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Sea-level rise and local tidal range changes in coastal embayments: An added complexity in developing reliable sea-level index points *

Elevação do nível do mar e variações locais da amplitude da maré em reentrâncias costeiras: uma complexidade suplementar no estabelecimento de pontos fidedignos indicativos do nível do mar

Eduardo Leorri @, 1, Ryan Mulligan 2, David Mallinson 1, Alejandro Cearreta 3

ABSTRACT

This paper re-evaluates the late Holocene sea-level reconstructions from Delaware Bay and assesses the possible effect of tidal range changes over the last 4000 years. Previous work suggested that the differences found between the northern and southern areas of the Delaware Bay (USA) could be explained by isostatic rebound. However, our results derived from tidal modeling suggest that at least 25% of this difference could be explained by changes in the tidal range due to amplification or attenuation of tidal waves over shallower bathymetry. Furthermore, indications of large changes of the tidal range over short distances might suggest that integration of sea-level index points from different areas should be performed with caution. New sea-level trend estimates have been calculated at 1.17±0.2 mm yr^{-1} in the southern area, and 1.55±0.2 mm yr^{-1} in the north.

Keywords: Holocene, sea level, tidal range, estuary, Atlantic Ocean.

RESUMO

Neste trabalho reavalia-se a reconstituição da subida do nível médio do mar, em Delaware Bay (EUA), e o possível efeito das variações da amplitude das marés ao longo dos últimos 4000 anos. Vários autores consideram que as diferenças registadas entre as zonas norte e sul desta baía, podem ser explicadas por um fenómeno de ressalto isostático. No entanto os nossos resultados, obtidos a partir de modelação das marés, sugerem que pelo menos 25% desta diferença pode ser explicada por alterações da amplitude das marés, devido à amplificação ou à atenuação das ondas de maré contra uma batimetria pouco profunda. Além do mais, as grandes variações da amplitude das marés obtidas, quando estabelecidas em distâncias curtas, sugerem que a integração dos marcadores do nível do mar de áreas diferentes deve de ser feita com precaução. As estimativas agora obtidas para a subida do nível do mar em Delaware Bay, correspondem a 1,17 ± 0,2 mm ano^{-1} *na zona sul e a 1,55 ± 0,2 mm ano*$^{-1}$ *na zona norte da baía.*

Palavras chave: *Holocénico, nível do mar, amplitude das marés, estuário, Oceano Atlântico.*

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1. INTRODUCTION

The number of studies of sea-level trends over different time scales is increasing substantially due to the possible impact of this phenomenon in coastal areas and, therefore, in recreational, industrial, and military infrastructures. Many studies of sea-level trends utilize geological studies that, for instance, can be used to compare against current instrumental data (*e.g.:* Engelhart *et al.*, 2009). In this approach, the last 4000 years of sea-level trends are subtracted from the 20th century records since both are equally affected by the same vertical land movements (see for instance, Shennan & Horton, 2002; Engelhart *et al.*, 2009). This method provides an accurate pattern of changes in rates of sea-level rise. By subtracting the background, pre-industrial rate of local relative sea-level rise from the rate of rise determined for the 20th century, an estimate of relative sea-level rise acceleration can be made that is independent of millennial scale crustal movements, for example, isostatic recovery (Gehrels, 2010). This approach is usually based on a reevaluation of previously published data with large vertical errors (*e.g.,* Engelhart *et al.*, 2009) and does not assess possible sea-level oscillations within the error limits during that period. Since geological sea-level recontructions will be used as a local background value to ascertain indrustrial and postindustrial trends, they are essential for regional projections that will be used by local and regional goberments to develop adaptation strategies to the current climatic scenario.

One potential source of error in this approach is the possible change in the tidal range (Shennan & Horton, 2002). While a precise paleo-bathymetry and fine grid (*e.g.,* <1 km) is needed to produce high resolution reconstruction, this is not always possible due to the lack of such data; however, it is clear that tidal ranges in coastal regions might have changed over time as the continental shelf is transgressed (Austin, 1991; Hinton, 1996) and reconstructions of tidal currents might incur additional errors not yet accounted for.

