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A Multi-scale Approach for Simulating Tidal Marsh Evolution

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38 **Abstract**

39 This study presents a new approach to modeling marsh evolution. The Tidal Marsh Model
40 (TMM) has been developed as a module within the SCHISM framework (Semi-implicit Cross-scale
41 Hydroscience Integrated System Model). Some unique features of the TMM are dynamic rates, cross-
42 scale simulations, and incorporation of anthropogenic stressors, which allow it to overcome many
43 limitations that current marsh models possess. To evaluate model performance, the TMM was applied
44 in Carter Creek and Taskinas Creek within the York River system (Virginia, USA). We assessed
45 model outputs against field observations focusing on two main aspects: marsh boundary evolution and
46 distribution of marsh sediments. Marsh migration is captured with an accuracy of 81% in Carter Creek,
47 and an accuracy of 78% in Taskinas Creek. Different statistical descriptors were used to evaluate the
48 model's ability to reproduce the distribution of observed marsh sediment fractions. Results in both
49 study areas show a satisfactory agreement between sediment model outputs and field observations.
50 This innovative modeling approach will help close some critical knowledge gaps in the current
51 understanding of the system dynamics and allow better implementation of management actions to
52 preserve these ecosystems and their services.

53
54 **Keywords:** marsh evolution model, sea-level rise, cross-scale simulation, unstructured grid, SCHISM.

57 **1. Introduction**

59 Marshes perform multiple ecological functions and have special characteristics that make them
60 important and valuable natural resources. They provide habitat for many organisms; offer storm surge
61 protection as well as upland erosion protection, given their capacity to attenuate wave energy; and play
62 an important role in water quality, due to their ability to filter several pollutants; and trap sediments
63 from both aquatic and terrestrial inputs (Fisher and Acreman 2004; Mitsch and Gosselink 2007).

64 Marsh habitats are experiencing growing threats from sea-level rise (SLR) and recurrent
65 flooding due to climate change. With current SLR rates on the order of 5-6 mm/yr and accelerating
66 (Boon and Mitchell 2015), the Chesapeake Bay region is one of the most vulnerable areas in the U.S.
67 (Glick et al. 2008). Higher levels of relative SLR can be attributed to a combination of increased

68 absolute sea-level rise and land subsidence in this region, mainly due to glacial isostatic processes and
69 local excessive groundwater withdrawal (Eggleston and Pope 2013). In addition, recent studies (e.g.
70 Sallenger et al. 2012; Ezer et al. 2013; Rahmstorf et al. 2015) have implicated a relatively recent (mid-
71 2000's) weakening and path shift of the Gulf Stream as a contributing factor to SLR along the mid-
72 Atlantic (Ezer et al. 2013; Hansen et al. 2016). The temporal effect of this change in circulation pattern
73 is still unknown. The accelerated rates of SLR observed along the mid-Atlantic coast have raised
74 concerns over tidal marsh sustainability within the Chesapeake Bay region (Glick et al. 2008; Mitchell
75 et al. 2017). It is crucial to increase understanding and improve predictions of how changes in sea level
76 will impact coastal marshes across geographic scales to inform policy, localized protection, and
77 restoration aimed at sustaining these habitats in the near and long-term. It is well established that tidal
78 marshes can respond to SLR (e.g., Morris et al. 2002; Kirwan and Murphy 2007; Raposa et al. 2017;
79 Horton et al. 2018) through vertical accretion and horizontal migration (Figure 1). Inorganic sediment
80 sources to the marsh include bank erosion, sediments from upland runoff, and tidally delivered
81 sediments. In addition, marshes vertically accrete via accumulation of below and above ground plant
82 biomass.

83 Different geomorphic settings present different hydrodynamics, sediment supplies, and marsh
84 plant communities. For that reason, the response of marshes to changing sea level is expected to vary
85 by geomorphic settings (Cahoon and Guntenspergen 2010; Kolker et al. 2010; Jørgensen and Fath
86 2011a). It is important to understand how local conditions influence marshes, in particular how
87 temporal and spatial variations in sediment supply, deposition, and surface erosion affect the
88 sustainability of these habitats. Because these factors are quite variable in many coastal and estuarine
89 systems, the development of dynamic simulations of marsh evolution at fine spatial resolutions is
90 important for informed management of current and future marsh resources.

91 Due to the increased need to assess tidal marsh vulnerability in the light of changing
92 environments, different models have been developed to predict marsh spatial extent and future

93 distribution, as well as to assist resource managers and habitat restoration practitioners in their
94 decision-making process. Current models are constrained by the limitations of the two commonly used
95 modeling approaches: landscape-scale models and site-specific models. Landscape-scale models (e.g.
96 Sea Level Affecting Marshes Model, SLAMM (Clough et al. 2010)) often use fixed rates (e.g. erosion
97 rates) during the entire simulation. They simulate general trends over large areas, but typically at a
98 relatively coarse resolution. For that reason, these types of model are not suitable for site-specific
99 research and management uses because scaling down the results to local levels is not feasible, thereby
100 limiting their accuracy and usefulness to local applications. Conversely, site-specific models (e.g.
101 Marsh Evolution Model, MEM (Morris et al. 2002)) are more mechanistic. They are employed to
102 simulate responses for a specific site with a particular set of conditions and settings. Like the landscape
103 models, site-specific models have scaling limitations as well. Using results from an individual site to
104 make long-term projections at larger spatial extents is challenging due to the broad range of
105 geomorphic settings across landscapes (Titus et al. 2009). Moreover, shoreline structures that interfere
106 with the natural migration of wetlands as a response to sea-level rise are not considered in these
107 approaches.

108 In recent years, several studies that used landscape-scale models incorporated different
109 dynamic approaches to particularly evaluate marsh vertical accretion. For example, Clough et al.
110 (2016) used SLAMM to evaluate the potential effect of SLR on the marshes along the New York coast
111 using a 5m horizontal resolution. To improve model results, the authors combined SLAMM data with
112 a mechanistic approach to estimate marsh vertical accretion by applying MEM (at a site-specific level).
113 In addition, Alizad et al. (2016) developed and applied a spatially-explicit model called Hydro-MEM
114 in the Timucuan salt marsh, located along the lower St. Johns River (Florida). This integrated approach
115 combines spatial dynamics of salt marshes and predicts the impacts of possible future sea-level
116 conditions. Hydro-MEM is a zero-dimensional model coupled with the hydrodynamic model ADCIRC
117 (ADvanced CIRCulation Model) (Luettich and Westerink 2006) to create a dynamic 2-dimensional

marsh model. Even though the approach refines the simulation of some processes, the resolution in that study is very limited due to the inherent stability constraints in the circulation model (Zhang et al. 2019). Moreover, several numerical models have been proposed to determine salt marsh survival under different scenarios of SLR (e.g., Temmerman et al. 2003b; Van Proosdij et al. 2006; D'Alpaos et al. 2007a; Mariotti and Fagherazzi 2010; Kirwan et al. 2016). These models attempt to quantify the evolution of salt marshes under different physical and ecological drivers. In many of these models, the sediment transport dynamics of salt marsh evolution are highly simplified, and only represent a starting point for the system. Even though current marsh models are valuable tools to address particular questions, there is still a need to model marshes over a broad geographic extent, but with the spatially explicit resolution currently available only from site-specific marsh evolution studies.

