Curr Clim Change Rep (2016) 2:232–241
DOI 10.1007/s40641-016-0044-8

Spatial and Temporal Variability in Tidal Range: Evidence, Causes, and Effects

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Published online: 28 July 2016

Abstract Tidal range is one factor in determining the vertical location of local mean sea level, and it is also a contributor to total water levels and coastal flooding. It is therefore important to understand both the spatial distribution of tidal range and the temporal variation in tidal range, over a wide range of scales. Knowledge of historic tidal range is obtained both through observations and through modeling. This paper reviews numerous observational and modeling studies of historic tidal range variations on decadal to millennial timescales. It also discusses many of the physical processes that are responsible for these variations. Finally, this paper concludes with discussion of several modeling studies that seek to constrain future changes in tidal range in coastal environments.

Keywords Tidal range · Tidal modeling · Tide gauges · Sea level change · Tidal dissipation

Introduction

Coastal water level variations are the response of the Earth's oceans to a variety of forcing mechanisms including gravity, surface stress, radiative fluxes, and coastal freshwater discharge. As illustrated in Fig. 1 (adapted from [44]), these variations span a wide range of timescales and the different frequency bands have relevance to a variety of physical processes of interest. For example, capillary waves increase surface roughness and allow for accurate remote sensing of coastal waters [40]. Gravity waves are among the most energetic and are primary drivers of coastal erosion [84]. Low-frequency, narrow-banded content comes from the semi-diurnal and diurnal tidal oscillations due to the sun and moon.

The spatial variability of tidal amplitudes (e.g., Fig. 2) is considerable and is due primarily to bathymetric variations at basin [71], shelf [28], and local [25] scales. The temporal variability of tidal amplitudes is similarly complex, with variations observed at seasonal [59] and decadal (e.g., 18.6-year nodal cycle; [50]) timescales as well as longer-term secular trends (century to millennium, e.g., [35, 69]).

Changes in tidal range, either MN (mean range of tide—difference between mean high water (MHW) and mean low water (MLW)) or GT (great diurnal range—difference between mean higher high water (MHHW) and mean lower low water (MLLW)), inform estimates of relative sea level (RSL) change. MHW is defined as the average of all high water heights over a given time period (tidal epoch), while MHHW is the average of the higher high water height of each day over the epoch. Low tidal datums are defined similarly. A proxy-based change in RSL ($\Delta\xi_{rsl}$) at a given location (ϕ) and time (τ) can be expressed as [75]

$$\Delta\xi_{rsl}(\tau,\phi) = \Delta\xi_{eus}(\tau) + \Delta\xi_{iso}(\tau,\phi) + \Delta\xi_{tect}(\tau,\phi) + \Delta\xi_{local}(\tau,\phi) \quad (1)$$

where the terms on the right-hand side represent eustatic, isostatic, tectonic, and local effects. The local effects, in turn, are expressed as

$$\Delta\xi_{local}(\tau,\phi) = \Delta\xi_{tide}(\tau,\phi) + \Delta\xi_{sed}(\tau,\phi) \quad (2)$$

and include the effects of tidal range change and sediment consolidation. To illustrate the specific role played by

This article is part of the Topical Collection on *Sea Level Projections*

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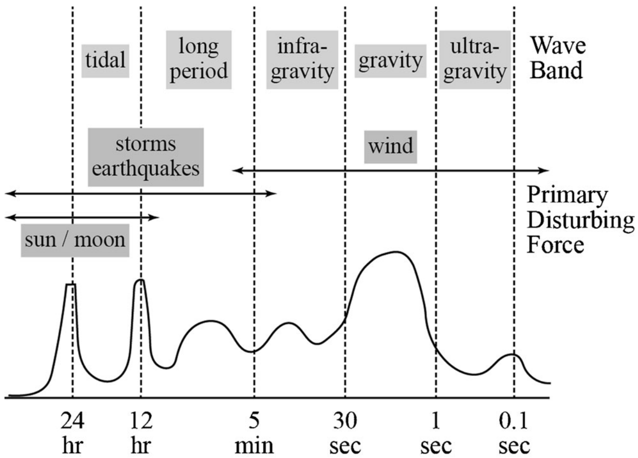