In fact, tidal range variations may occur on Milankovitch time-scales as tidal characteristics are modulated by obliquity with a 20.9 kyr period, (Pugh, 1987) similar to the 18.6 yr lunar nodal cycle (McKinnell & Crawford, 2007). Changes, then, in the tidal range might be reflected in sea-level reconstructions for the Holocene as they depend on calculations that include the tidal range (*e.g.,* Leorri *et al.*, 2008).

At present, several reconstructions of Holocene sequences rely on data not corrected for possible tidal effects (*e.g.,* Engelhart *et al.*, 2009). These reconstructions are then used to infer vertical land movements as differences between local trends are assumed to reflect isostatic adjustments (Leorri *et al.*, 2006). However, some of these curves present obvious inflection in the rate of rise, as in the case of Delaware (Leorri *et al.*, 2006), while isostatic adjustment should be steady.

The aim of this paper is to assess the possible influence of tidal-range changes on late Holocene sea-level reconstructions as they are essential to understand current trends and calibrate isostatic models.

2. MATERIALS AND METHODS

2.1 Field observations

We focused our analysis on Delaware Bay, USA (Figure 1) as it has been the subject of intense sea-level studies (see Leorri *et al.*, 2006 for a review) and two different trends have been identified between the southern (below index point UTM 380500 N; Delaware Geological Survey website) and the northern regions (Leorri *et al.*, 2006; Engelhart *et al.*, 2009). We reviewed the database available online at the Delaware Geological Survey Radiocarbon Database and Leorri *et al.* (2006) following Shennan & Horton (2002) and the results are summarized in Figure 2. All samples were re-evaluated in terms of carbon 14 age, $\delta C^{13}/\delta C^{12}$ ratios and indicative meaning and discarded if age reversals were found. Elevation of sea-level index points was recalculated based on tidal frame calculations. In addition, we chose the year 1900 AD as the origin for trend calculations (see discussion).

Figure 1. Geographical location of Delaware Bay (USA). Key: location 1-Leipsic River area; location 2-Wolfe Glade-Cape Henlopen area.

Figura 1. *Localização de Delaware Bay (EUA). Legenda: ponto 1 - zona do rio Leipsic; ponto 2- zona de Wolfe Glade - Cape Henlopen.*

2.2 Tidal modeling

To simulate the water levels and currents in Delaware Bay in response to sea-level rise over the Holocene, we used the Delft3D hydrodynamic model described by Lesser *et al.* (2004). Delft3D uses a finite difference scheme that numerically solves the horizontal momentum and continuity equations. The equations and model description are provided in detail in Lesser *et al.* (2004). In this paper we include