We present a new approach to modeling marsh evolution. The Tidal Marsh Model (TMM) has been developed based on the SCHISM framework (Semi-implicit Cross-scale Hydroscience Integrated System Model; schism.wiki) (Zhang et al. 2016). SCHISM is a next-generation hydrodynamic modeling system developed for riverine, estuarine, coastal, and ocean applications. Some of the unique features the TMM includes are dynamic rates (most importantly, erosion rates and sediment deposition rates), cross-scale simulations, and incorporation of anthropogenic stressors, which allow it to overcome many limitations that current marsh models present. The initial version of TMM integrates the physical and human components needed to simulate and assess the evolution and persistence of tidal marshes under different SLR scenarios. The TMM effectively interpolates site-specific information across critical conditions, creating the capacity to assess marsh vulnerability under present and potential future conditions. The TMM was tested using a hindcast approach in two different estuarine marsh systems in Chesapeake Bay. Nevertheless, this model has the capability to be exportable (i.e., it can be applied to any marsh system), which considerably increases its applicability. Due to the variability in marsh plants, primary production, and decomposition rates, as well as the lack of widespread spatially explicit biological data, we initially assume biological processes to be constant

and focus on simulating the physical factors and processes that drive marsh evolution, leaving the assessment of the biological processes for our next stage of model development. We attempt to acquire a better spatially explicit understanding of the physical processes related to marsh sustainability based on available physical and anthropogenic data. This insight will allow us to effectively preserve and manage marsh resources and the ecological services that they provide.

2. Background Information

2.1. Marsh Vertical Accretion

Marshes can accrete vertically through mineral sedimentation and organic matter accumulation. Both sources of material are important in maintaining a proper marsh platform elevation for the marsh to persist. Long-term marsh stability requires that the soil surface elevation increases at a rate similar to the local rate of relative SLR (Reed 1995). Based on Morris et al. (2016), marshes possess a theoretical maximum vertical accretion rate of 5 mm yr⁻¹. This is the expected rate from the combined inputs of inorganics and organics at the highest sediment loading rates. The rate of vertical accretion of 5 mm yr⁻¹ is comparable to the current SLR rate for the southeastern part of the Chesapeake Bay (e.g. Sewell's Point, current SLR rate is 5.1 mm yr⁻¹, accelerating 0.16 mm yr⁻¹) (Boon and Mitchell 2015). Morris et al. (2016) showed that contributions from organic production are mainly driven by belowground biomass in tidal salt marshes and the labile organic matter does not add new volume since its production and decay rate are in equilibrium. Nevertheless, the refractory fraction of belowground production contributes to a change in soil volume and can be associated with the production of lignin. The study found that the upper limit for belowground dry weight production of 2500 g.m⁻² yr⁻¹, encompassing 10% lignin content, provides a theoretical steady-state vertical accretion of about 3 mm yr⁻¹. This is an average rate of organic matter contribution to the vertical

168 accretion process. Therefore, it is unlikely that marshes can indefinitely survive a higher rate of SLR in
169 the absence of a significant source of inorganic sediment. The supply, deposition, and erosion of
170 sediments vary significantly along estuaries, and appropriate representation of those variations is
171 critical to accurately determine marsh futures.

172

173 **2.2. Marsh Horizontal Migration**

174 Tidal marsh edge stability depends on the health and production of the marsh plants, as well as
175 the effect of wave energy and SLR. Wave energy is the dominant driver of tidal marsh erosion
176 (Fegherazzi et al. 2013). As sea level rises, the time of inundation occurring during the high end of the
177 tidal range increases as well (Ezer and Atkinson 2013). Therefore, this inundation controls the
178 landward extent of these habitats. An increase in inundation at the water's edge of the marsh may
179 erode the marsh edge or cause conversion to mud flats, which are less stable and more erodible than
180 vegetated marshes (Silinski 2015; Rahman 2015). Tidal marshes have the capacity to respond to SLR
181 conditions by moving horizontally to higher elevations, either to adjacent land or into adjacent areas of
182 open water, if they are filled with sediment. In order for marshes to migrate inland, they need to have
183 an adjacent open space in the gradual slope that allows transgression. Migration is truncated in many
184 cases by natural escarpments or steeply sloped shorelines, increased coastal development, or hardened
185 shoreline structures used to stabilize the shoreline and protect upland properties from erosion and SLR
186 (Titus et al. 2009; Gittman et al. 2015; Hill 2015; Enwright et al. 2016). Thus, the presence of
187 shoreline structures (e.g. riprap, bulkhead) is a key feature that needs to be included when modeling
188 the future spatial distribution of tidal marshes. Anthropogenic stressors that interfere with marsh
189 transgressions are crucial parameters that need to be well understood to accurately evaluate marsh
190 response to SLR (Kirwan and Megonigal 2013).

191 A different process of horizontal migration occurs in marshes behind barrier islands. These
192 systems respond to SLR by migrating toward the mainland when sand is overwashed from the barrier

193 island and rolls over onto the back barrier marsh. The overwash deposition allows marshes to increase
194 in elevation and migrate (Finkelstein and Ferland 1987; Fitzgerald et al. 2007; Walters et al. 2014).
195 However, at rapid and high rates of SLR, barrier island migration can outpace marsh migration toward
196 the mainland, yielding a significant marsh loss (Deaton et al. 2017). The interactions between back
197 barrier marshes and barrier islands play a significant role in determining how coastal systems will
198 evolve in the future due to SLR.

199

200 **2.3. SCHISM (Semi-implicit Cross-scale Hydrosience Integrated System Model)**

201 SCHISM (Zhang et al. 2016; schism.wiki) is a derivative product of SELFE v3.1dc (Zhang and
202 Baptista 2008). SCHISM belongs to a new generation of unstructured-grid models (Figure 2) with
203 unique features that help overcome the challenges of simulating multi-scale processes. It is a next-
204 generation hydrodynamic modeling system developed for riverine, estuarine, coastal, and ocean
205 applications. It has been extensively tested against standard ocean/coastal benchmarks, and applied to a
206 number of bays, estuaries, and coasts around the world (e.g. Stanev et al. 2017, 2018; Chao et al. 2017;
207 Yu et al. 2017; Liu et al. 2018; Ye et al. 2018; Guerin et al. 2018; Du et al. 2018) in the context of
208 general circulation, tsunami and storm-surge inundation, water quality, oil spill, sediment transport,
209 coastal ecology, wave-current interaction, and ice dynamics (e.g. Rodrigues 2009; Burla et al 2010;
210 NTHMP 2012; Pinto 2012; Roland 2012; Azevedo et al. 2014). It is built on a hybrid finite-
211 element/finite-volume approach using mixed triangular-quadrangular unstructured grids in the
212 horizontal, and a very flexible coordinate system in the vertical, called LSC² (Zhang et al. 2015, 2016).
213 The application of unstructured grids to coastal ocean processes presents a great advantage for
214 nearshore studies. The superior boundary fitting and local refinement ability of unstructured grids
215 make them ideally suitable for nearshore applications involving complex bathymetry, shoreline
216 geometry and upland slopes. The flexibility enabled by the design of horizontal and vertical grids

217 allows a single SCHISM grid to seamlessly morph between full 3D, 2DH, 2DV and 1D cells in
218 different parts of the domain (Zhang et al. 2016).

219 One of the most important strengths of this modeling system is that it is designed for an
220 effective simulation of 3D baroclinic circulation across creek-to-ocean scales (Yu et al. 2017),
221 addressing a wide range of physical and biological processes. These cross-scale interactions of
222 different processes in time and space are possible due to the use of unstructured grids and a semi-
223 implicit time stepping scheme in the simulations. SCHISM employs an efficient and robust semi-
224 implicit (i.e., no mode splitting) finite-element/finite-volume method together with an Eulerian-
225 Lagrangian method to solve the Navier-Stokes equations. As a result, numerical stability is greatly
226 enhanced. SCHISM can enable the use of hyper-resolution (~ few meters) with little penalty on the
227 time step, thereby greatly reducing the need to eliminate key physical-chemical-biological processes to
228 efficiently run high resolution model simulations. The finite-element method allows the use of very
229 skewed (typically considered poor quality) elements in the model grid, which will be critical in
230 resolving highly irregular marsh complexes. SCHISM incorporates wetting and drying in a natural way
231 to capture tidal creek swelling and bank overtopping, which is crucial for accurate inter-tidal
232 ecosystem model simulations.

