. Oglet Bay (Location 4) did show a consistent pattern but this pattern changed depending on the threshold applied. For both the HWS thresholds (Fig. 15 (i) and (j)), the simulations that contained the Northoglet channel were exceeded for a slightly smaller proportion of the year than the simulations without, whereas for both the HWN thresholds (fig. 15 (k) and (i)) the opposite was true.

The biggest variation in threshold exceedance duration can be seen at Oglet Bay for the median HWN threshold level (Fig.15(e)). Here the simulations that contained the Northoglet channel exceeded the threshold for an additional 0.7% of the year (equivalent to 60 additional hours of inundation) compared with the runs which did not include the Northoglet channel. This variation drops off noticeably at locations 5 & 6.

Although the duration of inundation at thresholds between the 0 – ~ 0.5 m depth range (dry bank depth to approximate depth of the pool at LW – See discussion, assumption 2) was not specifically tested, Figure 11 indicates that at these depths (depending on the precise threshold depth chosen) a much larger change of inundation duration would occur at Oglet Bay in the simulations that included the Northoglet channel compared to those that did not. This substantial change in the duration of exceedance is not evident at Decoy Marsh because in all simulations the bank dries (See Fig. 12). The changes in the duration of inundation at Oglet Bay are in response to the change in width of the tidal wave, which is variable with height (Fig. 11). At Decoy Marsh the change in shape of the tidal wave is negligible (Fig. 12), thus variability in the duration of threshold exceedance is relatively uninfluenced.

5. Discussion

The principle aim of this project was to investigate whether localised changes in tidal dynamics, range and asymmetry could provide an explanation for Mills' (2011) anomalous saltmarsh-based sea-level reconstruction at Oglet Bay. In order to explore what our results might mean a brief overview of how MTL is reconstructed is first given.

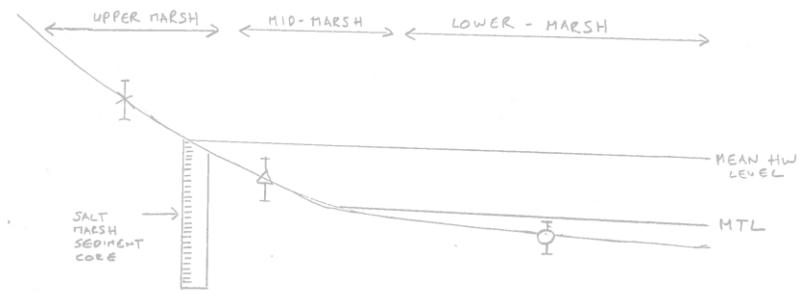

Figure 16: A schematised cross section of an estuary saltmarsh. 3 different hypothetical foram species are shown. The 'O' foram prefers to live in the lower part of the upper marsh, the 'Δ' foram in the mid part of the upper marsh-marsh and the 'X' foram in the upper part of the upper-marsh.

In addition to taking a sediment core to identify the time-variation in foram distribution, a survey over a cross-shore transect is carried out to identify where present-day foram species prefer to live relative to the present day tidal levels (e.g. mean HWS).

The core is then divided into smaller segments of the order a few centimetres and these segments are then dated using radionuclide analysis. The number of each foram species within each segment is then tallied to identify the tidal regime at this location through time (as explained in Fig 17 below.)

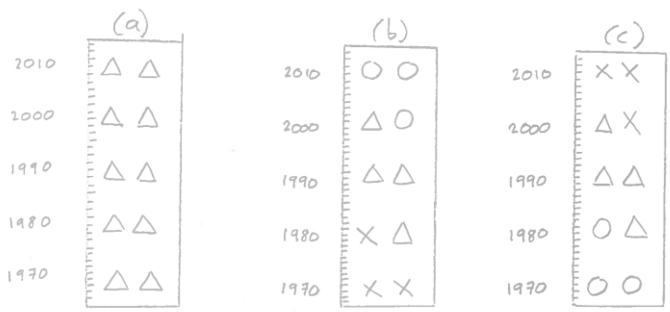

Figure 17: Three separate cores which suggest three versions of events. (a) suggests that MTL has remained unchanged over the period 1970-2010 whereas (b) suggests a rise and (c) suggests a fall. The foram species represented by each symbol are defined in Fig. 16.