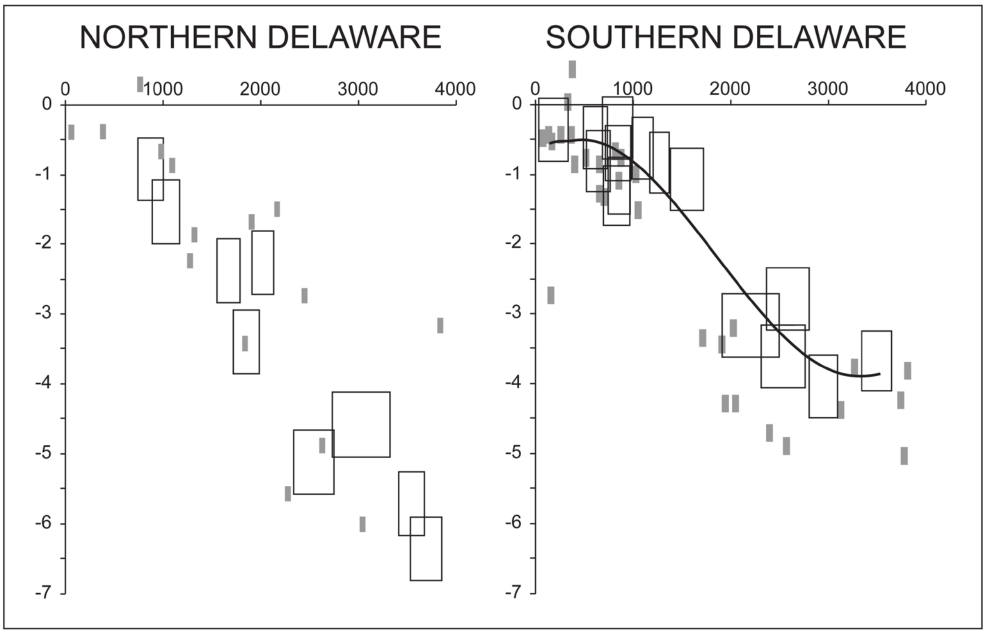

Figure 2. Plot of sea-level index point points (as described by Shennan and Horton, 2002) from Delaware Bay for the past 4000 yr, showing calibrated age against depth relative to present MTL (mean tide level, m). Grey rectangles: intercalated peats (error bars are not indicated), open boxes: basal peats (the size indicates the error), solid line: polynomial trend line for southern basal peats.
Figura 2. *Projecção dos marcadores do nível do mar (segundo Shennan & Horton, 2002) em Delaware Bay, ao longo dos últimos 4 000 anos; eixo das abscissas: idades calibradas; eixo das ordenadas: profundidade, em metros, relativamente ao nível médio das marés actual – MTL (m); rectângulos a cheio: turfas intercalares (sem indicação do erro); rectângulos abertos: turfas basais (a dimensão representa o erro); linha a cheio: curva polinomial para as turfas basais da zona sul da baía.*

forcing by the astronomical tides at the outer boundary, near the shelf break offshore of Delaware Bay. Earth's rotation was accounted for with a spatially variable Coriolis parameter, bottom friction was expressed using a roughness coefficient equivalent to $C_D = 2.3 \times 10^{-3}$ and other default model parameter settings were used. Horizontal eddy viscosity was set to $A_H = 1\ m^2/s$, and no vertical turbulence closure schemes were necessary in the 2D hydrodynamic simulation. The model has been successfully applied to many coastal regions for current reconstructions such as a shallow Arctic river delta system (Mulligan *et al.*, 2010), the Lunenburg Bay in Nova Scotia, Canada (Mulligan *et al.*, 2008) and long-term (500 years) morphological changes in tidal inlets in the Netherlands (Elias & van der Spek, 2006).

Our model approach simulates the tidal hydrodynamics for both present day bathymetry and a paleo-oceanographic scenario with lower mean sea level to understand the response of the different basin geometries in Delaware Bay. Bathymetry was obtained from the U.S. National Geophysical Data Center coastal relief model (NOAA, 2011) at 3 arc-second resolution. The digital elevation model includes bathymetry integrated from the U.S. National Ocean Service Hydrographic Database, the U.S. Geological Survey, the U.S. Army Corps of Engineers, and other institutions. The data was interpolated onto a spherical structured Delft3D model grid with approximately 300 m spatial resolution, covering a domain of 183 km in the alongshore direction and 229 km in the offshore direction. The model was run in 2D (depth-averaged) barotropic mode on a spherical structured grid with approximately 300 m spatial resolution. The open boundary was placed at the shelf break in the Atlantic Ocean, and forcing applied using the primary astronomic tidal constituent (M_2) with 0.5 m amplitude. Lentz *et al.* (2001) analyzed tidal data along the shelf and determined that the M_2 amplitude at the shelf break off the coast of Delaware Bay was 0.45-0.50 m. The model was run for two cases: 1) present day mean sea level; and 2) mean sea level 5 m lower, corresponding to approximately 4000 years ago (Figure 3). Based on the current relative sea-level estimates for the late Holocene in Delaware Bay (Leorri *et al.*, 2006) we estimate a 5 m regional relative sea-level rise since 4000 years ago. Thus, we invoke a sea-level elevation of -5 m on the modern bathymetry to assess tidal changes. The 5 m value is calculated from current estimates that range from -3.2 to -7.6 m at 4000 years ago, with most estimates between -4.8 and -6.8 meters (referred to mean tide level, MTL). Considering these ranges, 5 meter sea-level rise over the last 4000 years is in the lower end of estimates and seems a conservative number for this region. The boundary conditions were held constant and no changes in bathymetry were applied other than a reduction of the water depth. While we are aware of shelf and coastal evolution could affect model predictions, at present the quality of field data precludes from precisely reconstruct those changes.