233 Developing the TMM within this framework allows for unique model capabilities to be
234 naturally incorporated into the simulations. In this initial version of the model, we focused on a 2D
235 barotropic model configuration due to large uncertainties that exist in some marsh process inputs. For
236 processes as complex as marsh migration, it is important to start from a simple approach, investigate
237 the relative importance of contributing factors, and gradually build up model complexity. While the
238 polymorphism in SCHISM allows efficient simulation of marshes in hybrid 3D-2D mode (Liu et al.
239 2018), the current 2D model already incorporates most of the physics.

240

241

3. Methods

3.1. Study Area

The development of the TMM utilized two study sites within the York River system, Virginia, USA (Figure 3a): Carter Creek (Figure 3b), and Taskinas Creek (Figure 3c., a component of the Chesapeake Bay National Estuarine Research Reserve (CBNERR)). The York River is one of the five major tributary systems in the Chesapeake Bay. It is a partially-mixed, microtidal estuary (Sisson et al. 1997) characterized by a main channel flanked by wide shoals. The salinity regimes range from tidal freshwater to polyhaline. Poor water clarity, mainly driven by suspended sediments and phytoplankton, is a persistent problem in the York River (Reay 2009). Near-surface, mid-channel total suspended solids (TSS) concentrations increase with distance upriver, with long-term average TSS concentrations on the order of $<10 \text{ mg L}^{-1}$ in polyhaline regions, $\sim 15 \text{ mg L}^{-1}$ in mesohaline, and $\sim 35 \text{ mg L}^{-1}$ in oligohaline waters (Reay 2009). This tributary has a primary (ETM) and a secondary (STM) estuarine turbidity maximum located approximately 52 km and 30 km, respectively, from the mouth of the river (Lin and Kuo 2001); the location of the turbidity maximums may change seasonally. TSS concentrations within the ETM and STM are $30\text{-}35 \text{ mg L}^{-1}$ in the near surface waters, and $80 - 105 \text{ mg L}^{-1}$ in the near bottom waters (Reay 2009).

The York River system incorporates several geomorphic marsh settings, including fringe, embayed, and extensive marshes (Table 1), distributed along gradients of inundation and salinity. For the TMM development, marshes associated with different geomorphic settings and land uses were selected for simulations. Carter Creek is characterized by a considerable extent of fringe and embayed marshes, while Taskinas Creek is classified as an embayed marsh system. The dominant low marsh plant species for both Carter and Taskinas Creeks is *Spartina alterniflora*. In high marsh zones, *Spartina patens* and *Distichlis spicata* are present. Carter Creek is located on the northern side of the York River, approximately 22 km from the mouth of the river. Its watershed is characterized mainly by residential and agricultural land uses. Taskinas Creek is located on the southern side of the York River,

approximately 38 km from the mouth of the river. Its watershed is characterized by forested and agricultural land uses.

TABLE 1. Tidal marsh geomorphic settings (*Adapted from Barnard and Doumlele 1979*)

Form	Diagram	Description
Fringe marsh		A marsh which borders along a section of shoreline and generally has a much greater length than width.
Embayed marsh		V-shaped marshes that form along the edges and upper reaches of creeks
Extensive marsh		A large marsh where the length and depth or width are roughly comparable; most extensive marshes are drained by many tidal channels and creeks; attached to land on one edge

3.2 Tidal Marsh Model (TMM)

The TMM presents an advanced modeling framework that integrates the physical, and human components needed to simulate and assess the evolution and persistence of tidal marshes under different sea-level rise scenarios. The TMM is a finite-element model that uses a flexible unstructured grid in the simulations. Appendices A and B describe the physical and numerical formulations, respectively. The TMM is coupled to three major components in SCHISM: the hydrodynamic core that serves as the foundation of the SCHISM modeling system; the wind wave model (WWM-III); and the 3D sediment transport model (CSTMS) (Figure 2). Governing equations for WWM-III and CSTMS are displayed in Appendix C. Relative SLR is explicitly accounted for in all modules. The TMM was

283 tested through hindcasting in two case study regions. The SLR rate (4 mm yr^{-1}) for these areas during
284 the study period (the past 40 years) was obtained from the literature and NOAA Sea Level Trends
285 (NOAA Tides and Currents). This rate was imposed via the boundary condition at the model's ocean
286 boundary (the calculated elevation and velocity are shared by all components of the model). WWM-III
287 (Roland 2009; Roland et al. 2012) is a community-driven, parallel and advanced numerical framework
288 that can be applied to study wave-current interactions based on unstructured grids. CSTMS is an
289 adaptation from Warner et al. (2008).

290 Using a process-based morphodynamic model to conduct long-term simulations requires
291 intensive computational time. This is due to the fact that morphological changes take place over a
292 much longer time period than hydrodynamic changes. To reduce the computational burden, a
293 morphological acceleration factor (MAF) was used. The MAF is an approach introduced by Lesser et
294 al. (2004) and Roelvink (2006) for coastal morphodynamic modeling, and broadly explained in
295 Roelvink and Reniers (2011). In this approach, the speed of morphological changes is scaled up by a
296 rate that is appropriate given the underlying hydrodynamics. This is accomplished by multiplying the
297 bed level changes (sediment fluxes from and to the bed) by a constant factor (i.e., MAF) after each
298 hydrodynamic time step. This allows the simultaneous computation of sediment transport and
299 morphological change with the hydrodynamics (Moerman, 2011; Styles et al. 2016). For instance, a
300 simulation of 1 year and a MAF of 40 would produce 40 years of sediment transport and
301 morphological change with the computational time associated with only 1 year of simulation time.
302 This factor is applied after all hydrodynamic and sediment transport processes have been computed for
303 each time step. This procedure is repeated at each time step. A basic assumption is that most of the
304 sedimentary processes are periodic in nature (but not necessarily linear, as the feedback between
305 hydrodynamics and morphology can be nonlinear as well). Episodic and extreme events (e.g., storms,
306 hurricanes) can be accounted for by 'turning off' the morphological acceleration during such periods.
307 In this study, for the hindcast, the sediment transport model was run with morphological acceleration

308 (i.e., simulation = 1 year and MAF = 40). The model was calibrated primarily by adjusting the
309 erodability constant and the time step (with a final chosen value of 75 seconds). Ancillary outputs from
310 the hydrodynamic, sediment, and wind wave modules include surface and bottom elevations, bed
311 fraction, and wave height, among others.

312 The TMM simulates marsh migration under the joint influence of tides, wind waves, sediment
313 transport (including loading from upland erosion), shoreline structures, land use, and precipitation.
314 TMM utilizes inundation frequency based on the water-surface level predicted by the modeling system
315 to drive inundation and horizontal marsh migration. This new approach accounts for shoreline changes,
316 marsh accretion through mineral sediment deposition, upland erosion inputs at the marsh edge (derived
317 from the Revised Universal Soil Loss Equation - RUSLE) (Renard et al. 1991), and marsh upland
318 transgression under a changing sea level with constraints from physical barriers (e.g., shoreline erosion
319 control structures). Shoreline hardening structures that protect upland property from erosion (e.g.,
320 seawalls, revetments, and bulkheads) act not only as barriers for marshes to migrate inland, but also
321 represent barriers for sediment exchange between the marsh habitat and the upland. In the model, these
322 structures are treated as impenetrable barriers for sediment transport (but can be topped by water). We
323 have not currently incorporated other more specific processes related to marsh stability; for example,
324 sophisticated wave erosion formulations near the marsh edge (e.g., Beudin et al. 2017); these are left
325 for future studies.

326 Unlike other marsh models (e.g., Clough et al. 2010; Odink 2019), the TMM is generated using
327 an unstructured grid, which allows highly resolved marsh areas (1-meter cross-shore and 5-10 meters
328 along-shore for fringe marshes) that are needed to accurately capture the migration process over a long
329 time period. At the moment, marsh elements (i.e., grid cells denoted as marsh) are represented by an
330 increased bottom roughness factor (Ye et al. 2013). Marsh areas were assigned with a roughness factor
331 of 50 mm, while non-marsh areas were designated with a value of 1 mm. Nevertheless, the vegetation

332 effects (form drag and turbulence) (Zhang et al. 2019) can be incorporated into the model once more
333 detailed information on vegetation parameters is obtained; this is left for future work.

