1-16-2018

# Tidal Response to Sea-Level Rise in Different Types of Estuaries: The Importance of Length, Bathymetry, and Geometry

JB Du
*Virginia Institute of Marine Science*

J Shen
*Virginia Institute of Marine Science*

YL Zhang
*Virginia Institute of Marine Science*

F Yei
*Virginia Institute of Marine Science*

Z Liu
*Virginia Institute of Marine Science*

***See next page for additional authors***

**Authors**
JB Du, J Shen, YL Zhang, F Yei, Z Liu, ZG Wang, YP Wang, X Yu, M Sisson, and HV Wang

AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2017GL075963

**Key Points:**
- Tidal response to SLR is spatially uneven and varies among different estuaries
- Tidal range changes under SLR scenarios are heavily dependent on an estuary's length and bathymetry
- Estuaries with a narrow channel and large low-lying areas are likely to experience decreased tidal ranges under higher sea levels

**Supporting Information:**
- Supporting Information S1

**Correspondence to:**
J. Du,
jiabi@vims.edu;
jiabi.du@gmail.com

**Citation:**
Du, J., Shen, J., Zhang, Y. J., Ye, F., Liu, Z., Wang, Z., … Wang, H. V. (2018). Tidal response to sea-level rise in different types of estuaries: The importance of length, bathymetry, and geometry. *Geophysical Research Letters*, *45*, 227–235. https://doi.org/10.1002/2017GL075963

Received 10 OCT 2017
Accepted 15 DEC 2017
Accepted article online 22 DEC 2017
Published online 4 JAN 2018



# Tidal Response to Sea-Level Rise in Different Types of Estuaries: The Importance of Length, Bathymetry, and Geometry

**Jiabi Du[1,2], Jian Shen[1], Yinglong J. Zhang[1], Fei Ye[1], Zhuo Liu[1], Zhengui Wang[1], Ya Ping Wang[3], Xin Yu[1], Mac Sisson[1], and Harry V. Wang[1]**

[1]Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, VA, USA, [2]Department of Marine Science, Texas A&M University at Galveston, Galveston, TX, USA, [3]Ministry of Education Key Laboratory for Coast and Island Development, Nanjing University, Nanjing, China

**Abstract** Tidal response to sea-level rise (SLR) varies in different coastal systems. To provide a generic pattern of tidal response to SLR, a systematic investigation was conducted using numerical techniques applied to idealized and realistic estuaries, with model results cross-checked by analytical solutions. Our results reveal that the response of tidal range to SLR is nonlinear, spatially heterogeneous, and highly affected by the length and bathymetry of an estuary and weakly affected by the estuary convergence with an exception of strong convergence. Contrary to the common assumption that SLR leads to a weakened bottom friction, resulting in increased tidal amplitude, we demonstrate that tidal range is likely to decrease in short estuaries and in estuaries with a narrow channel and large low-lying shallow areas.

## 1. Introduction

Mean sea level is projected to increase by 0.63–0.98 m by the end of the 21st century in the Intergovernmental Panel on Climate Change Fifth Assessment Report (Church et al., 2013; IPCC, 2014), while a larger increase of up to 2.0 m is considered possible due to uncertainties in the contribution of ice melt (DeConto & Pollard, 2016; Miller et al., 2013; Rahmstorf, 2007; Rohling et al., 2008; Vermeer & Rahmstorf, 2009). Increasing evidence suggests an accelerated sea-level rise (SLR) in the past two centuries (Church & White, 2006, 2011; Rignot et al., 2011). Continued SLR is likely to cause significant changes in coastal and estuarine systems (FitzGerald et al., 2008; Kirwan & Megonigal, 2013; Najjar et al., 2010; Nicholls & Cazenave, 2010). Studies using numerical modeling and long-term monitoring data commonly agree that SLR will significantly impact estuarine tidal dynamics, circulation, saltwater intrusion, water quality, shoreline erosion, storm surge, and wetland migration or transformation (Ali, 1995; Bhuiyan & Dutta, 2012; Chua & Xu, 2014; Hilton et al., 2008; Lee et al., 2017; Reed, 1990; Rice et al., 2012; Ross et al., 2017; Sinha et al., 1997; Tebaldi et al., 2012).

While estuaries are among the most productive ecosystems in the world, serving as nursery areas and feeding grounds for a large number of marine species, they are extremely sensitive to external perturbation and continuous climate change (Harley et al., 2006). Estuarine coastlines comprise 80–90% of the U.S. East and Gulf of Mexico Coasts and exist on every continent (Friedrichs & Aubrey, 1988). The response of estuarine dynamics to SLR, however, is highly specific (e.g., Hall et al., 2013; Hong & Shen, 2012; Lee et al., 2017; Yang et al., 2015), making it difficult to apply findings from one estuary to another. There is a lack of systematic knowledge of the tidal response to SLR, as most studies only focus on one or two individual estuaries.

One of the most basic questions is: *Will the tidal range increase or decrease when sea level rises*? The change of tidal range holds wide-ranging implications, such as the flushing capacity of an estuary, vertical migration of the wetland, and inundation of the low-lying area (Arbic & Garrett, 2010; Craft et al., 2009; Monsen et al., 2002). Tidal response to SLR varies among different estuaries depending on the estuarine characteristics. The success of applying findings from one estuary to other estuaries depends on the similarities between the different systems. It is therefore necessary to determine which factors dominate tidal response to SLR.

The propagation of tidal waves in semienclosed estuaries is influenced by several processes, including amplification due to shoreline or bathymetric convergence, damping due to bottom friction, internal dissipation, and reflection at the end of the estuary (Savenije et al., 2008; van Rijn, 2011). These processes are strongly influenced by the length, bathymetry, and geometry of an estuary (Aiken, 2008; Ensing et al., 2015; Jay, 1991; Prandle, 2003; Savenije & Veling, 2005). Thus, it is vital to understand how these factors determine the response of tides in estuaries to SLR before applying the finding from one estuary to another.