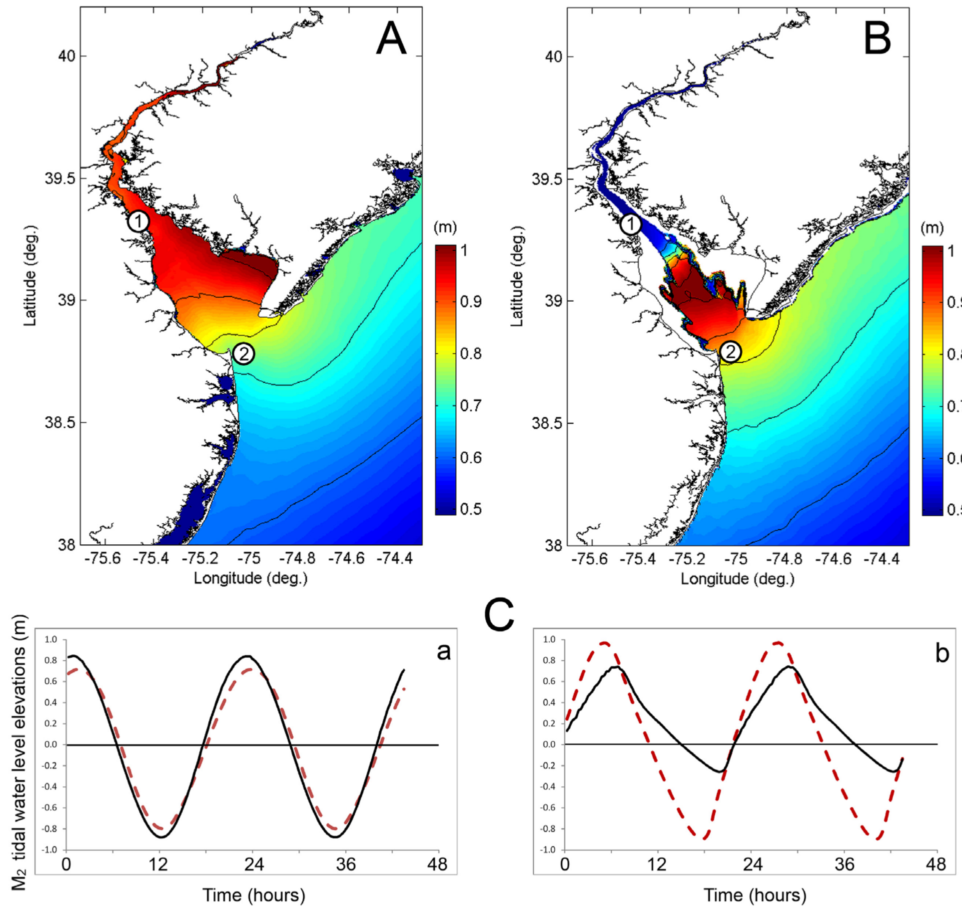

Figure 3. A: M_2 tidal amplitude contours for present MTL (mean tide level, m). The locations of core sites 1 and 2 are shown.
B: M_2 tidal amplitude contours for a paleo-oceanographic scenario corresponding to approximately 4000 yr cal BP when MTL was 5 m lower than present. The location sites 1 and 2 are shown.
C: Time series of M_2 tidal water level elevations at present day MSL (red dashed line) and the paleo-oceanographic case with MSL 5 m lower (black continuous line) at a) site 1 (left), and b) site 2 (right) (see also Figure 1).
Figura 3. *A: M_2 representação da amplitude das marés relativamente ao nível médio das marés actual - MTL, em metros; pontos 1 e 2: localização das sondagens de sedimentos.*
B: M_2 representação da amplitude das marés há cerca de 4000 anos cal BP, considerando um cenário paleoceanográfico com nível médio das marés – MTL, 5 m abaixo do actual; 1 e 2: localização das sondagem de sedimentos.
C: Séries temporais do nível médio das marés M_2, relativamente ao nível médio do mar actual - MSL (linha vermelha, a tracejado) e do cenário paleo-oceanográfico de há 4000 anos, com o nível médio do mar 5 m abaixo do actual (linha negra, a cheio) no ponto 1 (à esquerda – a) e no no 2 (à direita - b); eixo das abscissas: tempo em horas; eixo das ordenadas: alturas de água; ver Figura 1.