334 The TMM code stipulates that marshes migrate into an area if the sediment bed elevations fall
335 within the ‘suitable’ elevation range relative to mean-sea level (MSL). In this region, marshes occur
336 from MSL to 1 m above MSL. Note that MSL is changing over time due to SLR; therefore, marshes
337 will drown in a region if the sediment bed elevation falls below MSL. The sediment bed elevation is
338 dynamically calculated at each time step by the CSTMS, which simulates sediment erosion, deposition
339 and transport. In the code, marsh presence/absence is marked within each unstructured-grid cell.
340 Additional constraints are imposed for migration: a cell can become ‘marsh’ at the new time step only
341 if at least one of its adjacent cells was marsh at the previous time step; and anthropogenic structures
342 serve as barriers to migration (i.e., these cells can never become marsh and prevent adjacent upland
343 cells from becoming marsh). To that end, a spatially explicit and highly resolved inventory of shoreline
344 conditions (i.e., riparian land use, shoreline structures, and bank height) are used as data inputs in the
345 model. As mentioned before, shoreline erosion control structures placed on the landward edge of the
346 marsh will not only represent an impediment for marsh transgression, but also will act as barriers for
347 sediment exchange between the marsh and adjacent upland.

348 The main TMM outputs are files depicting marsh distribution at specified output time intervals.
349 Files are then exported to a GIS environment for further spatial analysis and visualization (e.g.,
350 interactive map viewers).

351

352 **3.3. Data Collection and Processing**

353 A suite of major input datasets was used by the TMM and supporting models (Table 2).
354 Historic (Moore and Silberhorn 1976; Moore and Silberhorn 1980) and current (CCRM 2016) tidal
355 marsh inventories were employed for model input and calibration purposes. Tidal marshes were
356 initially mapped and catalogued for the York River watershed over a period of time starting in 1973

357 through 1980, depending on location and locality. The process generated 1:24,000 scale maps
358 delineating tidal marshes. The current Tidal Marsh Inventory for the York River is based on a survey
359 conducted in 2010. Marshes were digitized (1:1000 scale) using high resolution, geo-referenced natural
360 color imagery collected in 2009 by the Virginia Base Mapping Program. Marsh boundaries were field
361 checked. In addition, data from drone flights (DJI Mavic Pro Drone) were collected and analyzed for
362 this study. The photos taken of the study area were 12-megapixel resolution and the videos were 4K
363 resolution.

364 Two types of sediment core samples were manually collected at both study sites, tidal creek
365 bottom sediments and marsh surface sediments. Tidal creek bottom cores were gathered to provide
366 model input information on roughness and shear strength, whereas marsh surface cores were used for
367 model verification purposes. Surficial (upper 10 cm) tidal creek cores were collected along 8 transects
368 in the primary tidal creeks. At each transect, 3 sediment cores were taken, one in the middle of the
369 creek bed and the other ones at each creek bank, for a total of 24 samples. Surficial (upper 8 cm) marsh
370 surface sediment cores were collected along 20 transects at each study site (Figure 4); each transect
371 consisted of 3 stations, incorporating the marsh-water interface, middle marsh, and marsh-upland
372 interface, for a total of 60 cores.

373 Sediment texture was classified using the Wentworth scale into gravel: 2-4 mm, sand: 0.062-2
374 mm, and mud (i.e., silt and clay): < 0.062 mm. Taskinas Creek bottom samples were predominantly
375 mud, with less than 3-6% of organic content and insignificant amounts of carbonates. These core
376 samples were sieved for grain size analysis (Folk 1980, Poppe et al 2003, Haywick 2004). Taskinas
377 Creek marsh samples and Carter Creek bottom and marsh samples were processed using sieve analysis
378 (Folk 1980, Poppe et al. 2003). Prior to sieving, removal of organics was performed using loss on
379 ignition, and carbonates were removed by HCl acidification of the dried samples (Dean 1974; Heiri et
380 al. 2001; Santisteban et al. 2004).

381 Additional field work activities were conducted to improve specific data inputs for the study
382 areas. Shallow water bathymetry data were collected using a Humminbird 1197 side imaging sonar
383 unit, an HDS 10 first generation with an HST_DFSBL Deep water transducer, and a vertically
384 controlled, atmospheric pressure corrected YSI 6600 V2 sonde to correct for water level changes
385 during bathymetric survey periods. Bathymetric data were interpolated with LIDAR data (USGS,
386 2011) to create a seamless topobathy surface (i.e., Digital Elevation Model, DEM) in each of the study
387 areas, using ESRI ArcGIS® v10.4.1. Outside the study areas (i.e., York River and Chesapeake Bay),
388 elevation data were extracted from the USGS Topobathymetric Digital Elevation Model for the
389 Chesapeake Bay (Danielson et al. 2016).

390 To perform the hindcast, the DEM was modified to reflect initial elevation conditions for the
391 marshes. Due to limited historic data to recreate the initial marsh elevations, certain topographic
392 adjustments were incorporated into the DEM. Different topographic correction methodologies have
393 been used in similar studies to estimate the elevations of the marsh platform (e.g., Clough et al. 2010;
394 Geselbracht et al. 2011; Glick et al. 2013; Mogensen and Rogers 2018; Alizad et al. 2018). For
395 example, one technique adjusted the DEM by applying the same elevations of other marsh systems that
396 have analogous marsh productivity and density of similar species. Another approach is a retrospective
397 analysis that forces the present DEM to represent a prior time period through the modification of
398 elevations based on the historic rate of SLR. These approaches, as well as any other alteration, create
399 uncertainties associated with the corrected DEM.

400 Based on the data available for the study areas, we decided to perform topographic adjustments
401 using the historic tidal marsh layers (Moore and Silberhorn 1976; Moore and Silberhorn 1980) to
402 spatially identify suitable elevations for marsh establishment. These historic datasets, generated by
403 ground surveys, provided the most accurate available information of marsh presence for the initial
404 conditions. The historic marsh polygon layers represent the areal extent of elevations within the
405 'suitable' range for marsh establishment (i.e., from MSL to 1 m above MSL). Geoprocessing tools in

406 ArcGIS were used to recode those marsh areas associated with elevations outside the suitable range.

407 Only some areas of the historic marsh polygons were associated with elevations below MSL. These

408 areas of the DEM were adjusted to 0.5 m (above MSL), the midpoint of the suitable elevation range for

409 marshes. The midpoint method was employed to minimize the error between the two extremes of the

410 elevation range for marsh presence. As with any other topographic adjustment, it is recognized that this

411 approach adds uncertainty to the methodology. Nevertheless, the midpoint method provided a more

412 realistic initial condition using the available data. This adjustment assured that the spatial extent of all

413 historic marshes had elevations within the suitable tidal range to start the hindcast. Other elevations

414 within the domain were not modified to avoid introducing extra uncertainty in the simulations.