In addition to altered peak water levels, changing tidal range may cause several important impacts on estuarine and ecosystem dynamics. For instance, change of tidal range affects the tidal prism and, hence, the residence time and the flushing capacity of an estuarine system (Du & Shen, 2016; Monsen et al., 2002). SLR is generally believed to reduce flushing capacity and enhance residence time, because of the enlarged water volume (Hong & Shen, 2012), even though this impact is partially compensated by the strengthened estuarine circulation in partially mixed estuaries (Du, 2017). Change of tidal range could cause profound impacts on important ecosystems such as tidal marshes, which have been experiencing rapid change in the past few decades due to coastline erosion and slow sedimentation along most coastlines (Donnelly & Bertness, 2001; Reed, 1990; Scavia et al., 2002). At present, most studies rely heavily on the accurate estimation of sediment availability from the adjacent catchment to predict potential changes in marsh extent (e.g., Craft et al., 2009; Reed, 1990). Changing tidal range was rarely recognized as a potential factor controlling the vertical migration of tidal marshes, because over the past few decades SLR was moderate and the change of tidal range was negligible in many estuaries (Flick et al., 2003). As SLR is expected to accelerate in the 21st century, changing tidal range is likely to play a more important role in reshaping the coastline and its impact on marshlands should not be neglected.

## 2. Methodology

This study was designed to systematically investigate tidal responses to SLR in different types of estuaries characterized by different length, bathymetry, and geometry through numerical simulations of idealized estuaries (Figures S4 and S5 in the supporting information) in order to improve understanding of how tides may alter across different estuarine systems. The Semi-implicit Cross-scale Hydroscience Integrated System Model (SCHISM, www.schism.wiki) is employed in this study (Ye et al., 2016; Zhang et al., 2016).

A total of 40 separate idealized runs was conducted to simulate estuaries of different length (i.e., 40, 80, 160, and 320 km), different estuary geometries (prismatic, moderately converging, and strongly converging), and different bathymetry types (triangular with fixed shorelines, triangular with moving shorelines, and narrow deep channel flanked by wide low-lying banks). Two runs for each model configuration were conducted, a base run and a 1 m SLR run. To simulate the wetting-drying in low-lying area, model grids were refined near the edges of the channel (Figure S4). The details of the model grids and configurations can be found in the supporting information.

The simulation results were cross-checked with well-established analytical solutions summarized by van Rijn (2011). To determine how the idealized estuary runs capture tidal responses in realistic estuaries, results were compared with SLR simulations of nine realistic estuaries in the Chesapeake Bay estuarine system (Figure S6). Comparison between predicted and observed tides under present conditions verified the model was able to replicate tidal characteristic in Chesapeake Bay (RMSE = 2.17 cm for the $M_2$ amplitude over eight selected stations within and near the Chesapeake Bay, see Table S1).

## 3. The Role of Estuarine Length and Geometry in the Tidal Response to SLR

The length and geometry of an estuary are commonly known to greatly affect tidal wave propagation, but their importance on the change of tidal range due to SLR has not thoroughly been investigated. The sensitivity of tide to changing mean sea level in a total of 12 idealized estuaries was examined (Figures S4 and S5). These idealized estuaries were characterized with a V-shape lateral bathymetry, a maximum depth of 12 m at the middle, and a minimum depth of $-2$ m along the edges.

The simulation results demonstrate that the length of the channel is a key factor in controlling the tidal response to SLR, in terms of the magnitude and the trend of tidal range change. For a long channel (e.g., a 320 km channel with two nodal points), tidal range increases over the majority of the channel, with maximum increases at the head of the channel and in the middle between the two nodal points (Figures 1d and 1g). For a channel of medium length (e.g., 160 km channel with one nodal point), the change of tidal range between the lower reach and the upper reach is distinctly opposite, with an increased tidal range near the head and a

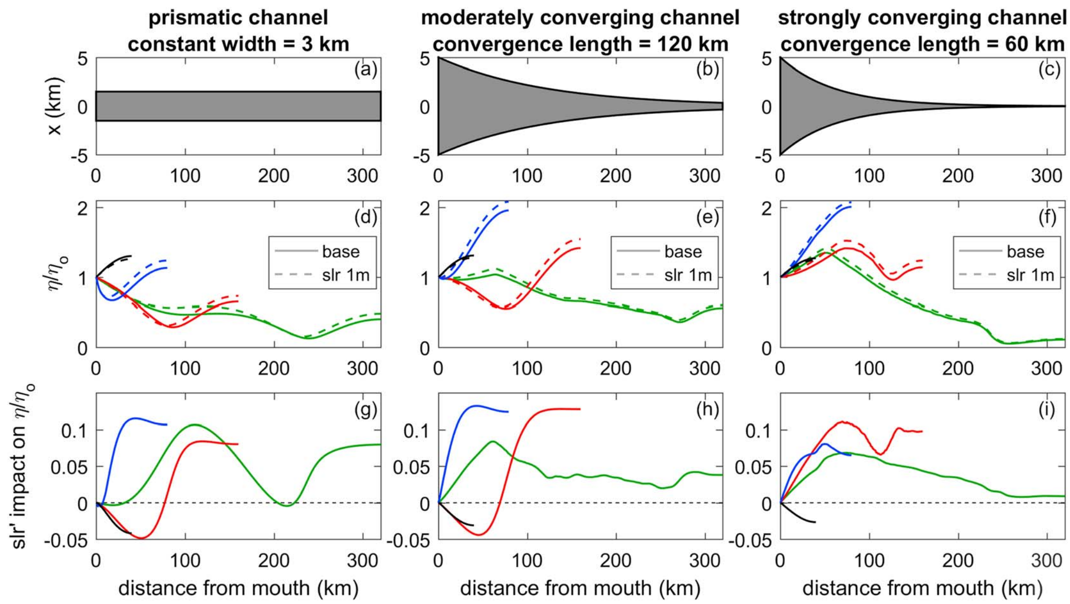


**Figure 1.** The response of tidal range to SLR in channels characterized by different types of geometry and different lengths. (a–c) Outlines of three types of geometry, (d–f) tidal ranges along the channel of different estuaries in base run and SLR run, and (g–i) changes of the tidal range due to SLR denoted by the difference between the base run and SLR run. The tidal range ($\eta$) along the channel is normalized by the tidal range at the mouth of the channel ($\eta_o$). Four lengths of channel are tested, namely, 40, 80, 160, and 320 km, represented by different line colors. The prismatic channels are characterized by a constant width, while the converging channels are characterized by an exponentially decreasing width from the mouth to the head.

decreased tidal range near the mouth. For a channel with near resonance length (e.g., 80 km, approximately one quarter of the tidal wavelength), the tidal range is more sensitive to the change of water depth, which is verified by the analytical results (Figures S1–S3). For a short channel (e.g., 40 km), the tidal range is reduced throughout the entire channel.