3. RESULTS

3.1 Field observations

In this paper, trends are then adjusted by choosing a sea-level elevation of -0.33 m at 1900 as the “origin” (see discussion below) and keeping the sea-level elevation of -5 m fixed at 4000 cal yr BP, yielding a long-term average rate of 1.1±0.2 mm yr^{-1} (n=14) in the southern area, whereas in the northern area the rate is 1.7±0.2 mm yr^{-1} (n=9). The inclusion or not of intercalated peats does not affect trend calculations in the northern area but it does affect them in the southern region. The difference between both trends equates to *ca.* 2 m vertical elevation difference for sea-level index points at 4000 years ago.

3.2 Tidal modeling

Figure 3 summarizes the modeling results. Present day (Figure 3A) M_2 tidal amplitudes near the bay mouth are approximately 0.75 m and are even higher on the north side of the bay and up the river where they reach 1.0 m.

For the paleo-oceanographic case (Figure 3B), the bay is much smaller and the river channel is narrower as result of the extensive shallow (1-3 m depth) modern tidal flats inside Delaware Bay. The effect of lowering the water level by 5 m is dramatic as it changes the size and morphology from a funnel-shaped coastal bay to an elongate wide river-type estuary. This results in a shift of the hydrodynamic behavior, with tidal amplification in the smaller and shallower bay. This is reflected in the southeast-northwest pattern with an initial increase and then a reduction of the amplitude, with greater amplitudes in the southern bay and greater phase with respect to the boundary forcing (Figure 3C). Time series of water level elevations at field sites 1 and 2 are compared in Figure 3C. These sites were chosen based on their proximity to locations where field data was collected. If we analyze site 1 (northern site), differences between current and late Holocene model reconstructions as indicated by the residual water levels suggest that the elevation of high tide may have been *ca.* 50 cm (*ca.* 50 %) lower (in relation to MTL) in the past when the basin presented a different morphology and size. In addition, the elevation of MTL may have been *ca.* 25 cm higher. Reconstructions at the southern site (site 2) also suggest significant tidal changes. In that site, the elevation of high tide may have been *ca.* 15 cm (*ca.* 20 %) higher than present mean high water (MHW) level.

4. DISCUSSION

Leorri *et al.* (2006) observed a very different sea-level response between southern Delaware Bay and northern Delaware Bay when radiocarbon dates of basal peats were examined (n=24; Figure 2). The rate of sea-level rise was estimated by these authors at around 0.8±0.64 mm yr^{-1} (n=15) in the southern area, whereas in the northern area the rate was approximately 1.9±0.30 mm yr^{-1} (n=9). These estimations used only basal peats because peats intercalated in the sediment tend to overestimate the sedimentation rates due to compaction of the sediment (Figure 2). These results are similar to those reported by Engelhart *et al.* (2009) who calculated rates of 1.2±0.2 mm yr^{-1} for southern Delaware Bay and 1.7±0.2 mm yr^{-1} for northern Delaware Bay. Differences might be related to the fact that Engelhart *et al.* (2009) limited the sea-level index points from southern Delaware Bay to the last 2000 years and used a larger number of points in northern Delaware Bay. For our calculations we used the same data set as Leorri *et al.* (2006) but we included in the calculations the 20th century sea-level rise as suggested by Gehrels (2010). Sea-level rise in the past century has departed significantly from late Holocene trends. If the year 1900 was chosen as the "origin", trends would be less steep than the reported relative sea-level rise (see for instance Figure 2 in Gehrels, 2010). The National Oceanic and Atmospheric Administration (NOAA) reported in their website (http://www.co-ops.nos.noaa.gov/sltrends/sltrends.shtml) that the rate of 20th century mean sea-level rise at Lewes, DE (southern Delaware Bay) is 3.2 mm yr^{-1} (1919-2006), 3.46 mm yr^{-1} (1956-2006) at Wilmington, DE (northern Delaware Bay), and 2.79 mm yr^{-1} (1900-2006) at Philadelphia, PA (further north and outside the region of this study). As indicated above, trends are then adjusted by choosing a sea-level elevation of -0.33 m at 1900 as the "origin" and keeping the sea-level elevation of -5 m fixed at 4000 cal yr BP, yielding a long-term average rate of 1.1±0.2 mm yr^{-1} (n=14) in the southern area, whereas in the northern area the rate is 1.7±0.2 mm yr^{-1} (n=9). The inclusion or not of intercalated peats does not affect trend calculations in the northern area but it does affect them in the southern region. The difference between both trends equates to *ca.* 2 m vertical elevation difference for sea-level index points at 4000 years ago.