415

416 TABLE 2. Primary input datasets used for TMM and supporting models

Dataset	Source
Historic Tidal Marshes (1:24,000)	Tidal Marsh Inventories – CCRM, VIMS
Current Tidal Marshes (Scale: 1:1,000)	
Shoreline Structures	Shoreline Inventory Program – CCRM, VIMS
Riparian Land use (distance: 100 ft.)	Shoreline Inventory Program – CCRM, VIMS
LIDAR data	United States Geological Survey (USGS)
Bathymetry	NOAA and CBNERR, VIMS
Bottom Type (grain sizes)	VIMS, Maryland Geological Survey (MGS), and field samples
River Input (average daily values)	United States Geological Survey (USGS)
Total Suspended Solids	Chesapeake Bay Program
Atmospheric Forcing	North American Regional Reanalysis (NARR)
Tides	US East Coast Tidal Database

417

3.4. Grid Generation

The grids used in this study were generated using the Surface-water Modeling System (SMS) developed by Aquaveo, LLC (aquaveo.com). SMS is a graphical interface used to create, visualize, manipulate, and analyze numerical data representing surface water. Spatial data are exported to feature objects in SMS to define all relevant features within the domain (i.e., adjacent riparian upland, marshes, shoreline structures, channels, as well as other important physical features affecting water circulation). Marsh areas are highly resolved (i.e., fringe marshes are 1-m cross-shore and 5-10 m along-shore; embayed marshes have the same resolution as fringe marshes in the outer 10 m, and 10-20 m resolution in the interior of the marsh). A finer grid resolution was applied in uplands adjacent to marshes to accurately capture marsh transgression from SLR; beyond these areas, a transition to coarser resolution was used to account for rare inundation. Figures 5 and 6 show the grid generated for Carter Creek and Taskinas Creek respectively. These figures show the high resolution that is used within marsh systems as well as the adjacent upland areas to assess marsh transgression. Extremely rapid transitions in grid resolution are used to save computational cost (the grid size would be more than 10 times larger if smooth transitions were used). The superior stability of the modeling system allows very skewed elements (i.e., grid cells) to be used, with skewness being defined as the ratio of the largest side of a triangle and its equivalent diameter (diameter of a circle having the same area as the triangle). For reference, an equilateral triangle has a skewness of 1.35. The TMM supports very skew elements (skewness exceeding 20), which are common around high resolution areas. This approach combines both high resolution and efficiency in the modeling process and offers an important advantage when compared with other model approaches.

After the grid was generated, grid nodes were populated with elevation data using a DEM without any further smoothing as is commonly done by other models (Ye et al. 2018). A seamless topo-bathy layer derived from USGS was used for the section of the York River and the Chesapeake Bay. The USGS dataset is an interpolation from LIDAR data and NOAA bathymetry data, with

443 uniform 1m resolution for the Chesapeake Bay. Inside Carter Creek and Taskinas Creek, bathymetry
444 data were updated with field measurements to achieve more accurate shallow water depths. In this case,
445 new interpolations were conducted using the LIDAR data and the updated bathymetry to generate a
446 seamless topo-bathy surface. TMM is an elevation driven model, so accurate elevations are critical for the
447 reliability of the model outputs.

448

449 **4. Results and Evaluation of Model Performance**

450 The main purpose of this evaluation was to demonstrate that model formulation and
451 performance were sufficiently accurate for the purpose of the study. It is recognized that there are
452 degrees of uncertainty associated with both modeling and field observation methodologies.

453 A critical step in this process was to verify that assumptions and principles were accurately
454 represented in the mathematical equations and computer code. Different components of the modeling
455 system have been rigorously benchmarked by many groups (Roland 2012; Pinto 2012; Zhang et al.
456 2019), and the base code is also regularly subjected to regression tests via Apache Subversion (SVN)
457 as part of our software engineering process. SVN is a software versioning and control tool.

458 We assessed model outputs against field observations focusing on two main aspects: (1) marsh
459 boundary evolution and (2) distribution of marsh sediments. The evaluation of these two features
460 allowed us to determine the degree of agreement between model prediction and observations. Various
461 statistics and metrics were calculated to describe model performance; descriptions are provided below.

462

463 **4.1. Marsh Boundary Evolution**

464 Outputs from the TMM were exported to the GIS environment using Matlab and Fortran
465 scripts. Spatial analyses were conducted using ESRI ArcGIS® v10.4.1.

466 Historic and field data were used for calibration and verification purposes. Model performance
467 was evaluated by conducting a hindcast using the historic VIMS Tidal Marsh Inventory as the initial

marsh conditions for the model simulations. The modified DEM based on the historic tidal marsh layers (Moore and Silberhorn 1976; Moore and Silberhorn 1980) was used for the initial elevation conditions. The TMM was run to the present time (simulation: past 40 years), and the model outputs were then compared with the current Tidal Marsh Inventory developed by CCRM, VIMS. Figures 7 and 8 display the spatial marsh distribution pattern generated by the model. These outputs are products not only of the model formulations, but also reflect the accuracy of the model inputs (i.e., initial conditions). For example, in the case of Taskinas Creek, the marsh loss observed in the upper tributary corresponds to an initial condition (i.e., historic tidal marsh inventory), indicating marsh presence in that particular area. Over the 40-year simulation, that section of the marsh was fragmented, creating a channel; the model outputs correspond with the current observations of marsh extent in that zone.

Model outputs of marsh boundaries reflect the results of the physical processes expected in these systems. For example, outside the mouth of Taskinas Creek on the main stem of the York River, we observe substantial marsh loss at the leading edge, most likely due to the high fetch and wave energy. In addition, within the inner creek, the model captures sediment deposition on the inner bank of the meander (convex side), and erosion on the outer bank of the creek (concave side), which is typical of meandering creek dynamics. This pattern is also observed in the upper region of Carter Creek, where the creek adopts a sinusoidal form. Since marshes in Carter Creek are associated with different land uses, we observe different patterns in marsh transgression. Marsh boundary outputs show how the model captures marsh transgression in open areas (this pattern is seen in Taskinas Creek as well), and how this inland marsh migration is truncated by the presence of structures or development, such as in the case of roads located at the marsh-upland edge.

Error matrices were created to statistically quantify the degree to which the model reproduced the observed data. These allowed the assessment of the overall accuracy of the model and to calculate the Kappa statistic, a measure of agreement between the model output and the reference data (i.e., the current Tidal Marsh Inventory). Kappa is a robust statistic and is the most commonly reported measure

493 in assessing model agreement using categorical variables with multiple levels (McHugh 2012; Tang et
494 al. 2015).

495 In each study area, an error matrix was developed by using 100 random sample points (Figure
496 9), which were employed to determine if the current marsh conditions at those locations agree with the
497 conditions predicted by the model. Tables 3 and 4 display the results of the matrices. Table 5 shows a
498 commonly cited scale to interpret the value of the Kappa statistic (Landis and Koch 1977; Viera et al.
499 2005). In Carter Creek, the model performed with an overall accuracy of 81% and with a Kappa
500 statistic of 0.630, which can be translated as a “Substantial Agreement” (Viera et al. 2005). In Taskinas
501 Creek, the model is performing with an overall accuracy of 78% and with a Kappa statistic of 0.613,
502 which can be translated as a “Substantial Agreement” as well.

503
504 TABLE 3. Error Matrix for Carter Creek based on 100 random sample points. Each point was used to
505 evaluate if the current marsh conditions at that location agree with the conditions predicted by the
506 model. Gray diagonal represents the counts where model outputs and current conditions agree.
507

CARTER CREEK	Current Tidal Marsh Inventory					
		No Change	Marsh Gain	Marsh Loss	TOTAL	Commission Error
Tidal Marsh Model (TMM)	No Change	45	2	7	54	0.17
	Marsh Gain	2	8	0	10	0.20
	Marsh Loss	8	0	28	36	0.22
	TOTAL	55	10	35	100	
	Omission Error	0.18	0.20	0.20		0.19

508
509 Commission and omission errors defined as:

510
511
$$CE = 1 - \frac{TMM_{sample\ point\ count}}{Total_{sample\ point\ count}}$$

512
513
$$OE = 1 - \frac{TMI_{sample\ point\ count}}{Total_{sample\ point\ count}}$$

514

515 TABLE 4. Error Matrix for Taskinas Creek based on 100 random sample points. Each point was used to
516 evaluate if the current marsh conditions at that location agree with the conditions predicted by the
517 model. Gray diagonal represents the counts where model outputs and current conditions agree
518

TASKINAS CREEK	Current Tidal Marsh Inventory					
Tidal Marsh Model (TMM)		No Change	Marsh Gain	Marsh Loss	TOTAL	Commission Error
	No Change	48	5	6	59	0.19
	Marsh Gain	3	16	0	19	0.16
	Marsh Loss	8	0	14	22	0.36
	TOTAL	59	21	20	100	
	Omission Error	0.19	0.24	0.30		0.22

519
520 TABLE 5. Interpretation of the model performance measures

Levels of Agreement						
	Less than chance agreement	Slight agreement	Fair agreement	Moderate agreement	Substantial agreement	Almost perfect agreement
Kappa Statistic ^a	<0	0.01-0.20	0.21-0.40	0.41-0.60	0.61-0.80	0.81-0.99
Levels of Agreement						
	Unsatisfactory	Satisfactory	Good		Very Good	
NSE ^b	< 0.50	0.50 < NSE < 0.65	0.65 < NSE < 0.75		0.75 < NSE < 1.0	
RSR ^c	> 0.70	0.60 < RSR < 0.70	0.50 < RSR < 0.60		0.00 < RSR < 0.50	
Levels of Agreement						
	Possible values		Optimal value		Preferred values	
MAE ^d	0 to ∞		0		Low values	
Willmott index of agreement ^e	0 to 1		1		0.5 to 1.0 ^f	
					> 0.8 ^g	

521
522 Based on: ^aViera et al. 2005; ^bMoriassi et al. 2007; ^cSingh et al. 2004; ^dBennett et al. 2013, ^eWillmott et
523 al. 2012; ^fMachiwal and Jha, 2015; ^gDe Jager, 1994.