It is then possible to create a MTL chronology based on the abundance of different foram species that are found to be present at each depth in the sediment core.

In Mills' (2011) the Oglet Bay reconstruction suggests that MTL dropped by around 50 cm sometime around 1993 before rising 50 cm again in 2003. As sea-level is unlikely to have fallen locally, something else must account for it.

Three assumptions have been made in the reconstruction process.

Assumption 1

The first assumption is that the tidal range at Oglet Bay is the same at Gladstone Dock.

Foram species that occupy the upper marsh area live at a far narrower range of altitudes than lower marsh foram and consequently have less uncertainty attached to them. Because of this it is typical to use the core to reconstruct a higher tidal level (e.g. mean HWS) and MTL will then be inferred by subtracting the difference between a higher tidal level, e.g., mean HWS, and MTL found at the nearest tide-gauge (in this case Gladstone Dock) to arrive at the local MTL. Should this difference between HWS and MTL at Oglet Bay change over time in response to a change in tidal range then the inferred MTL could be erroneous. In the case of a substantially lower tidal range than at Gladstone Dock the inferred MTL may have been systematically under-estimated.

Unfortunately we are unable to know the MTL at the locations that dry out during the tidal cycle (locations 4-6) because we do not have information about LW levels (due to the drying out of the bank at the coring site as the waters drop) however, for the first 2 locations which always remain wet, the tidal range (calculated by subtracting the depth of the lowest tide of 2008 from the highest and dividing by 2) increased from 4.84 m at Gladstone Dock to 4.95 m at Liverpool Albert Dock, suggesting that the range is unlikely to remain fixed. Such a change is also suggested by Ridgway et al. (2012) through a change in tidal amplitude.

In light of the response of the tide at each location and scenario, it seems unlikely that the tidal range remains the same as Gladstone Dock. Although if a consistent difference was applied through time it would enable the extraction of the long-term trend as long as the local difference in mean HWS and MTL remained constant in time. If a location is susceptible to channel migration, using a constant difference can lead to deviations from the background trend in SL. This is discussed further in Assumption 2.

Assumption 2

Another assumption that has possibly been made is that the mean tidal range at a given location remains constant throughout the period of deposition. If we were inferring the MTL from the mean HW level by subtracting a fixed difference in altitude, and this difference turned out to vary in time depending on channel position, then this would make it more difficult to accurately infer the MTL. At Oglet Bay the 'mean HWS' to 'MTL at Gladstone Dock' difference in altitude varies between 4.38 and 4.41 m for the 5 different channel configurations under present day sea-level (and between 4.32 and 4.41 m if the runs where SL has been lowered by 5.46 cm are included), which suggests that for any given location, migration of the channel is unlikely to greatly influence HW amplitude.

If a channel similar to the Northoglet channel had migrated into Oglet Bay, Figure 10 suggests that the bank (at the precise coordinates under investigation) would have undergone a change from being permanently inundated throughout the tidal cycle to becoming dry at low tide. The presence of the channel reduces the inundation time due to effective drainage of the saltmarsh surface. This was likely caused by water being pooled or slowly draining at a lower tidal elevation when the Northoglet channel was absent and draining away when the Northoglet channel was present reducing inundation time. This is a consequence of the local change in shallow bathymetry due to the presence of the channel (see Fig. 18). No such pooling was observed at Decoy Marsh as the banks dried out (see Fig. 19).