The north-south trend differences were explained as the result of vertical land movements in previous works (*e.g.*, Leorri *et al.*, 2006; Engelhart *et al.*, 2009). However, and although Delaware Bay has been the subject of intense sea-level studies, the influences of isostatic rebound have not been successfully addressed. Furthermore, Leorri *et al.* (2006) suggested a non-linear trend for the southern area (see Figure 2) supported by the distribution pattern derived from intercalated peats. When reviewing the literature, no isostatic model seems to recognize a similar inflection, although there is evidence for growth of the Greenland Ice Sheet and small glaciers during the late Holocene (Gehrels, 2010).

While the isostatic rebound can partially explain the differences in elevation between the two regions and a sea-level inflection (slow down or fall) as a result of glacier growth might also be inferred, the pattern recognized in the southern region does not relate only to vertical land movements in response to isostatic rebound and a significant global sea-level oscillation should be recorded in both sites. Therefore, local factors might be contributing to the observed patterns.

For this study, we created a model to identify possible changes in the tidal pattern inside Delaware Bay. This model is not aimed to precisely reconstruct former tidal ranges but is instead designed to understand the possible role of tidal range variations in sea-level reconstructions. We, therefore, only applied uniform changes of the eustatic type to the existing bathymetric model. Nevertheless, future models should consider the possible magnitude and extent of other bathymetric changes, both to assess the quality of the present approximation, and with a view to refining models (Austin, 1991). However, at present the quality of field data precludes this approach.

The 4000 cal yr BP boundary for our model was selected based on the late Holocene meltwater contributions and is consistent with the methods of Shennan & Horton (2002). The contribution of global ice melt to sea-level change during the past 2000 years is considered to be 0.1±0.1 mm yr^{-1} (see references in Gehrels, 2010) and we assume here that the same conditions have prevailed over the last 4000 years, following Shennan & Horton (2002) and Gehrels (2010). This is in agreement with the eustatic functions in GIA models (Peltier, 2002). The overall effect of consider some late Holocene ice-equivalent sea-level rise is that the crustal motion derived from relative sea-level trends will be smaller (see Gehrels, 2010 for a review). In summary, current knowledge suggests little or no contribution of meltwater for the last 4000 years.

There are numerous examples of numerical models to estimate tidal hydrodynamics in coastal regions. Galperin & Mellor (1990) developed a circulation model of Delaware Bay, and evaluated the performance for a large set of tidal constituents, finding amplification up the bay and river system. Shaw *et al.* (2010) used radiocarbon dating of organic

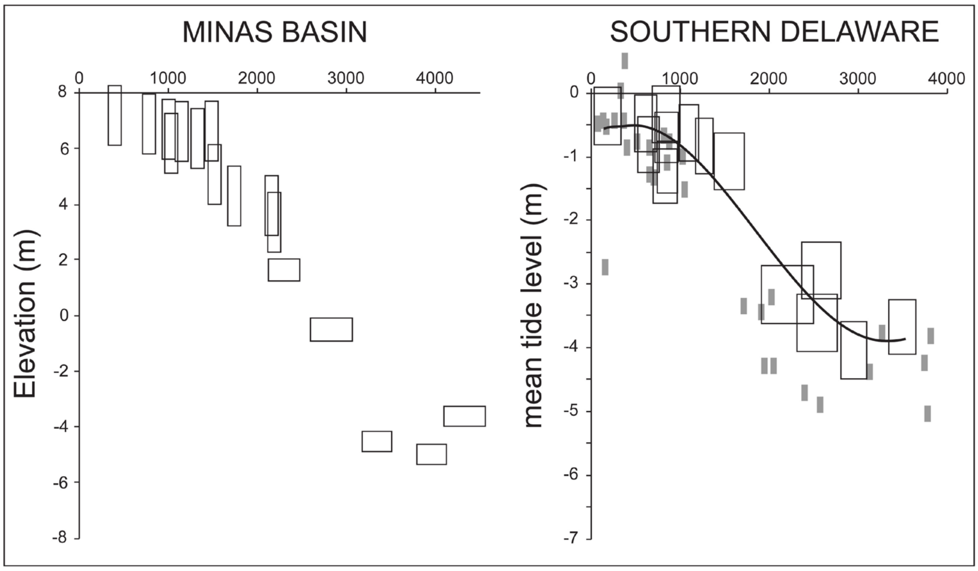

Figure 4. Salt marsh elevation data from Minas Basin in the Bay of Fundy, Canada (modified from Shawn et al., 2010) and plot of sea-level index points from southern Delaware Bay for the past 4000 yr, showing calibrated age against depth relative to present MTL (m). Grey rectangles: intercalated peats (errors are not indicated), open boxes: basal peats (the size indicates the error), solid line: polynomial trend line for southern basal peats.