4.2. Spatial Distribution of Sediments – Grain size

Regarding the spatial distribution of sediment texture across the marshes, surface sediments in Carter Creek are characterized mainly by coarse sediments (e.g., sand) distributed throughout the creekbank, in the middle of the marsh, and by the marsh-upland interface. This may be a reflection of Carter Creek being located in a higher energy setting (as compared to Taskinas Creek, which is a more protected embayed marsh). Carter Creek has fringing ‘type’ marshes that allow for greater interaction between the entire marsh system with storm and upland deposition events. In Taskinas Creek, coarser textured sediments tend to be located at the marsh-water edge, with fine sediment (i.e., mud) characteristics of marsh interior sites. Exceptions occur at some upland edges that receive upland erosion deposits.

Different statistical descriptors were used to evaluate the model’s ability to reproduce the distribution of observed marsh sediment fractions (i.e., sediment texture). For this study, model outputs and field observations were compared using the most commonly employed model assessment or model efficiency statistics (e.g. Legates and McCabe Jr., 1999; Bennet et al. 2013; Moriasi et al. 2007; Willmott et al. 2015; Meskini-Vishkaee and Davatgar, 2018): the mean absolute error of measured values (MAE); Willmott (1982) index of agreement (dr); the coefficient of determination (NSE), and the RMSE-standard deviation ratio (RSR). Appendix D displays the equations for these statistical performance measures. Table 5 shows the range of values of these statistics and the interpretation of the model performance. Values obtained for both study areas are presented in Table 6.

Results for Carter Creek show a strong agreement between model outputs and observations (Table 6). All statistics support the model predictions of the surface sediment distribution along the marshes. These results suggest that the TMM captures very well the physical processes related to marsh evolution, which are critical to maintain marsh stability and sustainability. Model outputs regarding sediment fractions for Taskinas Creek present a good model performance when compared with observations based on the Willmott Modified Index of Agreement and the MAE. The NSE and

RSR statistics fall within the satisfactory agreement category (based on Moriasi et al. 2007; Singh et al. 2004). These two statistics display a lower agreement between the model prediction and observations when compared with the results of Carter Creek area. This difference can be attributed to disagreement between model outputs and field observations in three marsh sections sampled in Taskinas Creek. Field samples were verified and sites were examined again through field visits and drone flights. The Taskinas Creek system has areas with localized anomalies (e.g. Figures 10 a, b, and c), such as terrain depressions, very narrow marsh channels, high slope upland-marsh banks, and upland-marsh interface vegetation with different tree canopies, which affects plant marsh growth and soil conditions. In some cases, these differences could also be attributed to temporal variations in TSS loadings not captured by the model.

TABLE 6. Marsh sediment fraction distribution: comparison between model outputs and field observations (from grain size analysis)

		Mean Absolute Error (MAE)	Observations Standard Deviation Ratio (RSR)	Nash_Sutcliffe Efficiency (NSE)	Willmott Modified Index of Agreement (dr)
Carter Creek	Sand	0.08	0.43	0.81	0.86
	Mud	0.08	0.43	0.81	0.86
Taskinas Creek	Sand	0.10	0.61	0.62	0.83
	Mud	0.10	0.61	0.62	0.83

5. Discussion and Implications

We have developed a new approach to simulate marsh evolution. This innovative model, tested for accuracy via hindcasting, will advance the state of the science by building a better foundation to model marsh extent and distribution. Major features included in the TMM are cross-scale simulations through the use of unstructured grids; semi-implicit time stepping; dynamic rates incorporated in the simulations (i.e., rates vary in space and time as determined by changes in the hydrodynamic conditions of the system); and highly resolved marsh transgression. The TMM has been successfully applied in two marsh creek systems in the York River estuary (USA). The sites present different physical settings (i.e., wave regime, sediment supply, topography), and distinctive anthropogenic stressors (i.e., riparian land use, shoreline hardened structures). In addition, both creeks are dominated by different marsh geomorphic settings (i.e., embayed, and fringe marshes). The TMM has been developed to be exportable to other geomorphic systems, including estuaries, back-barrier islands, fluvially-dominated deltas, and lagoons. Application of this model to other regions will be limited mainly by the available input data for the target areas.

The initial version of this dynamic high-resolution model incorporates key physical processes that directly influence marsh persistence, such as erosion, inundation, sediment transport, and surface elevation change, all of which directly affect marsh vertical accretion and horizontal migration. Based on accelerated projections of SLR, it is expected that marshes will rely considerably on inorganic sediment supplies to offset changes in water level. Once primary production and organic deposition of marsh plants reach maximum rates, the fate of marshes will depend on their capacity to capture and retain inorganic sediment, as well as the ability to migrate inland if there are adjacent open spaces that allow transgression. For that reason, understanding and successfully simulating physical factors and processes are critical initial steps to forecast the fate of tidal marshes.

592 The model results are largely consistent with field observations. The model produced a good
593 representation of the horizontal sediment distribution along marshes in Carter Creek. For Taskinas
594 Creek, the horizontal distribution of sediments was satisfactorily captured by the model. Major
595 differences between model outputs and field observations in Taskinas Creek can be attributed to the
596 heterogeneity of the system at sub-grid scales. Ultimately, there is a trade-off between increasing
597 resolution and complexity, and exportability of the model. Efforts to maximize details as well as to
598 increase the degree of freedom generally lead to excessive parameterization, larger model uncertainty,
599 and error propagation (Anderson 2005; Hood et al. 2006). For that reason, it is imperative to clearly
600 define the purpose of the model and the type of research and management questions that model
601 simulations are to address. In addition, it is fundamental to have the necessary data to support
602 parameterization. In the case of a heterogeneous system (i.e., with multiple geomorphic settings), end
603 users need to evaluate the overall purpose and application of the model, as well as the amount of error
604 that they are willing to accept.

605 We have demonstrated that the TMM is able to successfully simulate the physical processes
606 related to marsh persistence and evolution. Simulations of marsh boundary evolution (i.e., marsh
607 landward migration and marsh erosion) produced a substantial agreement with the current marsh
608 conditions in both study areas. Marsh migration into open areas was well captured, as well as the
609 negative effect of hardened shoreline structures and development on the natural capacity of marshes to
610 migrate inland as sea-level rises.

611 The unique high-resolution simulations attained by the TMM allow us to model the fate of
612 narrow fringing marshes. These types of marshes provide many ecosystem services that extensive
613 marshes offer (Bilkovic et al. 2016). Different studies show that more than 60 % of the wave
614 attenuation by marshes occurs within the first meters of the marsh (Knutson et al. 1982; Morgan et al.
615 2009; Shepard et al. 2011), indicating the importance of fringe marshes in dampening wave energy,
616 hence, reducing upland erosion. In addition, it has been established that a high percentage of the

617 sediment and nutrient removal by marshes occurs along the marsh edge and upland border (Tobias et
618 al. 2001; Neubauer *et al.* 2002; Burke *et al.* 2005). These findings suggest that narrow fringe marshes
619 also play a critical role in water quality. For that reason, it is essential to capture these narrow habitats
620 when modeling marsh evolution in order to more accurately assess overall marsh stability and
621 sustainability of the system.