Fig. 1 Conceptual frequency spectrum of ocean surface waves. Adapted from Kinsman [44]

changing tides, note that the establishment of a sea level index point requires information on the geographic location, age, and indicative meaning of a sediment sample [19]. The indicative meaning is the elevation relative to a contemporaneous tide level [66], or reference water level, and this indicative meaning will vary depending upon the biological indicator in the sediment sample. As an example, Horton, Edwards, and Lloyd [41] developed a foraminiferal-based transfer function that provides a standardized water level index (SWLI) as a function of species. The effect of tides and tidal range change comes in through the relationship between the chosen reference water level (e.g., mean high water spring tide (MHWST) for foraminifera) and other tidal datums such as diurnal tide level (DTL—arithmetic mean of MHHW and MLLW) or mean sea level (MSL).

Figure 3a shows two sediment samples (containing the same species), one at 0 ka (kiloannum; present day) and one at 5 ka. The modern-day (0 ka) DTL is indicated. If it is assumed that paleotides (5 ka) were the same as modern-day tides, then the RSL change ($RSLR_{5(a)}$) from 5 ka to 0 ka is simply the same as the vertical offset between the two samples. Figure 3b illustrates the effect of changing tidal range. The same sediment sample is shown at its 5-ka location. The tidal datums and relative sea level rise (RSLR) annotated with the 5(a) subscript correspond, as they did in Fig. 3a, to the assumption of constant tidal range. The tidal datums with the 5(b) subscript correspond to the case of larger paleotides. The amplification of the tides at 5 ka produces a larger RSLR than occurred under the assumption of constant tides.

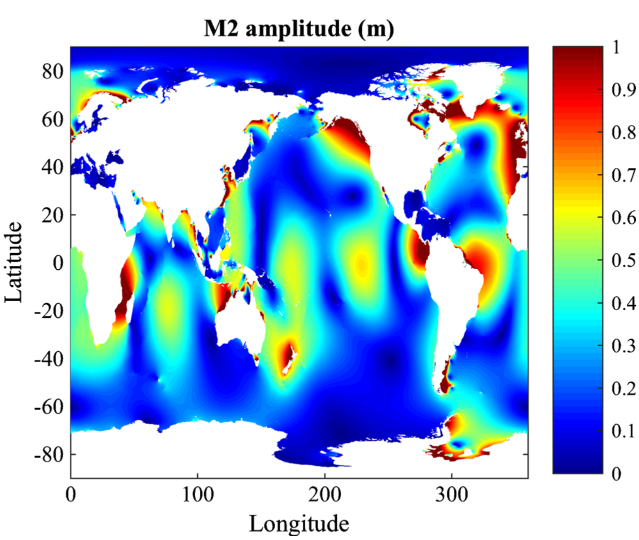

Fig. 2 Distribution of M2 tidal amplitude from the FES2004 tidal model [52]

An understanding of tidal range changes is therefore an important element of understanding past and future changes in RSL. It is also important from a coastal flooding point of view as tidal elevations are a contribution to total water levels. This paper begins with a brief review of observational and modeling studies of historic changes in tidal ranges. It then discusses several of the underlying physical mechanisms contributing to these changes. It concludes with some remarks about modeled future changes in tidal range and the effects of these changes on RSL.

Observations of Tidal Range Change

Direct observations of changes in tidal datums are, of course, limited by data availability. Figure 4 illustrates the periods of record and the latitudinal coverage of global tide gauges, as well as the locations of the gauges themselves. These data are taken from the Permanent Service for Mean Sea Level [38, 68] and cover 1445 different gauges (historic and current). Note that PSMSL also distributes a more limited set of data from bottom pressure gauges; those records are not included here. Similarly, data from satellite altimetry are not considered in this review. The average period of record of the tidal gauges is 37 years and the longest is 208 years, and the greatest spatial coverage is in the mid-latitudes of the northern hemisphere. These records provide information on tidal amplitudes and phases through harmonic analysis. Information on tidal datums comes either from direct analysis of the gauge times series or through algorithms (e.g., [56]) that directly convert amplitudes and phases to datums.