Figura 4. *Representação da elevação do sapal de Minas Basin, em Bay of Fundy – Canadá (adaptado de Shawn et al., 2010) e da projecção dos marcadores do nível do mar na zona sul de Delaware Bay, ao longo dos últimos 4000 anos; eixo das abscissas: idades calibradas; eixo das ordenadas: profundidade, em metros, relativamente ao nível médio das marés actual – MTL (m); rectângulos a cheio: turfas intercalares (sem indicação do erro); rectângulos abertos: turfas basais (a dimensão representa o erro); linha a cheio: curva polinomial para as turfas basais da zona sul da baía.*

layers in salt marsh samples to define the paleobathymetry of the Bay of Fundy, and applied a tidal model to understand the response of the bay to mean sea-level changes over the Holocene. The authors suggest that a sand barrier was rapidly broken down 3400 years ago resulting in both catastrophic salt marsh flooding and amplification of the tidal range in the larger basin. The model used here has been successfully applied to many coastal regions. Elias & van der Spek (2006) used the model to determine the long-term (500 years) morphological changes of tidal inlets, and identified the responses of the inlet system in the Netherlands. Mulligan *et al.* (2008) applied the model to Lunenburg Bay, Canada, and determined the flushing rates and relative magnitudes of currents generated by tides, storm surges, surface waves and winds during hurricanes. The model was also used for a large, shallow Arctic river delta system (Mulligan *et al.*, 2010) to estimate the strength of river, tidal and wind forcing of a river plume.

The results for the present day case (Figure 3A) agree in general with the tidal response in Delaware Bay determined by Galperin & Mellor (1990), suggesting that the performance for Delaware Bay is reliable. M_2 tidal amplitudes near the bay mouth are approximately 0.75 m and on the north side they reach 1.0 m.

The paleo-oceanographic case (Figure 3B) reflects a shift of the hydrodynamic behavior, with tidal amplification in the smaller and shallower bay. This is evident by the increase in tidal range in the Southern part of the bay, while the Northern part of the bay responded with reduced tidal amplitude, a phase shift with respect to the boundary forcing and asymmetrical tidal currents with a longer ebb phase (Figure 3C). Time series of water level elevations at field sites 1 and 2 are compared in Figure 3C. These sites were chosen based on their proximity to locations where field data was collected. If we analyze site 1 (northern site), differences between current and late Holocene model reconstructions as indicated by the residual water levels suggest that the elevation of high tide may have been *ca.* 50 cm (*ca.* 50 %) lower (in relation to MTL) in the past when the basin presented a different morphology and size. In addition, the elevation of MTL may have been *ca.* 25 cm higher. Reconstructions at the southern site (site 2) also suggest significant tidal changes. In that site, the elevation of high tide may have been *ca.* 15 cm (*ca.* 20 %) higher than present mean high water (MHW) level. While other factors such as wave action and wind tides are also important in coastal areas, transitional ecosystems such as salt marshes seem to be strongly controlled by tidal flooding (*e.g.*, Leorri *et al.*, 2008). Since these are the tarjeted environments for high-resolution sea-level reconstructions, even small changes in the tidal range might be significant.