622 The model's capacity to predict future marsh extent and distribution based on the simulation of
623 physical processes and anthropogenic factors has diverse implications for coastal managers. Under
624 higher sea-level-rise scenarios, many marshes will likely cross thresholds and experience significant
625 and irreversible changes, such as marsh fragmentation and total disintegration due to erosion or
626 drowning. It is imperative to develop monitoring strategies and simulation models to determine if an
627 ecosystem is approaching a threshold. This can increase knowledge of the system dynamics. The
628 highly resolved TMM outputs will allow coastal planners and managers to more precisely identify,
629 prioritize, and develop protection and restoration activities and strategies to preserve these essential
630 ecosystems, and to test potential impacts of human modification to coastal systems.

631 At this initial phase, we have achieved a satisfactory simulation of changes in marsh position
632 over a 40-year period of observation based on physical processes and factors. At this stage of model
633 development, biological processes have not been incorporated in the simulations, which may limit the
634 model's applicability to other areas where the vertical accretion of marshes is currently dominated by
635 organic matter production and/or deposition. A biological model is currently being developed to
636 contribute to the physical model. Nevertheless, this unique approach of simulating marsh evolution
637 based only on physical processes and factors will provide coastal managers with a more accurate tool
638 to initially determine the fate of tidal marshes over large areas, especially in those cases where
639 biological parameters are extremely variable and detailed data are too limited to properly simulate the
640 biological response of marshes as sea level rises.

Beyond the lack of a biological component, TMM can be improved on multiple fronts to address many rather complex processes. The coupling of TMM to SCHISM requires predictive values from different tools, and yet the corresponding governing evolution equations used by these tools and those described in Appendix C may be too simplistic to capture the real-world physics. For example, as mentioned above, more sophisticated formulations for wave erosion at marsh edges may improve the localized processes for marsh stability there. A 3D model that includes salinity and temperature together with a new biological module can further improve the model's predictive capability for the fate of certain marsh species under climate change. Although some sensitivity to mesh resolution has been carried out, more analysis on this in the larger context of other uncertainties should be explored further. Lastly, more site-specific input information is being collected that may be able to further validate and improve the model.

6. Conclusions

A multi-scale model to simulate marsh evolution has been presented. This novel model, developed as a module within the SCHISM framework, has been shown to be suitable to efficiently interpolate site-specific information across critical conditions creating the capacity to assess marsh vulnerability under present and potential future condition. The TMM will advance the state of the science by building a better foundation to simulate marsh extent and distribution, allowing coastal planners to more accurately manage these valuable habitats and their ecological services.

List of Figures:

Fig. 1 Diagram of vertical and horizontal marsh responses to sea-level rise

Symbols courtesy of the Integration and Application Network (ian.umces.edu/symbols/), University of Maryland Center for Environmental Science

Fig. 2 SCHISM modeling system. The dashed box indicates the TMM and key supporting components. The hydrostatic core serves as the pillar of the system to provide hydrodynamic variables to other models as well as to facilitate exchange of variables between models in a parallel software environment

Fig. 3 a) York River system; b) Carter Creek and c) Taskinas Creek: study areas in the York River. Bright green areas represent tidal marshes. Background Image: VBMP2017/VBMP2017_WGS - Virginia Geographic Information Network (VGIN)

Fig. 4 Locations of marsh near surface (upper eight cm) sediment cores sampled in a) Carter Creek (33 cores) and b) Taskinas Creek (27 cores). Background Image: VBMP2017/VBMP2017_WGS - Virginia Geographic Information Network (VGIN)

Fig. 5 a) Unstructured TMM grid used for Carter Creek marshes; b) The marsh layer (in green) is displayed on top of the grid (in yellow). Upland adjacent to the marsh is highly resolved to more accurately capture marsh transgression. Background Image: VBMP2017/VBMP2017_WGS - Virginia Geographic Information Network (VGIN)

Fig. 6 a) Unstructured TMM grid used for Taskinas Creek marshes; b) The marsh layer (in green) is displayed on top of the grid (in yellow). Upland adjacent to the marsh is highly resolved to more accurately capture marsh transgression. Background Image: VBMP2017/VBMP2017_WGS - Virginia Geographic Information Network (VGIN)

Fig. 7 Marsh boundary evolution output for Carter Creek – Hindcast outputs: changes in marsh boundary after 40 years of simulation with a sea-level rise of 4 mm/yr. Background image: VBMP2017/VBMP2017_WGS - Virginia Geographic Information Network (VGIN)

Fig. 8 Marsh boundary evolution output for Taskinas Creek – Hindcast outputs: changes in marsh boundary after 40 years of simulation with a sea-level rise of 4 mm/yr. Background image: VBMP2017/VBMP2017_WGS - Virginia Geographic Information Network (VGIN)

Fig. 9 Points used to generate the error matrices in a) Carter Creek (100 points) and Taskinas Creek (100 points). Points were generated using ArcGIS point generator. Background image: VBMP2017/VBMP2017_Infrared_WGS - Virginia Geographic Information Network (VGIN)

Fig. 10 Aerial drone photos of Taskinas Creek – a) it displays different soil conditions around marsh channels; b) localized depressions can be seen close to the upland edge (red box); c) it shows marsh areas affected by the presence of tree canopies

Fig. 11 Basic 3D computational unit (triangular element) in SCHISM. The elevation (η) is defined at node (vertex) of a triangular element, horizontal velocity (u, v) at side center and whole levels, vertical velocity (w) at element centroid and whole level, and tracers (C) at the prism center

713 References

- 714 Alizad K., Hagen SC, Morris JT, Bacopoulos P, Bilskie MV, Weishampel JF, Medeiros SC (2016) A
715 coupled, two-dimensional hydrodynamic-marsh model with biological feedback. *Ecol. Modell* 327:29–
716 43. <https://doi.org/10.1016/j.ecolmodel.2016.01.013>
717
- 718 Anderson T (2005) Plankton functional type modeling: Running before we can walk? *Journal of*
719 *Plankton Research* 27(11):1073–1081. <https://doi.org/10.1093/plankt/fbm024>
720
- 721 Azevedo A, Oliveira A, Fortunato AB, Zhang Y, Baptista AM (2014) A cross-scale numerical
722 modeling system for management support of oil spill accidents. *Marine Pollution Bulletin* 80:132-147.
723
- 724 Barnard T, Doumlele DG, Silberhorn GM (1979) City of Virginia Beach Marsh Inventory: Volume 2
725 Lynnhaven River, Lake Rudee and Their Tributaries. Virginia Institute of Marine Science. SRAMSOE
726 217. <https://doi.org/10.21220/V5MH85>
727
- 728 Bennett N, Croke BFW, Guariso G, Guillaume JHA, Hamilton SH, Jakeman AJ, Marsili-Libelli S,
729 Newham LTH, Norton JP, Perrin C, Pierce SA, Robson B, Seppelt R, Voinov AA, Fath BD,
730 Andreassian V (2013) Characterising performance of environmental models. *Environmental Modelling*
731 *& Software* 40:1–20. <https://doi.org/10.1016/j.envsoft.2012.09.011>
732
- 733 Beudin A, Kalra TS, Ganju NK, Warner JC (2017) Development of a coupled wave-flow-vegetation
734 interaction model. *Computers & Geosciences* 100:76–86. <https://doi.org/10.1016/j.cageo.2016.12.010>
735
- 736 Bilkovic DM, Mitchell M, Mason P, Duhning K (2016) The role of living shorelines as estuarine
737 habitat conservation strategies. *Coastal Management Journal* 44:161-174.
738 <http://dx.doi.org/10.1080/08920753.2016.1160201>
739
- 740 Boon JD, Mitchell M (2015) Nonlinear Change in Sea Level Observed at North American Tide
741 Stations. *Journal of Coastal Research* 31(6):1295–1305. [https://doi.org/10.2112/JCOASTRES-D-15-](https://doi.org/10.2112/JCOASTRES-D-15-00041.1)
742 00041.1
743
- 744 Burke D, Koch EW, Stevenson JC (2005) Assessment of Hybrid Type Shore Erosion Control Projects
745 in Maryland’s Chesapeake Bay—Phases I & II. Final Report for Chesapeake Bay Trust. Annapolis,
746 MD.
747
- 748 Burla M, Baptista AM, Zhang Y, Frolov S. (2010) Seasonal and interannual variability of the
749 Columbia River plume: A perspective enabled by multiyear simulation databases. *Journal of*
750 *Geophysical Research*, 115, C00B16.
751
- 752 Cahoon DR, Guntenspergen GR (2010) Climate change, sea-level rise, and coastal wetlands. *National*
753 *Wetlands Newsletter* 32:8-12.
754
- 755 CCRM (Center for Coastal Resources Management) (2016) Shoreline & Tidal Marsh Inventory.
756 College of William and Mary. Virginia Institute of Marine Science, Gloucester Point, Virginia.
757 <http://www.vims.edu/ccrm/research/inventory/index.php>. Accessed 9 January 2017.
758
- 759 Chao Y, Farrara JD, Bjorkstedt E, Chai F, Chavez F, Rudnick D, Enright W, Fisher JL, Peterson WT,
760 Welch GF, Davis CO, Dugdale RC, Wilkerson F., Zhang HC, Zhang YL, Ateljevich E (2017) The