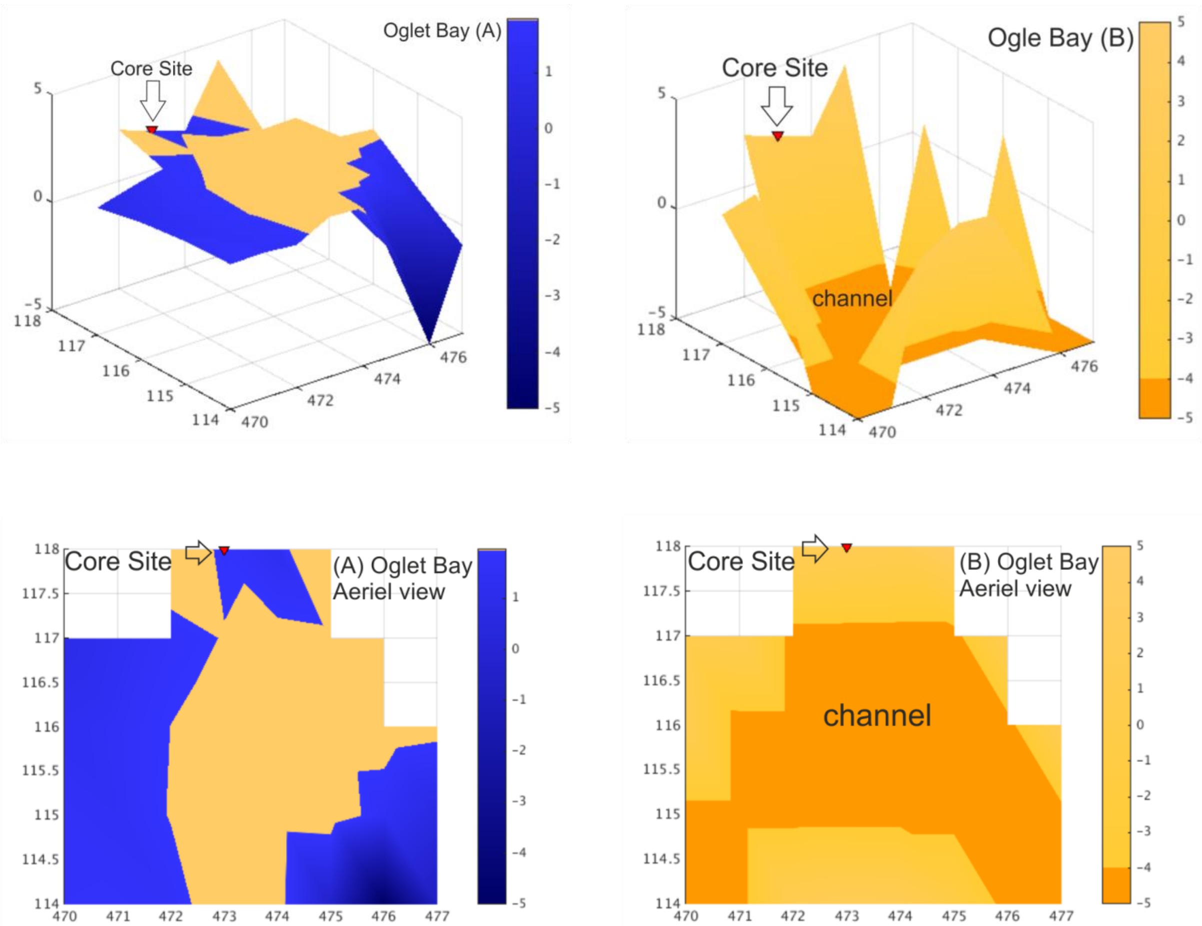

Figure 18: (a) shows the 3D bathymetry of Oglet Bay at the core site location when the 5 m deep

Northoglet channel is absent. When the water level (in blue) falls to a depth of 14 cm above the saltmarsh surface the 'blue pool' is completely cut off from the rest of the Mersey. (b) shows the 3D bathymetry of Oglet Bay when the 5 m Northoglet channel is imposed in the model. The orange colour in (b) indicates the bottom of the channel (4-5 m deep).