Despite the considerable impact estuarine shape has on tidal range along an estuary, this property has limited impact on the tidal response to SLR with the exception of strongly convergent systems. The width of many converging estuaries can be expressed as an exponential function of the distance from the mouth, $b = b_o \times \exp(-x/L_b)$, where $b$ is the width, $b_o$ is the width at the mouth (here we use 10 km), $x$ is the distance from the mouth, and $L_b$ is the convergence length (Friedrichs & Aubrey, 1994; Lanzoni & Seminara, 1998). Moderate and strong convergences were examined in this study, with convergence lengths of 120 km and 60 km, respectively (Figures 1b and 1c). The tidal response in estuaries with moderately converging channels showed a similar trend as the prismatic channel estuaries (Figures 1e and 1f); however, the magnitude of the change was larger for the moderately converging estuaries (Figures 1g and 1h). For estuaries with strongly converging channels, the tidal range is increased throughout the entire channel for estuaries 80 km and longer (Figures 1f and 1i). One of the major differences seen for a strongly convergent system is that the tidal range of the entire channel of 160 km estuary is increased under SLR (Figure 1i). This distinctly differs from the 160 km prismatic and moderately converging channels, where tidal range decreases in the lower estuary under SLR conditions (Figures 1g and 1h). In addition, the location where the largest difference between base tides and SLR tides occurs shifts downstream relative to the moderately converging and prismatic channel estuaries, while the increase of tidal range at the head of the channel is less profound compared to the prismatic channel.

To verify the result of numerical simulations, we conducted analysis using well-established analytical solutions described by van Rijn (2011). The spatial distribution and the response of tidal range to SLR in different length channels are well explained by the analytical solution (Figures S1–S3). Since Lorentz (1926) linearized the bottom friction term, solutions for prismatic and converging channels have been well developed (e.g., Aubrey & Speer, 1985; Cai et al., 2012; Friedrichs, 2010; Friedrichs & Aubrey, 1988, 1994; Jay, 1991; Officer, 1976; Prandle, 2003; Savenije et al., 2008; Speer & Aubrey, 1985; van Rijn, 2011). The analytical solutions assist in identifying the dominant factors governing the response of a system without involving numerical simulations or detailed observation (Holleman & Stacey, 2014), thereby assisting to predict SLR response with little computational effort. Despite its efficiency, the analytical method is limited in its ability to address the impact of complex geometry, bathymetry, and spatially varying bottom roughness. As a consequence numerical simulations with these capabilities were employed for this study.

Tidal response to the SLR in estuaries with V-shape channel bathymetry is the result of increased water depth that alters incoming tidal wave amplitude and shifts nodal points. In a V-shape channel, a 1 m SLR will increase the mean water depth by 0.5 m, which decreases bottom friction and reduces energy dissipation. This subsequently increases wave speed (assuming a shallow-water wave), wavelength, and amplitude of the incoming tidal wave (Holleman & Stacey, 2014; Ross et al., 2017). Consequently, the nodal point, which occurs at (1 + 2n)/4 of the tidal wavelength from the end of the channel, moves downstream, leading to a spatially uneven distribution of tidal response. For an estuary with a length close to the resonance length (approximately one-quarter wavelength), the tidal response to altered water depth is extremely sensitive (Green, 2010; Greenberg et al., 2012; Pelling & Green, 2013; Zhong et al., 2008). For the tested 80 km channel in this study, the increased water depth brings the channel closer to resonance status and dramatically increases the tidal range, whereas for a shorter estuary (e.g., 40 km), increasing the water depth shifts the estuary farther away from the resonance length, leading to a decreased tidal range. It is important to note that the length of a channel is meaningful only when it is normalized by the tidal wavelength (Li & O'Donnell, 2005).

## 4. The Role of Lateral Bathymetry on Tidal Response to SLR

Allowing flooding of low-lying lands and the area of low-lying land subject to flooding, can dramatically alter the tidal response to SLR, as illustrated by multiple numerical studies (e.g., Hall et al., 2013; Lee et al., 2017; Lopes & Dias, 2015; Pelling & Green, 2013; Pelling et al., 2013; Ward et al., 2012). For estuaries with a large low-lying area relative to the channel area, tidal response to SLR may be dramatically altered and even reversed (e.g., Lee et al., 2017).

To investigate the role of bathymetry we examined tidal response to SLR for three distinctly different bathymetries, namely, Type A, B, and C bathymetries (Figures 2a–2c). These three types of bathymetries are very representative as they are frequently found in coastal systems. Type A is characterized by two straight walls at its channel edges, where wetting and drying are prohibited; Type B is characterized by a V-shape channel, where wetting and drying are allowed; Type C is characterized by a large low-lying area in both shallow banks, where extensive areas will be submerged when sea level rises. Types A and B also represent two anthropogenic adaptation strategies to the future SLR, namely, defend or retreat, where "defend" involves building seawalls or dykes at present-day coastlines and "retreat" allows shorelines to move as low-lying land is inundated. Type C estuaries are similar to those surrounded by large tracts of marsh or wetland environments, where the defend option is unfeasible. For these simulations the estuary geometry employed was prismatic and the same different lengths used in the previous experiments were applied (Figure S4).

The simulation results demonstrate that the spatial distribution of the tidal range response to SLR was strongly affected by the channel bathymetry. The change in tidal ranges for bathymetries Type A and Type B show similar trends, but with differing magnitudes, while for bathymetry Type C tidal response exhibits an opposing trend (Figure 2). Taking the 320 km channel, for instance, the tidal range in Type C is reduced in response to SLR for the majority of the estuary, distinctly different from the Type A or Type B estuaries, where the tidal range increases under SLR condition.