Early studies tended to be local, analyzing one or more gauges at or near a particular site. More recent studies have been regional, quasi-global, or global, taking advantage of ongoing efforts to improve the quality of and access to global datasets. Table 1 lists many of the studies of tidal range at the decadal-to-century timescale permitted by the observational data illustrated in Fig. 4. Note that the studies in Table 1 are limited to those that specifically evaluated changes in tidal amplitudes. There are many other (e.g., [55]) studies that have instead used gauge data to evaluate trends in extreme water levels themselves.

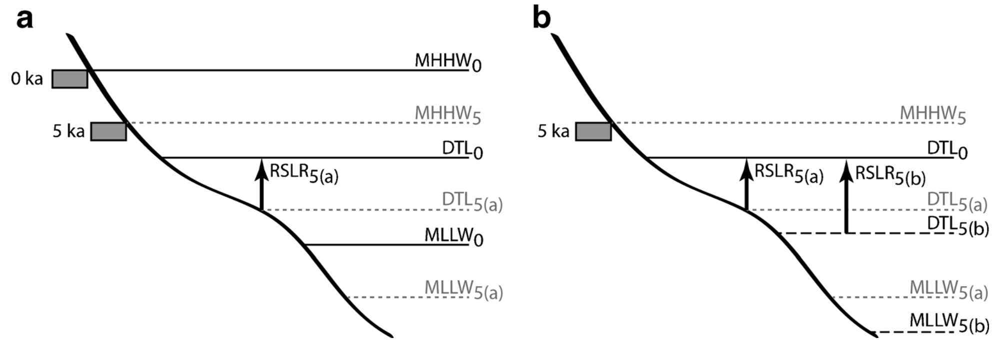

Fig. 3 Schematics of tidal datums and inferred RSLR. **a** Constant tidal range between 5 ka and present day (0 ka). **b** Effect of changing tidal range

The results of these studies are inconclusive in terms of regional trends and correlations with changes in MSL. Furthermore, changes that were observed at a given location often varied across the tidal constituents. As an example, Ray [69] found that M_2 amplitudes have increased in the Gulf of Maine, while Ray [70] found that the S_2 amplitudes have decreased in that location. The larger-scale studies (e.g., [18, 87]) have in part been carried out in order to find regional trends, but larger-scale patterns have been elusive. Further complicating regional- to global-scale understanding is that local processes and factors often play a role in determining trends. For example, Zaron and Jay [89] note that some of their observed trends in the M_2 amplitude were due to changes in station timekeeping and data processing, and others were due to local morphodynamics. Stations where trends were not explained by either of these causes were noted as suggestive of a link between climate (RSL change) and tides.

Modeling Studies of Past Tidal Range Change

Modeling can fill the spatial gaps between observations (i.e., tide gauges) and the temporal gaps in observational records. An excellent recent review of barotropic tide models is provided by Stammer et al. [77]. Those authors provide a state-of-the-art comparison of many leading tidal models, including both assimilative (models that ingest observational data) and dynamical (models that only rely on physical first principles) models. Most modeling studies of changing tides have focused on millennial timescales rather than the decadal-to-century timescales of the observational studies. Table 2 summarizes many recent studies, including their geographic scope (local/regional vs. global) and their temporal scope. The included studies go back only as far as 65 ka; note that there are additional modeling studies not included here that go back much further, e.g., Hansen [34]. There are many important differences among these studies, including choices and assumptions regarding bathymetry, drag parameterization, and open boundary treatment in the case of non-global studies. Note also that many of the studies in Table 2 have coarse temporal resolution in the sense that they contrast tides at only one point in time to present-day tides. Other studies are more highly resolved with simulations performed at multiple times. One of the most dramatic and consistent results demonstrated by many of these studies is a strong amplification of the M_2 tide in the northern Atlantic Ocean at ~9 ka (Fig. 5).