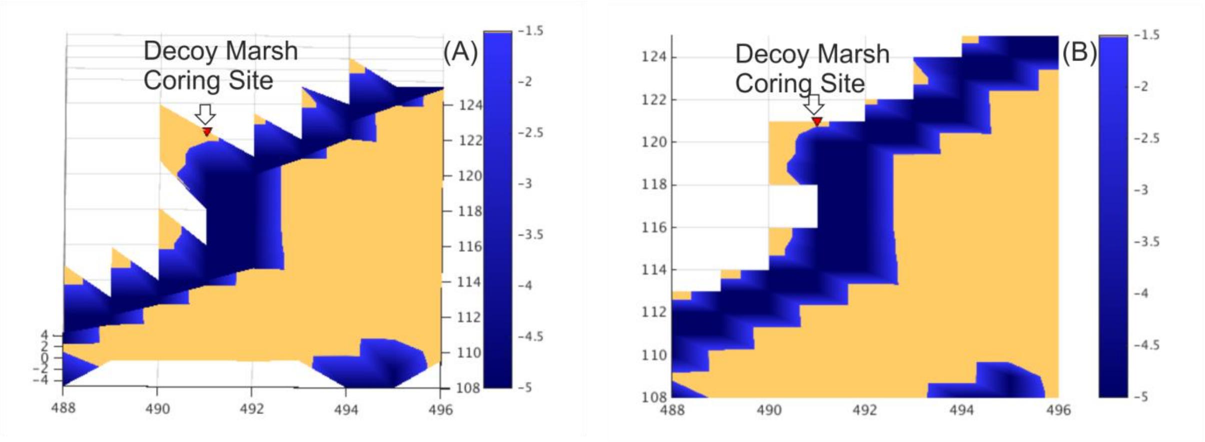

Figure 19: (a) Shows the coring site at Decoy Marsh (from an elevation of 80 degrees) drying out as the tidal level drops beneath it. Unlike the Oglet Bay coring site, no pools of water are evident. (b) shows the same as (a) just from an aerial view (an elevation of 90 degrees).

Bank drying would have extended the zone in which the foram could live in the downwards direction towards the channel across the bank (Fig. 20). The absence of the channel would enable forams that normally occupy lower elevations to occupy higher elevations due to a prolonged inundation period. The temporary presence of a channel, in contrast, would cause a temporary increase in the proportion of upper saltmarsh forams, suggesting a fall in sea-level. If the Northoglet channel had continued to migrate out of Oglet Bay, the forams would then have had to increase their bank altitude to return to the appropriate level of inundation as the marsh rebuilt. As this difference in the low water level only occurs at Oglet Bay (and not at Decoy Marsh) it is a possible explanation for the localised anomaly found in Mills' (2011) reconstruction of MTL at Oglet Bay. The change in low water depths varies from approximately 0.5 m to dry. The change in range is therefore relatively large and similar in magnitude to the dip in the reconstructed SL record.

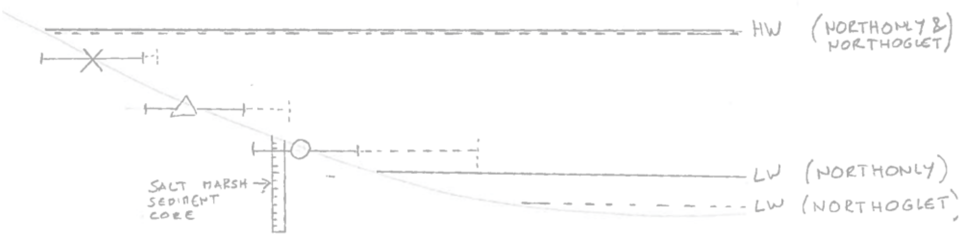

Figure 20: The 3 shapes represent different foram species that thrive at different saltmarsh altitudes (see Fig.