The impact of bathymetry on the tidal response to SLR can largely be explained by the alteration of mean water depth and the newly introduced tidal dissipation area. Increase of mean sea level, while preserving the original shoreline, could produce additional tidal amplification, consistent with previous studies (e.g., Holleman & Stacey, 2014; Hong & Shen, 2012). Applying the same SLR, the change of laterally averaged water depth in the channels with Type A bathymetry is twice as large as that in the channels with Type B bathymetry, leading to a larger change rate of tidal response to SLR in Type A bathymetry channels, which is consistent with the analytical results (Figure S1). The opposing trend in estuaries with Type C bathymetry suggests that a large low-lying area to be submerged could strongly alter the tidal response to SLR. For Type C estuaries, the

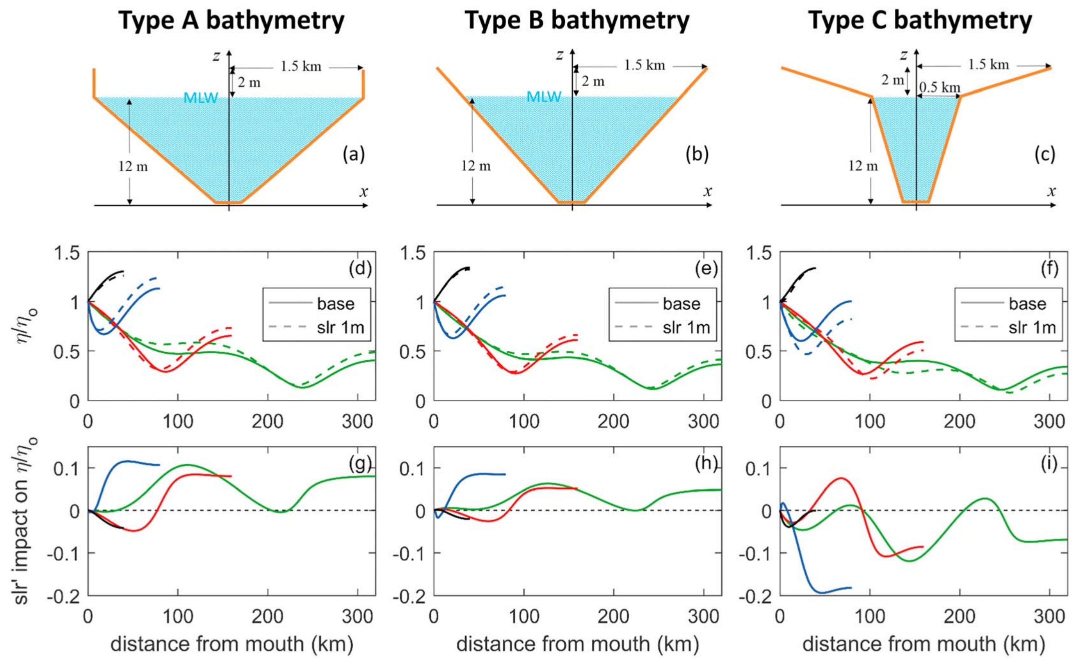


**Figure 2.** (a–c) Three types of lateral bathymetry, (d–f) tidal ranges along channels for different types of estuaries, and (g–i) the changes of tidal range due to SLR denoted by the difference between base run and SLR run. The tidal range ($\eta$) along the channel is normalized by the tidal range at the mouth of the channel ($\eta_O$). Four lengths of channel are tested, namely, 40, 80, 160, and 320 km represented by different line colors. Type A bathymetry is characterized by two side walls at the edges of the channels, wetting-drying processes prohibited. Type B bathymetry is characterized with a constant slope from the deep channel to its shallow bank, wetting-drying processes allowed. Type C bathymetry is characterized with a large low-lying area in its shallow banks, allowing intensive wetting-drying.

permanent inundation of low-lying areas reduces the mean water depth and results in a decreased tidal range in major regions.

For most deep and large estuaries, such as San Francisco Bay or Yangtze River estuary, the main channels have much larger areas than the low-lying tidal flats and the enlarged incoming tidal energy usually overwhelm the increase of tidal energy dissipation rate, leading to a Type A or Type B response. This is also the case in estuaries that are embanked with human-built levee systems. However, some specific types of systems that have large low-lying areas and extremely small bottom slopes are likely to have smaller tidal ranges under SLR (Hall et al., 2013; Lee et al., 2017). The most frequently seen examples are the intertidal flat and tidal-marsh creeks, which are distributed globally over the coast (Orson et al., 1985). A decrease of tidal range may also result from extremely large SLR scenarios (e.g., SLR = 5 m), as demonstrated by numerical tests for the European Shelf (Pelling & Green, 2014; Pickering et al., 2012; Ward et al., 2012). Under these conditions flooding over shallow banks was found to significantly enhance the tidal energy dissipation and reduce the tidal range.

## 5. Tidal Response to SLR in Realistic Estuaries

Due to the complex geometry and bathymetry, a realistic estuary may experience a range of tidal responses to SLR that differ from the idealized estuaries. In order to examine tidal responses in different realistic estuaries, a numerical simulation with domain covering the U.S. East Coast was conducted (Figure S6). Tidal response to 1 m SLR was examined along eight subestuaries and the main stem of Chesapeake Bay. The tidal range at each estuary is normalized by the tidal range at the mouth to exclude the influence of changed tidal range at the mouth of a given estuary. It is important to note that the SLR could cause a change of tidal amplitude in the open ocean and in the continental shelf (Flick et al., 2003; Green, 2010; Pickering et al., 2017), and it is therefore necessary to include the change of tidal amplitude at the mouth when applying the numerical results of the present study to a given estuary.