Paleobathymetries in these studies are obtained in a variety of ways. The simplest model is a spatially uniform change in water depth. This effectively assumes no relative bathymetric change. This model is relatively common in local studies (e.g., [74]), where the length scale of the domain is less than the length scale of glacial isostatic adjustment (GIA) variations but is also sometimes used in global studies (e.g., [57]) where it is less justifiable. Most large-scale studies have instead used spatially variable adjustments to bathymetry informed by GIA

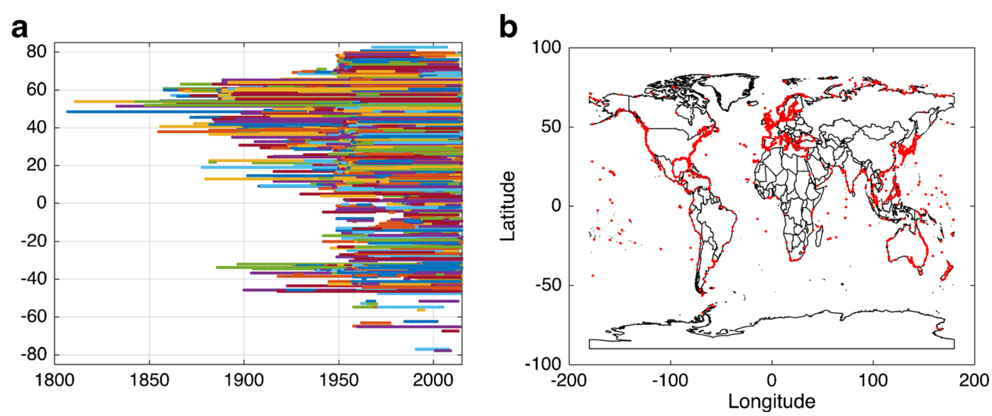

Fig. 4 Latitudinal distribution (**a**) of tidal gauges and their periods of record. The individual colors cycle through the gauges, with each gauge represented by a length corresponding to its period of record. Location of gauges is shown in (**b**)

Table 1 Summary of observational studies of changing tidal amplitudes

Citation	Study scope
Local	
Bowen [9]	Thames River, England
Cartwright [12]	Brest, France
Amin [1]	Thames River, England
Colosi and Munk [16]	Hawaii, USA
Regional	
Woodworth, Shaw, and Blackman [88]	British Isles; North Sea
Flick, Murray, and Ewing [23]	USA
Ray [69]	Gulf of Maine
Jay [42]	Eastern Pacific Ocean
Ray [70]	Western North Atlantic
Müller [58]	North Atlantic
Tai and Tanaka [78]	East China Sea
Zaron and Jay [89]	Pacific Ocean
Devlin et al. [18]	Western Pacific Ocean
Global	
Woodworth [87]	Quasi global
Müller, Arbic, and Mitrovica [60]	Quasi global
Mawdsley, Haigh, and Wells [54]	Global

models such as ICE-5G [64]. In both local and global studies, it is common to neglect temporal bathymetric variations due to river sedimentation and coastal geomorphological processes.

Table 2 Summary of modeling studies of historic tides

Citation	Region	Temporal range
Local/regional		
Scott and Greenberg [74]	Bay of Fundy	0–7 ka
Austin [7]	European shelf	Holocene
Hinton [36]	UK	Holocene
Gehrels et al. [27]	Bay of Fundy	0–7 ka
Tojo, Ohno, and Fujiwara [80]	Osaka Bay, Japan	Late Pleistocene
Uehara [81]	Yellow/East China Seas	Holocene
Shennan et al. [76]	UK	Holocene
Uehara et al. [82]	European shelf	0–last glacial maximum (LGM)
Leorri et al. [47]	Delaware Bay, USA	0–4 ka
Hill et al. [35]	Western North Atlantic	Holocene
Hall et al. [33]	Delaware Bay, USA	0–7 ka
Global		
Thomas and Sündermann [79]	Global	0 ka–LGM
Egbert, Ray, and Bills [22]	Global	0 ka–LGM
Montenegro et al. [57]	Global	0 ka–LGM
Arbic et al. [4]	Global	0–65 ka
Griffiths and Peltier [32]	Global	0 ka–LGM
Green et al. [31]	Global	0 ka–LGM