17). When the Northoglet channel is present the LW becomes lower and the species are able to live at lower altitudes.

Assumption 3

The third assumption is that saltmarsh altitudes at different tidal levels (e.g. mean HWS, mean HW and mean HWN) are always inundated for the same proportion of time. If a particular foram species is known to live at the mean HWS altitude at one location at one point in time, it does not necessarily mean that that foram species will always be found at the mean HWS altitude at other locations or under different channel scenarios. They will be found where the duration of exposure is the same, representing the optimum environment for them to thrive. Although the cross-sectional survey identifies the local HWS species, relative to present-day sea-level, local changes in tidal asymmetry in response to channel evolution can modify either or both the HWS elevation and the duration of inundation above this threshold. This can be a consequence of local tidal asymmetry and bank inundation modifying the exposure time. Figure 15 shows that for the mean and median HWN and HWS thresholds there is a fairly large variation between locations in the proportion of time that these thresholds are exceeded. For example for the control run, the HWN mean was inundated for around 16% of the year at Gladstone Dock but was only inundated for about 12% of the year at Oglet Bay. Forams that thrive around HWN may therefore live at lower altitudes in Oglet Bay than Gladstone dock to achieve the same duration of inundation per annum. The reason for the lower duration at Oglet Bay is likely to be related to the increase in the tidal distortion up estuary (see Fig. 14(a)). Figure 15 also shows that by altering the position of the main channel, it is possible to alter the proportion of time that a particular threshold is exceeded for at a particular location.

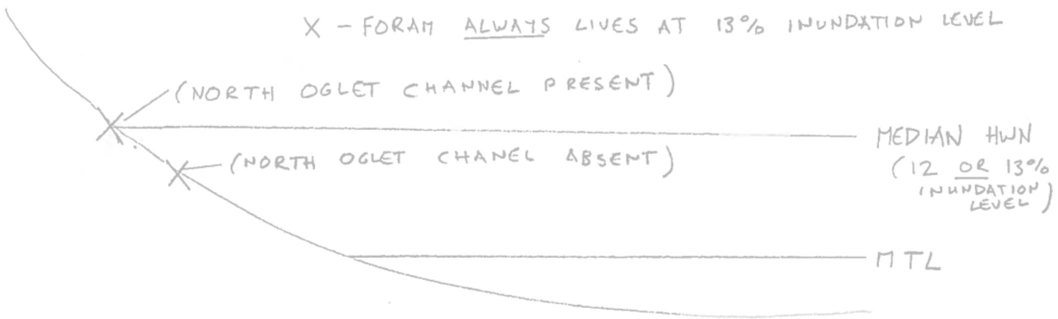

Figure 21: (a) A hypothetical foram species 'X' that lives at Oglet Bay at an altitude where it is inundated for 13% of the tidal cycle. This coincides with the median HWN level when a Northoglet channel is present. In scenario (b) the foram species still lives at a location where it is inundated for 13% of the tidal cycle, however, this no longer coincides with the median HWN level which is now only inundated for 12% of the tidal cycle in a scenario where the Northoglet channel is absent.

Figure 21 demonstrates the most extreme case that was found during this project (a 0.7% increase in duration of exceedance of the HWN threshold, see section 4.4) of a change in the tidal asymmetry (Fig. 15, Eq. 2 at Oglet Bay) and tidal distortion factor (Eq. 1) resulting in changes in the exceedance duration of a particular altitude. When the tidal wave changes, the assumptions that foram will live at the same fixed height difference from a given tidal level may not hold. The small increase in duration of tidal elevations above MHWN would have allowed this species of lower HW elevations to migrate to higher saltmarsh surface altitudes. The fact the crest of the wave (when the Northoglet channel is absent) is wider at lower elevations and the same at the peak of the crest suggests the lower HW species will have migrated over greater vertical differences than those that live at the highest elevations. This supports the suggestion the lower saltmarsh species would increase in abundance at a core site which could be interpreted as a rise in sea-level.