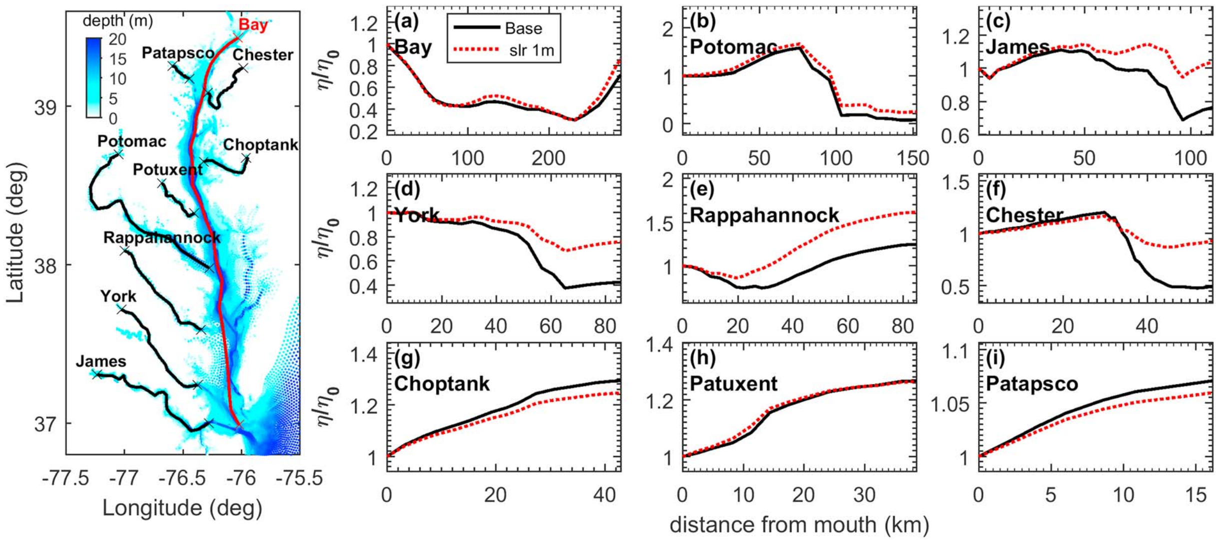


**Figure 3.** The tidal response to SLR in multiple realistic estuaries. Locations of the realistic channels are shown in the left panel, where the colored dot is the depth of the nodes of the unstructured grid. The tidal range ($\eta$) along the channel is normalized by the tidal range at the mouth of each estuary ($\eta_o$).

The tidal response to SLR in nine different estuaries shows the spatially uneven change of tidal range under SLR conditions and confirm that the length is the key parameter determining how estuarine tides are likely to change under future conditions (Figure 3). Our simulation shows a slight increase of tidal range in the Bay's main stem, which is consistent with the sensitivity test by previous studies that used a vertical wall coastline assumption (Hong & Shen, 2012; Ross et al., 2017) and can be attributed to the decrease of energy dissipation at the deep bottom and the change of resonance frequency. Zhong et al. (2008) suggest that a 1 m SLR will move the resonance band toward the diurnal band and cause an increased gain in amplitude in Chesapeake Bay. The seaward shifting of nodal points for the long estuary (Chesapeake main stem, Figure 3a) agrees well with the idealized estuary cases for bathymetry Type A and B. Note that these results differ from Lee et al. (2017), who showed future tides along the Chesapeake main stem decrease relative to present tides, exhibiting a similar response as in an idealized long estuary with Type C bathymetry. The reversed tidal response to SLR captured by Lee et al. (2017) was not replicated by the model in this study or that of Zhong et al. (2008), as the grids employed did not extend over the low-lying intertidal and marsh areas on the eastern shores of Chesapeake Bay, which are likely to be inundated under 1 m SLR and act as a significant tidal energy sink. The differences among these studies highlight the role altered geometry and bathymetry play in tidal response to SLR.

Not only in the main stem of the bay, tidal responses in other subestuaries exhibit similar trends as in idealized estuaries of similar length and geometry. The response in the Potomac estuary is similar to the moderate length, strongly converging estuary (160 km estuary in Figures 1c and 1f). While the estuary width does not appear to rapidly alter, the bathymetry of the main channel experiences a sharp constriction approximately 35 km from the mouth. For the York and Rappahannock estuaries, the tidal response to SLR is similar to the response of an idealized 80 km long estuary with a moderately convergent or prismatic channel and Type A or B bathymetry, which aligns with the characteristics of these subestuaries. The Chester subestuary exhibits a similar trend; however, SLR tides remain slightly lower than present-day tides over the lower half of the estuary, before significantly increasing relative to present-day tides in the upper half of the estuary. The protracted suppressed tide is likely due to the larger tracts of low-lying lands and intertidal areas for this subestuary. The strongly increased tides relative to present-day tides in the upper half of this subestuary may reflect a shift toward a more strongly converging geometry under SLR conditions. While both the Choptank and Patapsco subestuaries reflect reduced tides exhibited by idealized short estuaries (compare Figures 3g and 3i with Figure 1e), the Patuxent estuary tidal response differed, with a slightly higher or similar SLR tides relative to present-day tides. This may be due to the narrow deep channel (~20–30 m) present in this subestuary compared with the two other systems.

Because of irregular geometry and bathymetry, not all aspects of the tidal response to SLR in realistic estuaries can be matched with the idealized estuaries. Nevertheless, the comparisons between the realistic and idealized estuaries shown above demonstrate the potential to gain much needed insight into future changes in tides using fundamental estuary characteristics. By using the results presented for idealized estuaries in this study and matching them with estuary characteristics, researchers will be able to better predict how tides in an estuary may alter in the future, in the absence of numerical modeling studies.

## 6. Summary

This study examined the relative importance of different parameters of an estuary on the tidal response to SLR, providing general understanding of the change of tidal range in different types of estuaries. For estuaries with prismatic channels and small low-lying areas, whose channels are short, moderate, and long, SLR causes the tidal range to decrease, initially decrease then increase, and increase, respectively. These different responses demonstrate the key role estuary length plays on tidal response. With respect to bathymetry, estuaries composed of a triangular or rectilinear channel exhibite similar tidal responses to SLR, while changes in tides for estuaries with narrow channels flanked by wide shallow banks significantly differ from the two other scenarios. This suggests the importance of considering the estuary bathymetry, and not just the mean water depth, when predicting the impact of SLR on tides. While the geometry of the estuary strongly affects tidal amplification and attenuation, tidal response for both prismatic and moderately converging estuaries exhibite the same trend but with different magnitudes, with an exception of strongly converging estuaries. It is therefore necessary to consider the change of convergence characteristics change under SLR conditions when determining how tides may alter in the future.

The study demonstrated that tidal response to SLR is spatially uneven and differs depending upon estuary length, bathymetry, and geometry. Contrary to the common assumption that an enlarged tidal amplitude due to less bottom friction will result from SLR, we show that the tidal range will likely decrease in a short estuary and in estuaries with a narrow channel and a large low-lying area. Further, we demonstrate how tidal response to SLR may be predicted using knowledge of an estuary's length, geometry, and bathymetry and an understanding of how these properties are likely to alter under SLR conditions. In this way, the idealized results presented in this paper may be used to gain an initial understanding of how tides will alter in estuaries where detailed numerical modeling is not feasible, but an understanding of altered tidal dynamics is vital for future management of the estuary, adjacent lands, and associated ecosystems.