While this assumption is valid for large-scale studies (where those processes may be subgrid scale), it is less tenable for local (bay/estuary scale) studies where sediment infill may be an important control on tidal hydrodynamics.

Regarding drag, most models account for a turbulent bottom boundary layer through the use of a classical drag law [53]. Egbert and Ray [21] suggest that generation of internal tides (see [26]), in a globally averaged sense, is on the same of order of magnitude of bottom friction, in terms of a dissipation mechanism for surface tides. Green and Nycander [30] discuss several ways for incorporating internal tidal drag into global tidal models. It is difficult, however, to implement internal tidal drag parameterizations into paleotidal simulations since the stratification of the ocean is not well constrained at those earlier times. This is particularly consequential since, at those earlier times, the continental shelves are smaller in extent, which increases the dominance of (poorly constrained) internal tidal drag in the overall dissipation. Griffiths and Peltier [32] illustrate a path forward in their simulations, by using coupled atmosphere-ocean models to estimate the buoyancy frequency of the water column, from which the drag is parameterized.

Finally, local/regional tidal simulations necessarily have one or more open boundaries, at which the tides must be prescribed. Many studies assume that the paleotides at these open boundaries are the same as present day. In some cases, this is assumed for convenience or lack of knowledge of the paleotides. In other cases (e.g., [33]), the assumption is justified through global tidal models that demonstrate only marginal changes in tides at these boundaries. In the case of local/regional (e.g., [35, 82]) studies that span a large enough time range for significant tidal changes to occur at the open boundaries, nested modeling approaches must be used in order to correctly specify the open boundary tides.

Physical Mechanisms of Tidal Range Change

Tidal amplitudes at a coastal location are controlled both by far-field and local effects. As Fig. 5 demonstrated, tidal amplitudes in the western North Atlantic are relatively spatially coherent and are determined largely by the geometry of the basin. In this way, the tides in a local estuary on the east coast of the USA are controlled by the Atlantic. However, there is also considerable variability in tidal amplitudes along that coast and this variability is controlled by the particular bathymetry (open coast vs. inner estuary vs. upriver, etc.) of each gauging location. Therefore, changes in tidal range can originate from changes to larger basin-scale characteristics or from changes to local characteristics.

Beginning with local effects, much is known about the propagation of tidal waves in estuaries and rivers [37, 73]. Variations in depth and width interact with frictional effects and river flow to produce a complex structure of tidal