While a direct comparison cannot be made since the two systems have completely different tidal energy balance, the pattern here obtained resembles that of Minas Basin, Bay of Fundy (Figure 4; Shaw *et al.*, 2010). In that case, the pattern is related to the rapid break down of a barrier positioned at the mouth of the basin, and the rapid tidal extension which occurred as result. This no-linnear pattern suggested us that tidal-range changes might strongly influence sea-level reconstructions under certain conditions. In fact, the oscillation observed at the East Atlantic by Leorri & Cearreta (2009) might be related to the development of sand bars in the mouth of the Iberian estuaries that started at ca. 5000-4000 years BP (Cearreta *et al.*, 2007) and that controlled the exchange of waters between the estuary and open ocean and therefore the tidal range inside the estuary. Similar signatures of tidal-range changes may be seen in the estuaries of northeastern North Carolina, where barrier island collapse occurred between ca. 5000 and 3500 years ago (Culver *et al.*, 2007) resulted in the formation of tidalites and a four-fold increase in sedimentation likely due to an increase in tidal range (Mallinson *et al.*, 2011). Similar oscillations have been recorded elsewhere (Milne *et al.*, 2005).

While sea-level estimates indicate *ca.* 2 m difference in elevation between the north and south Delaware Bay, the accumulated changes in tidal range are *ca.* 1 m, large enough to explain a significant part of these differences. In fact, when the sea-level index points (SLIP) are calculated (see equation below), tidal reconstruction estimates indicate that should be *ca.* 50 cm higher in the northern site and 15 cm lower in the southern site 4000 years ago. These errors are relatively small compared with the 5 m sea-level change, but they are significant if different sites (such this case) are compared with each other since changes occurred had opposite sings. Based on these calculations new trends can be estimated at 1.17±0.2 mm yr^{-1} in the southern area, and 1.55±0.2 mm yr^{-1} in the north, reducing the difference by 25 %.

The inherent vertical error from vertical tidal changes in the determination of sea-level is a result of how SLIPs are calculated. The vertical position of a SLIP used to reconstruct sea-level trends can be calculated relative to mean tidal level as Massey *et al.* (2008):

$$\text{SLIP} = H - D - I + C + A,$$

where H is the height of the core top relative to MTL, D is the depth of the sample in the core, I is the height of deposition of the sample (indicative meaning) relative to MTL as inferred from different proxies, C is the core compaction, and A is the autocompaction. In the study case, we are interested in the indicative meaning, where, for example, a sample that has a floral and/or faunal indication of forming within a salt marsh environment is assigned an indicative meaning close to mean high water. This calculation, then, assumes a known tidal reference frame. If the tidal reference frame changes large errors in the calculated SLIP would result. Based on current calculations, the change of tidal range would explain up to 25 % of the difference between the northern and southern trends, leaving 75 % to isostatic rebound. All this suggests also that current sea-level trends in the northern area are much greater, and trends in the southern area are smaller than they would be if tidal range changes are considered. This finding reflects the relevance of tidal processes in reconstructing sea level and the need for further research in this area.

In fact, Figure 3 indicates that even greater errors would occur if we use tidal reconstructions from inside the bay in the southern area. This region presents the highest tidal ranges but it is also subjected to greater influence by paleo-bathymetric changes, and reconstructions by our model might also be misleading as we have not invoked any changes to bottom elevation that would respond to the channel/estuary infilling. In any case, a second inference from this model is that spatial variations in tidal changes may have occurred over short distances, and clustering of SLIPs should be minimized if meaningful results are to be obtained. Future models should include tidal changes on the shelf as the sea-level rises. Future modelling efforts could include initializing models with the paleo-bathymetry derived from geophysical surveys, and/or modeling the morphological changes. This would potentially capture the effect of the changing tidal currents and sedimentary adjustments as sea level rose and flooded across the across the landscape, creating a suite of different shelf depths and basin geometries. An iterative method may be necessary where SLIPs are calculated based on model results that, in turn, generate new sea-level trends used to refine the tidal models.

CONCLUSIONS

Decelerating rates of eustatic sea-level rise over the late Holocene led to other factors becoming more important in governing the coastal evolution. These are primarily local factors, such as sediment availability, local wave climate or tidal changes. From the re-assessment of sea-level index points from the Delaware Bay we can observe that local trends are significantly affected by tidal range change over the late Holocene by at least 0.5 m. Further analysis of a larger set of tidal constituents may reveal that the paleo-oceanographic tidal amplitudes respond differently, particularly if tidal resonance occurs with a particular constituent. Therefore, coastal amplification of tides should be accounted for when estimating sea-level positions and determining the rate of sea level rise. This effect should be considered when reconstructing sea-level trends. Furthermore, regional estimates might present additional errors as tidal-range changes can occur over short (km scale) distances.

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