This study holds wide-ranging implications, from the change of flushing characteristics, to the potential vertical expansion of tidal marshes. The change of flushing capacity is likely to be spatially uneven because of the spatial heterogeneity of tidal response. For estuaries that have large low-lying areas, reduced tidal range may dramatically slow the flushing when sea level rises.

The decreased tidal range in both short estuaries and estuaries with large low-lying coastal lands may reduce the vertical expansion of the tidal marsh and lead to a larger reduction in tidal marsh areas than previously predicted. Given that the tidal response in realistic estuaries containing extensive tracts of tidal marshes is spatially variable, the impact on marsh systems due to changing tides is also likely to vary spatially. In order to determine the likely impact of changing tidal range on marsh systems under SLR, we recommend using the analytical tool and numerical models that account for tidal wave reflection, percentage of the low-lying area, and wetting-drying processes. The analytical solution could provide a first-order spatial pattern based on the channel length and converging factor, while the numerical model provides more accurate estimation for estuaries with complex bathymetry and geometry.

Changing tides under SLR could also affect coastal inundation and vulnerability to coastal hazards. Using the generic pattern revealed by the systematically designed numerical experiments, and the analytical tools provided by previous studies (e.g., Cai et al., 2012; van Rijn, 2011), one could have a reasonable prediction of the change of tidal range due to SRL in an estuary. It is important to note the potential alteration caused by the complexity of the specific bathymetry and geometry in realistic estuaries. The possible altered tidal amplitude in the coastal ocean under SLR should also be considered when applying the generic pattern revealed in this study to any coastal system.

**Acknowledgments**
We thank the anonymous reviewers who helped to improve the manuscript. This work is supported by the National Science Foundation (award 1325518), and the first author is also supported by the institutional fellowship by Texas A&M University. Simulations shown in this paper were conducted on the high-performance computer cluster Sciclone at the College of William and Mary. The data sets used in this study have been made available at http://doi.org/10.5281/zenodo.1008586. The source code for the model used in this study is freely available at http://ccrm.vims.edu/schismweb. This is contribution 3712 of the Virginia Institute of Marine Science, College of William and Mary.

## References

Aiken, C. M. (2008). Barotropic tides of the Chilean Inland Sea and their sensitivity to basin geometry. *Journal of Geophysical Research*, *113*, C08024. https://doi.org/10.1029/2007JC004593

Ali, A. (1995). A numerical investigation into the back water effect on flood water in the Meghna River in Bangladesh due to the south-west monsoon wind. *Estuarine, Coastal and Shelf Science*, *41*(6), 689–704. https://doi.org/10.1006/ecss.1995.0084

Arbic, B. K., & Garrett, C. (2010). A coupled oscillator model of shelf and ocean tides. *Continental Shelf Research*, *30*(6), 564–574. https://doi.org/10.1016/j.csr.2009.07.008

Aubrey, D., & Speer, P. (1985). A study of non-linear tidal propagation in shallow inlet/estuarine systems Part I: Observations. *Estuarine, Coastal and Shelf Science*, *21*(2), 185–205. https://doi.org/10.1016/0272-7714(85)90096-4

Bhuiyan, M. J. A. N., & Dutta, D. (2012). Assessing impacts of sea level rise on river salinity in the Gorai river network, Bangladesh. *Estuarine, Coastal and Shelf Science*, *96*, 219–227. https://doi.org/10.1016/j.ecss.2011.11.005

Cai, H., Savenije, H. H. G., & Toffolon, M. (2012). A new analytical framework for assessing the effect of sea-level rise and dredging on tidal damping in estuaries. *Journal of Geophysical Research*, *117*, C09023. https://doi.org/10.1029/2012JC008000

Chua, V. P., & Xu, M. (2014). Impacts of sea-level rise on estuarine circulation: An idealized estuary and San Francisco Bay. *Journal of Marine Systems*, *139*, 58–67. https://doi.org/10.1016/j.jmarsys.2014.05.012

Church, J. A., & White, N. J. (2006). A 20th century acceleration in global sea-level rise. *Geophysical Research Letters*, *33*, L01602. https://doi.org/10.1029/2005GL024826

Church, J. A., & White, N. J. (2011). Sea-level rise from the late 19th to the early 21st century. *Surveys in Geophysics*, *32*(4-5), 585–602. https://doi.org/10.1007/s10712-011-9119-1

Church, J. A., Clark, P. U., Cazenave, A., Gregory, J. M., Jevrejeva, S., Levermann, A., … Unnikrishnan, A. S. (2013). Sea level change. In T. F. Stocker, et al. (Eds.), *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 1137–1216). Cambridge, UK: Cambridge University Press.

Craft, C., Clough, J., Ehman, J., Joye, S., Park, R., Pennings, S., … Machmuller, M. (2009). Forecasting the effects of accelerated sea-level rise on tidal marsh ecosystem services. *Frontiers in Ecology and the Environment*, *7*(2), 73–78. https://doi.org/10.1890/070219

DeConto, R. M., & Pollard, D. (2016). Article contribution of Antarctica to past and future sea-level rise. *Nature*, *531*(7596), 591–597. https://doi.org/10.1038/nature17145

Donnelly, J. P., & Bertness, M. D. (2001). Rapid shoreward encroachment of salt marsh cordgrass in response to accelerated sea-level rise. *Proceedings of the National Academy of Sciences of the United States of America*, *98*(25), 14,218–14,223. https://doi.org/10.1073/pnas.251209298

Du, J. (2017). *Impact of climate variation and human adaptation on the physical transport processes and water exchange in Chesapeake Bay* (pp. 87–89). Gloucester Point, VA: College of William and Mary.