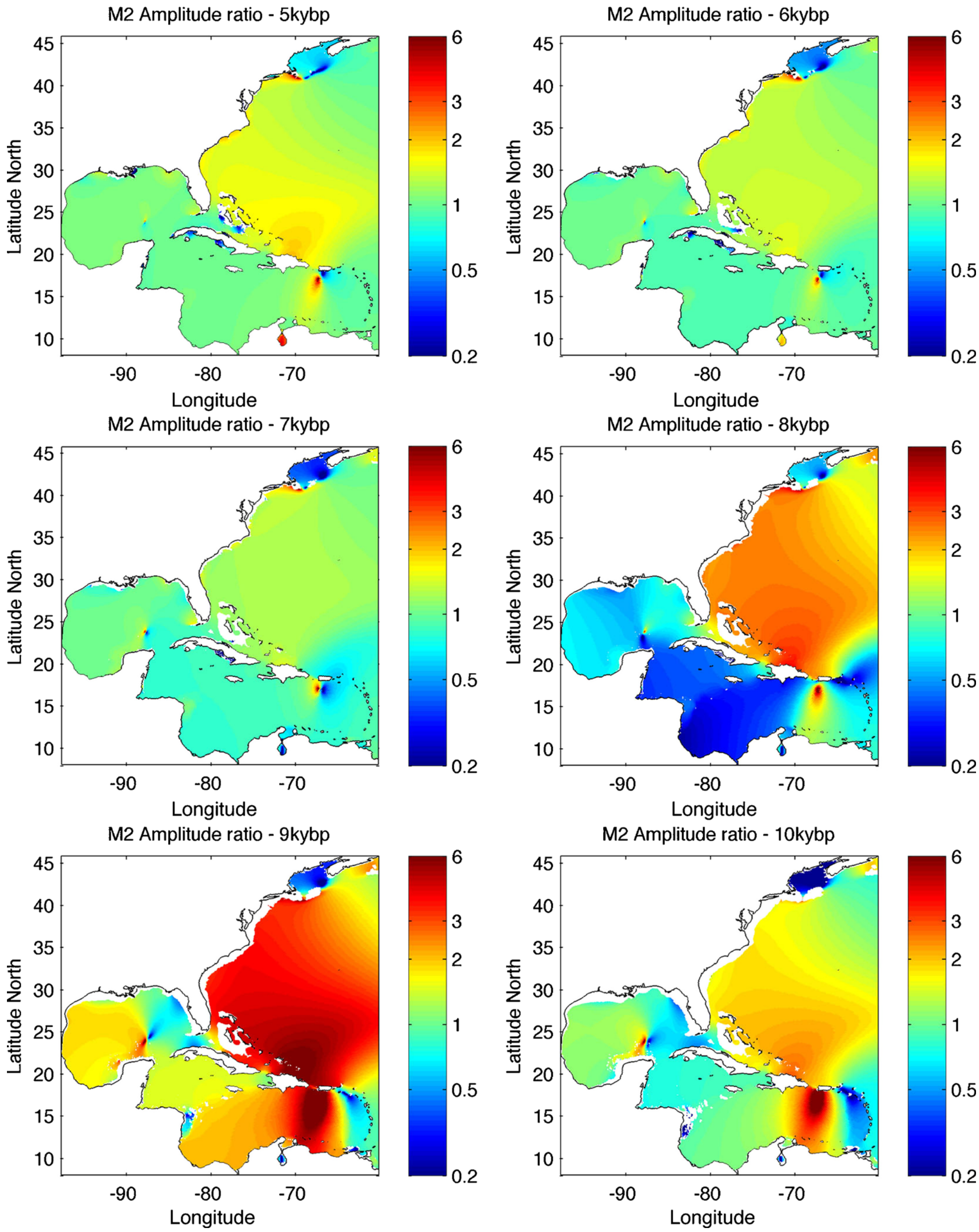

Fig. 5 Ratios of M_2 amplitudes at given time to those of present day (figure from [35])

amplitude along the length of a tidal river. As noted by Chernetsky, Schuttelaars, and Talke [14]; Cai et al. [10]; and Cai and Savenije [11], deepening of a channel can lead to significant increases in tidal range. The increases are not monotonic, however; beyond a critical depth, it is possible for the tidal amplitudes to reduce as the progressive tidal wave transitions to a standing wave. Local anthropogenic effects (reclamation, shoreline changes, etc.) have also been shown to impact not only tidal currents (e.g., [46]), but also tidal amplitudes [43, 63].

At a larger scale, the effect of continental shelf width (and depth) on tidal amplitudes has been considered (e.g., [2, 3, 5, 15, 17])). For a simple example, the study by Clarke and Battisti [15] suggests (see their Fig. 3) that shelf resonance occurs when the shelf scale

$$\frac{g\alpha}{\omega^2 - f^2}$$

is approximately equal to the shelf width. In the above, g is the gravity, α is the shelf slope, ω is the tidal frequency, and f is the Coriolis parameter. Figure 6 demonstrates the considerable loss of continental shelf width that accompanied the Holocene (~10 ka). While this quarter wave resonance is an important mechanism controlling shelf tides, it is clear that substantial changes to the resonance characteristics will require substantial changes to MSL.