This median HWN altitude was of particular interest because the presence or absence of the Northoglet channel caused a change in the proportion of time above this threshold for Oglet Bay but not Decoy Marsh. While interesting, the variations in the duration of inundation of these threshold is too small to account for the dip in Mills' Oglet Bay reconstruction. A much larger change in inundation duration would have been observed at Oglet Bay (see Fig. 11) had a 0 – 0.75 m depth threshold been applied. Such a threshold was not used due to mean/median HW being the lowest usable threshold over all 6 locations.

Ultimately while changes in tidal asymmetry and range may have occurred due to changes in the location of the main channel, this study has been unable to demonstrate such effects. HWs at Oglet Bay showed little variation and the dry banks masked any potential changes in the LWs. We have only been able to show at the local scale a change in the inundation of saltmarshes and small changes in duration of inundation, due to the change in width of the crest of the tidal wave.

6. Conclusions.

Changes to tidal range and asymmetry at Oglet Bay were difficult to quantify as the wetting and drying of the banks obscured the LWs. T-tide indicated a slight change in the tidal dominance factor (Eq. 2) between the simulations with the Northoglet channel and those without, but this result may be unreliable as T-tide's ability to calculate accurate tidal constituent amplitudes and phases may be compromised when applied to the clipped tidal curves of locations 4-6.

Using POLCOMS we find that estuarine channel positions influences the tidal dynamics at Oglet Bay in 2 different ways.

The first is that a change in tidal asymmetry can affect the proportion of time that specific thresholds are inundated for. The greatest example of this is the median HWN threshold being inundated for 13% of the year when a Northoglet channel is present but only 12% of the year when Northoglet channel is absent. This difference equates to a difference in inundation of approximately 85 hours over the year. However, it was also found that the presence of the channel led to a shorter exceedance duration (relative to the runs when the Northoglet channel was absent) when considering the mean and median HWS thresholds. This pattern is the result of a widening of the lower part of the tidal wave crest and thinning of the upper part. In consequence the HWN foram species could have migrated higher up the saltmarsh and the HWS foram species could have migrated lower down the saltmarsh, indicating a reduced tidal range. However, a change in the foram abundance toward a greater increase in the HWN species in this case, suggests a SL rise rather than fall.

The second more noticeable change is in the wetting and drying at the Oglet Bay location. The presence of a Northoglet channel at Oglet Bay led to a drying out of the banks when the tide was falling that did not occur when the channel was absent. This effect increases the intertidal zone towards the channel enabling the forams to migrate towards lower altitudes covering a larger width of marsh. The shift in forams at all tidal threshold towards the channel would indicate a sea-level fall. In this case the change in depth due to drying (~50 cm) is approximately the same as the discrepancy seen in the core.

As the first of these two effects appears to work to move the forams both up and down the banks (depending on the threshold in question), the latter is more likely to have had a net effect as all foram species would have migrated in the same direction. In our scenario the bank dried out when the Northoglet channel was present, foram could therefore live at lower altitudes than when the modelled site was permanently inundated. This could have resulted in a sediment core near to the modelled site that gave the impression of SL fall. This change (Fig. 11) is not far from the actual 50 cm drop observed (Fig. 3). As this effect only occurs at Oglet Bay and not Decoy Marsh or any of the other locations, it can potentially explain the localised drop found in Mills' (2011) sediment core reconstruction if indeed a channel did migrate in and then out of Oglet Bay during the period in question.

In order to simulate conditions in the Mersey 30 years ago, the Northoglet, Southonly and Northogletsouth simulation were run for a second time with SL dropped by 5.46 cm. Only very small changes in the proportion of time that different thresholds were exceeded for could be found as a result. Channel migration is therefore considered as the main driver that could explain the deviation in the sea-level reconstruction found by Mills (2011).

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