Du, J., & Shen, J. (2016). Water residence time in Chesapeake Bay for 1980–2012. *Journal of Marine Systems*, *164*, 101–111. https://doi.org/10.1016/j.jmarsys.2016.08.011

Ensing, E., de Swart, H. E., & Schuttelaars, H. M. (2015). Sensitivity of tidal motion in well-mixed estuaries to cross-sectional shape, deepening, and sea level rise: An analytical study. *Ocean Dynamics*, *65*(7), 933–950. https://doi.org/10.1007/s10236-015-0844-8

FitzGerald, D. M., Fenster, M. S., Argow, B. A., & Buynevich, I. V. (2008). Coastal impacts due to sea-level rise. *Annual Review of Earth and Planetary Sciences*, *36*(1), 601–647. https://doi.org/10.1146/annurev.earth.35.031306.140139

Flick, R. E., Murray, J. F., Ewing, L. C., & Asce, M. (2003). Trends in United States tidal datum statistics and tide range. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, *129*(4), 155–164. https://doi.org/10.1061/(ASCE)0733-950X(2003)129:4(155)

Friedrichs, C. T. (2010). Barotropic tides in channelized estuaries. In A. Valle-Levinson (Ed.), *Contemporary issues in estuarine physics* (pp. 27–61). Cambridge, UK: Cambridge University Press. https://doi.org/10.1017/CBO9780511676567.004

Friedrichs, C. T., & Aubrey, D. G. (1988). Non-linear tidal distortion in shallow well-mixed estuaries: A synthesis. *Estuarine, Coastal and Shelf Science*, *27*(5), 521–545. https://doi.org/10.1016/0272-7714(88)90082-0

Friedrichs, C. T., & Aubrey, D. G. (1994). Tidal propagation in strongly convergent channels. *Journal of Geophysical Research*, *99*(C2), 3321–3336. https://doi.org/10.1029/93JC03219

Green, J. A. M. (2010). Ocean tides and resonance. *Ocean Dynamics*, *60*(5), 1243–1253. https://doi.org/10.1007/s10236-010-0331-1

Greenberg, D. A., Blanchard, W., Smith, B., & Barrow, E. (2012). Climate change, mean sea level and high tides in the Bay of Fundy. *Atmosphere-Ocean*, *50*(3), 261–276. https://doi.org/10.1080/07055900.2012.668670

Hall, G. F., Hill, D. F., Horton, B. P., Engelhart, S. E., & Peltier, W. R. (2013). A high-resolution study of tides in the Delaware Bay: Past conditions and future scenarios. *Geophysical Research Letters*, *40*, 338–342. https://doi.org/10.1029/2012GL054675

Harley, C. D. G., Randall Hughes, A., Hultgren, K. M., Miner, B. G., Sorte, C. J. B., Thornber, C. S., … Williams, S. L. (2006). The impacts of climate change in coastal marine systems. *Ecology Letters*, *9*(2), 228–241. https://doi.org/10.1111/j.1461-0248.2005.00871.x

Hilton, T. W., Najjar, R. G., Zhong, L., & Li, M. (2008). Is there a signal of sea-level rise in Chesapeake Bay salinity? *Journal of Geophysical Research*, *113*, C09002. https://doi.org/10.1029/2007JC004247

Holleman, R. C., & Stacey, M. T. (2014). Coupling of sea level rise, tidal amplification, and inundation. *Journal of Physical Oceanography*, *44*(5), 1439–1455. https://doi.org/10.1175/JPO-D-13-0214.1

Hong, B., & Shen, J. (2012). Responses of estuarine salinity and transport processes to potential future sea-level rise in the Chesapeake Bay. *Estuarine, Coastal and Shelf Science*, *104-105*, 33–45. https://doi.org/10.1016/j.ecss.2012.03.014

IPCC (2014). Summary for policymakers. In C. P. Field, et al. (Eds.), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 1–32). Cambridge, United Kingdom and New York: Cambridge University Press.

Jay, D. A. (1991). Greens's law revisited: Tidal long-wave propagation in channels with strong topography. *Journal of Geophysical Research*, *96*(C11), 20,585–20,598. https://doi.org/10.1029/91JC01633

Kirwan, M. L., & Megonigal, J. P. (2013). Tidal wetland stability in the face of human impacts and sea-level rise. *Nature*, *504*(7478), 53–60. https://doi.org/10.1038/nature12856

Lanzoni, S., & Seminara, G. (1998). On tide propagation in convergent estuaries. *Journal of Phytological Research*, *103*(C13), 30,793–30,812. https://doi.org/10.1029/1998JC900015

Lee, S. R., Li, M., & Zhang, F. (2017). Impact of sea level rise on tidal range in Chesapeake and Delaware Bays. *Journal of Geophysical Research: Oceans*, *122*, 3917–3938. https://doi.org/10.1002/2016JC012597

Li, C., & O'Donnell, J. (2005). The effect of channel length on the residual circulation in tidally dominated channels. *Journal of Physical Oceanography*, *35*(10), 1826–1840. https://doi.org/10.1175/JPO2804.1

Lopes, C. L., & Dias, J. M. (2015). Tidal dynamics in a changing lagoon: Flooding or not flooding the marginal regions. *Estuarine, Coastal and Shelf Science*, *167*, 14–24. https://doi.org/10.1016/j.ecss.2015.05.043

Lorentz, H. A. (1926). *Report commission Zuiderzee 1918–1926 (in Dutch)*. Netherlands: Den Haag.

Miller, K. G., Kopp, R. E., Horton, B. P., Browning, J. V., & Kemp, A. C. (2013). A geological perspective on sea-level rise and its impacts along the U.S. Mid-Atlantic coast. *Earth's Future*, *1*(1), 3–18. https://doi.org/10.1002/2013EF000135

Monsen, N. E., Cloern, J. E., Lucas, L. V., & Monismith, S. G. (2002). The use of flushing time, residence time, and age as transport time scales. *Limnology and Oceanography*, *47*(5), 1545–1553. https://doi.org/10.4319/lo.2002.47.5.1545

Najjar, R. G., Pyke, C. R., Adams, M. B., Breitburg, D., Hershner, C., Kemp, M., … Wood, R. (2010). Potential climate-change impacts on the Chesapeake Bay. *Estuarine, Coastal and Shelf Science*, *86*(1), 1–20. https://doi.org/10.1016/j.ecss.2009.09.026

Nicholls, R. J., & Cazenave, A. (2010). Sea-level rise and its impact on coastal zones. *Science*, *328*(5985), 1517–1520. https://doi.org/10.1126/science.1185782

Officer, C. B. (1976). *Physical oceanography of estuaries (and associated coastal waters)*. New York: Wiley.

Orson, R., Panageotou, W., & Leatherman, S. P. (1985). Response of tidal salt marshes of the U.S. Atlantic and Gulf coasts to rising sea levels. *Journal of Coastal Research*, *1*, 29–37.