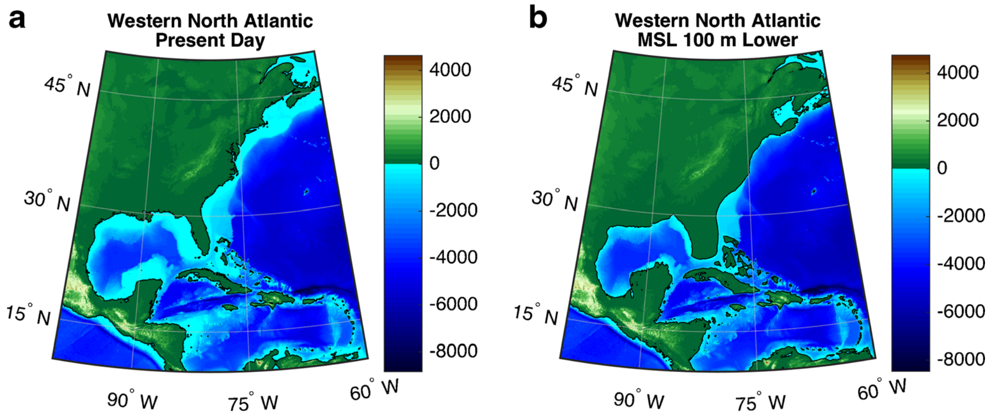

Fig. 6 Present-day (**a**) bathymetry/topography for the Western North Atlantic Ocean. Bathy/topo with a 100-m reduction in MSL is shown at (**b**)

At the largest scale, basin-scale tides are set by basin geometry (proximity of resonant modes to tidal frequencies; see, e.g., [67]) and dissipation. Many studies have identified key global sites such as the Hudson Bay/Strait system (e.g., [20, 48]), the Gulf of Maine, and the Patagonian shelf [3] as the main locations of dissipation of the M_2 tide. Removal of these sites (such as in the case of the lowered sea level in Fig. 6b) has been shown to lead to large increases in that tide. As with changes to shelf resonance, this mechanism for tidal range change requires large perturbations to MSL. Finally, as noted earlier, baroclinic motions are an important sink for barotropic tidal energy. Therefore, changes in ocean stratification (which controls the baroclinic motions) have the potential to lead to changes in the surface tides [42], although this is a relatively unexplored and, therefore, active research area. Wetzel et al. [86] investigate this by developing a two-layer analytical tidal model which serves as a framework for quantifying the sensitivity of surface tides to changes in stratification, and the simulations by Müller et al. [59] show that seasonal variations in the mixed layer depth affect the M_2 tide amplitude.

Modeling Studies of Climate Change and Future Tidal Range

It was noted previously that most modeling studies of changing tides were focused on paleotides and on millennial timescales. In recent years, there has been an increasing interest in the future of tides. This interest is largely driven by projected increases in sea level and concerns about coastal flooding. As just one example, Kopp et al. [45] use probabilistic methods to provide century-scale projections of RSL rise at a global network of tide gauge locations. An increasing tidal range will lead to greater flooding than predicted by changes in sea level alone. It was further noted earlier that changes in tides can originate from global drivers, i.e., changes in resonance characteristics of the major ocean basins, or from local drivers, i.e., changes in sea level, sedimentation, anthropogenic influences, and so on.