Pelling, H. E., & Green, J. A. M. (2013). Sea level rise and tidal power plants in the Gulf of Maine. *Journal of Geophysical Research: Oceans*, *118*, 2863–2873. https://doi.org/10.1002/jgrc.20221

Pelling, H. E., & Green, J. A. M. (2014). Impact of flood defences and sea-level rise on the European Shelf tidal regime. *Continental Shelf Research*, *85*, 96–105. https://doi.org/10.1016/j.csr.2014.04.011

Pelling, H. E., Green, J. A. M., & Ward, S. L. (2013). Modelling tides and sea-level rise: To flood or not to flood. *Ocean Modelling*, *63*, 21–29. https://doi.org/10.1016/j.ocemod.2012.12.004

Pickering, M. D., Wells, N. C., Horsburgh, K. J., & Green, J. A. M. (2012). The impact of future sea-level rise on the European Shelf tides. *Continental Shelf Research*, *35*, 1–15. https://doi.org/10.1016/j.csr.2011.11.011

Pickering, M. D., Horsburgh, K. J., Blundell, J. R., Hirschi, J. J. M., Nicholls, R. J., Verlaan, M., & Wells, N. C. (2017). The impact of future sea-level rise on the global tides. *Continental Shelf Research*, *142*, 50–68. https://doi.org/10.1016/j.csr.2017.02.004

Prandle, D. (2003). Relationships between tidal dynamics and bathymetry in strongly convergent estuaries. *Journal of Physical Oceanography*, *33*(12), 2738–2750. https://doi.org/10.1175/1520-0485(2003)033%3C2738:RBTDAB%3E2.0.CO;2

Rahmstorf, S. (2007). Projecting future sea-level rise. *Science*, *315*(5810), 368–370. https://doi.org/10.1126/science.1135456

Reed, D. J. (1990). The impact of sea-level rise on coastal salt marshes. *Progress in Physical Geography*, *14*, 24–40.

Rice, K. C., Hong, B., & Shen, J. (2012). Assessment of salinity intrusion in the James and Chickahominy Rivers as a result of simulated sea-level rise in Chesapeake Bay, East Coast, USA. *Journal of Environmental Management*, *111*, 61–69. https://doi.org/10.1016/j.jenvman.2012.06.036

Rignot, E., Velicogna, I., van den Broeke, M. R., Monaghan, A., & Lenaerts, J. (2011). Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea-level rise. *Geophysical Research Letters*, *38*, L05503. https://doi.org/10.1029/2011GL046583

Rohling, E. J., Grant, K., Hemleben, C., Siddall, M., Hoogakker, B. A. A., Bolshaw, M., & Kucera, M. (2008). High rates of sea-level rise during the last interglacial period. *Nature Geoscience*, *1*(1), 38–42. https://doi.org/10.1038/ngeo.2007.28

Ross, A. C., Najjar, R. G., Li, M., Lee, S. B., Zhang, F., & Liu, W. (2017). Fingerprints of sea level rise on changing tides in Chesapeake and Delaware Bays. *Journal of Geophysical Research: Oceans*, *122*, 8102–8125. https://doi.org/10.1002/2017JC012887

Savenije, H. H. G., & Veling, E. J. M. (2005). Relation between tidal damping and wave celerity in estuaries. *Journal of Geophysical Research*, *110*, C04007. https://doi.org/10.1029/2004JC002278

Savenije, H. H. G., Toffolon, M., Haas, J., & Veling, E. J. M. (2008). Analytical description of tidal dynamics in convergent estuaries. *Journal of Geophysical Research*, *113*, C10025. https://doi.org/10.1029/2007JC004408

Scavia, D., Field, J. C., & Boesch, D. F. (2002). Climate change impacts on U. S. *Coastal and Marine Ecosystems, Estuaries*, *25*(2), 149–164.

Sinha, P., Rao, Y., Dube, S., & Murty, T. (1997). Effect of sea level rise on tidal circulation in the Hooghly estuary, Bay of Bengal. *Marine Geodesy*, *20*(4), 341–366. https://doi.org/10.1080/01490419709388114

Speer, P. E., & Aubrey, D. G. (1985). A study of non-linear tidal propagation in shallow inlet/estuarine systems, Part II: Theory. *Estuarine, Coastal and Shelf Science*, *21*(2), 207–224. https://doi.org/10.1016/0272-7714(85)90097-6

Tebaldi, C., Strauss, B. H., & Zervas, C. E. (2012). Modelling sea level rise impacts on storm surges along US coasts. *Environmental Research Letters*, *7*(1), 014032. https://doi.org/10.1088/1748-9326/7/1/014032

van Rijn, L. C. (2011). Analytical and numerical analysis of tides and salinities in estuaries; Part I: Tidal wave propagation in convergent estuaries. *Ocean Dynamics*, *61*(11), 1719–1741. https://doi.org/10.1007/s10236-011-0453-0

Vermeer, M., & Rahmstorf, S. (2009). Global sea level linked to global temperature. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(51), 21,527–21,532. https://doi.org/10.1073/pnas.0907765106

Ward, S. L., Green, J. A. M., & Pelling, H. E. (2012). Tides, sea-level rise and tidal power extraction on the European Shelf. *Ocean Dynamics*, *62*(8), 1153–1167. https://doi.org/10.1007/s10236-012-0552-6

Yang, Z., Wang, T., Voisin, N., & Copping, A. (2015). Estuarine response to river flow and sea-level rise under future climate change and human development. *Estuarine, Coastal and Shelf Science*, *156*(1), 19–30. https://doi.org/10.1016/j.ecss.2014.08.015

Ye, F., Zhang, Y. J., Friedrichs, M. A. M., Wang, H. V., Irby, I. D., Shen, J., & Wang, Z. (2016). A 3D, cross-scale, baroclinic model with implicit vertical transport for the Upper Chesapeake Bay and its tributaries. *Ocean Modelling*, *107*, 82–96. https://doi.org/10.1016/j.ocemod.2016.10.004

Zhang, Y. J., Ye, F., Stanev, E. V., & Grashorn, S. (2016). Seamless cross-scale modeling with SCHISM. *Ocean Modelling*, *102*, 64–81. https://doi.org/10.1016/j.ocemod.2016.05.002

Zhong, L., Li, M., & Foreman, M. G. G. (2008). Resonance and sea level variability in Chesapeake Bay. *Continental Shelf Research*, *28*(18), 2565–2573. https://doi.org/10.1016/j.csr.2008.07.007