Table 3 summarizes many recent studies of changing tidal range under future scenarios, including their geographic scope and methods (mode of change). All of these studies are local

Table 3 Summary of modeling studies of future tides

Citation	Region	Methods
French [24]	Eastern England	+0.3 m SLR; managed retreat scenarios of defense structures; sedimentation effects
Greenberg et al. [29]	Bay of Fundy	Spatially variable SLR; simulations for 2055, 2085, 2100
Pickering et al. [65]	European Shelf	+2, +10 m SLR
Ward, Green, and Pelling [85]	European Shelf	−2, −1,…, +5 m SLR
Pelling, Uehara, and Green [63]	Bohai Sea, China	+1, +2, +3 m SLR; land subsidence and reclamation effects
Valentim et al. [83]	Portugal	+0.42 m SLR
Hall et al. [33]	Delaware Bay, USA	Spatially variable GIA adjustment plus eustatic SLR corresponding to +0.1, +0.3 ka
Rosier et al. [72]	Antarctic	Ice shelf thinning and retreat
Luz Clara et al. [51]	Patagonia Shelf	+1, +2, +10 m SLR
Holleman and Stacey [39]	San Francisco Bay, USA	+0.6, +1 m SLR
Arns et al. [6]	North Sea	+0.54 m SLR
Passeri et al. [62]	Northern Gulf of Mexico	Eight SLR scenarios from +0.1 to +2.0 m. Probabilistic model for shoreline and dune height changes

to regional in scope, which highlights the fact that future changes in tidal range, under realistic century-scale (a few meters) sea level rise (SLR) scenarios, will be controlled by local effects and conditions. Put another way, ocean basin-scale processes will not be noticeably affected by depth increases of this amount. The studies in Table 3 are focused on, or explicitly give results for, tidal amplitude changes. It should be noted that there are many more studies (e.g., [8, 13, 49]) that consider a more holistic approach to changing extreme water elevations, of which tides are a component. Studies that do not explicitly provide information on the changes to tidal amplitudes are not included in Table 3.

As with the modeling studies of past tides, there are important decisions to be made with regard to modeling strategy and the implementation of future conditions. Generally speaking, studies have modeled future conditions with a simple spatially constant increase (equal to the assumed SLR) in water depth, though there are exceptions [30, 33]. There is also variability in the treatment of inundation of formerly dry land as sea level rises. Some studies use a vertical boundary at the present-day coastline, which precludes inundation, while others use a combined bathy-topo model grid and allow for the landward migration of the coastline with SLR. One place of unanimity is that future open boundary tides are assumed to be equal to present-day tides, which is a well-justified assumption provided that the open boundary is in sufficiently deep water.

Typically, sedimentation effects and coastline change are ignored. French [24] is a noteworthy counter-example since that study modified the bathymetric change based both on SLR projections and on historic sedimentation rates. Similarly, Passeri et al. [62] use probabilistic methods to evolve the coastline and dune heights to accompany their adopted SLR scenarios. While many studies have reported modest increases in tidal amplitudes (M_2 is the most commonly studied constituent), it is difficult to generalize results due to the different characteristics of the various study sites.

Concluding Remarks

There is ample evidence that tidal amplitudes in coastal waters are not constant in time. These changes are not driven by changes in forcing but rather by changes in geometry (which alters resonance, wave speed, and other quantities) and in surface characteristics (i.e., changes in roughness which can alter damping). Tides play a major role in coastal total water levels, so constraining the range of changes that can be expected on a decadal-to-century timescale is valuable for hazard planning. Constraining these changes is also of value in terms of more accurately determining rates of RSL change at coastal locations.

Studies to date of changing tidal range have provided valuable insight into the magnitudes of the observed and likely future changes and into the physical mechanisms that contribute to these changes. Out of necessity, many of these studies have used simplified approaches, especially in terms of how to determine the geometry and boundary roughness of the model domain for paleo and future simulations. Because of this uncertainty, it is possibly most useful to think of existing studies of future tidal conditions as sensitivity experiments rather than predictive studies. Also, given the relatively modest (meter scale) increases in MSL expected in the coming centuries, tidal changes will likely be driven by local rather than far-field changes.

With increasing emphasis on the future of coastal waters and sustainability of coastal communities and ecosystems, it is likely that modeling efforts will become increasingly sophisticated in their ability to develop accurate future model grids (sedimentation, evolving land cover, and vegetation; see Passeri et al. [61] for a review). This continual refinement of models, their grids, and their boundary conditions will lead to increasingly accurate estimates of the future behavior of tides and local sea level changes.

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