761 origins of the anomalous warming in the California coastal ocean and San Francisco Bay during 2014-
 762 2016. *Journal of Geophysical Research-Oceans* 122:7537-7557.
 763 <https://doi.org/10.1002/2017JC013120>
 764
 765 Clough J, Polaczyk A, Popato M (2016) Modeling the potential effects of sea-level rise on the coast of
 766 New York: Integrating mechanistic accretion and stochastic uncertainty. *Environmental Modelling &*
 767 *Software* 84: 349–362.
 768
 769 Clough JS, Park RA, Fuller R (2010) SLAMM 6 beta technical documentation. Warren Pinnacle.
 770 http://warrenpinnacle.com/prof/SLAMM6/SLAMM6_Technical_Documentation.pdf. Accessed 19
 771 September 2018.
 772
 773 D’Alpaos A, Lanzoni S, Marani M, Rinaldo A (2007a) Landscape evolution in tidal embayments:
 774 Modeling the interplay of erosion sedimentation and vegetation dynamics. *J. Geophys. Res.* 112
 775 F01008. <https://doi.org/10.1029/2006JF000537>
 776
 777 Danielson J, Tyler D (2016) Topobathymetric Model for Chesapeake Bay Region - District of
 778 Columbia, States of Delaware, Maryland, Pennsylvania, and Virginia, 1859 to 2015.
 779 https://topotools.cr.usgs.gov/coned/chesapeake_bay.php. Accessed 2 October 2018.
 780
 781 Dean WE Jr (1974) Determination of carbonate and organic matter in calcareous sediments and
 782 sedimentary rocks by loss on ignition: Comparison with other methods. *Journal of Sedimentary*
 783 *Petrology* 44:242-248.
 784
 785 Deaton CD, Hein CJ, Kirwan ML (2017) Barrier-island migration dominates ecogeomorphic
 786 feedbacks and drives salt marsh loss along the Virginia Atlantic Coast, USA. *Geology* 45:123–126
 787
 788 De Jager JM (1994) Accuracy of vegetation evaporation ratio formulae for estimating final wheat
 789 yield. *Water SA* 20(4):307-314.
 790
 791 Du J, Shen J, Zhang YJ, Ye F, Liu Z, Wang Z, Wang YP, Yu X, Sisson M, Wang HV (2018) Tidal
 792 response to sea-level rise in different types of estuaries: The importance of length, bathymetry, and
 793 geometry. *Geophysical Research Letters* 45:227-235. <https://doi.org/10.1002/2017GL075963>
 794
 795 Eggleston J, Pope J (2013) Land subsidence and relative sea level rise in the southern Chesapeake Bay
 796 region. *US Geological Survey Circular* 1392. <https://dx.doi.org/10.3133/cir1392>
 797
 798 Enwright N, Griffith K, Osland MJ (2016) Barriers to and opportunities for landward migration of
 799 coastal wetlands with sea-level rise. *Frontiers in Ecology and the Environment* 14:307-316.
 800 <https://doi.org/10.1002/fee.1282>
 801
 802 Ezer T, Atkinson LP, Corlett WB, Blanco JL (2013) Gulf Stream's induced sea level rise and
 803 variability along the U.S. mid-Atlantic coast. *Journal of Geophysical Research: Oceans* 118:685-697.
 804 <https://doi.org/10.1002/jgrc.20091>
 805
 806 Fisher J, Acreman MC (2004) Wetland nutrient removal: a review of the evidence. *Hydrology and*
 807 *Earth System Sciences* 8:673-685. <https://doi.org/10.5194/hess-8-673-2004>
 808

809 Finkelstein K, Ferland MA (1987) Back-barrier response to sea-level rise, eastern shore of Virginia. In:
810 Nummedal D, Pilkey OH, Howard JD (eds) Sea-level fluctuation and coastal evolution. SEPM, SP 41,
811 pp 145–156.

812

813 Fitzgerald DM, Howes N, Kulp M, Hughes Z, Georgiou I, Penland S (2007) Impacts of rising sea level
814 to backbarrier wetlands, tidal inlets, and barriers: Barataria Coast, Louisiana. Proceedings of Coastal
815 Sediments 2007 CD-ROM13.

816

817 Folk RL (1980) Petrology of sedimentary rocks. Hemphill Publishing Company, Austin, TX.

818

819 Geselbracht L, Freeman K, Kelly E, Gordon DR, Putz FE (2011) Retrospective and prospective model
820 simulations of sea level rise impacts on Gulf of Mexico coastal marshes and forests in Waccasassa
821 Bay, Florida. Climatic Change 107:35–57. <https://doi.org/10.1007/s10584-011-0084-y>

822

823 Gittman RK, Fodrie J, Popowich AM, Keller DA, Bruno JF, Currin CA, Peterson CH, Piehler MF
824 (2015) Engineering away our natural defenses: An analysis of shoreline hardening in the US. Frontiers
825 in Ecology and the Environment 13(6):301–307. <https://dx.doi.org/10.1093%2Fbiosci%2Fbiw091>

826

827 Glick P, Clough J, Nunley B (2008) Sea-Level Rise and Coastal Habitats in the Chesapeake Bay
828 Region. Technical Report. National Wildlife Federation.

829

830 Glick P, Clough J, Polaczyk A, Couvillion B, Nunley B (2013) Potential effects of sea-level rise on
831 coastal wetlands in southeastern Louisiana. Journal of Coastal Research 63 (10063): 211–233.
832 <https://doi.org/10.2112/SI63-0017.1>

833

834 Guerin T, Bertin X, Coulombier T, de Bakker A (2018) Impacts of wave-induced circulation in the
835 surf zone on wave setup. Ocean Modelling 123:86–97. <https://doi.org/10.1016/j.ocemod.2018.01.006>

836

837 Hansen J, Sato M, Hearty P, Ruedy R, Kelley M, Masson-Delmotte V, Russell G, Tselioudis G, Cao J,
838 Rignot E, Velicogna I, Kandiano E, von Schuckmann K, Kharecha P, Legrande AN, Bauer M, Lo K-
839 W (2016) Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling,
840 and modern observations that 2 °C global warming could be dangerous. Atmospheric Chemistry and
841 Physics 16:3761–3812. <https://doi.org/10.5194/acp-16-3761-2016>

842

843 Haywick DW (2004) Pipette and Sieve Grain Size Analysis: Procedures Guide. Department of Earth
844 Sciences. University of South Alabama.

845

846 Heiri, O, Lotter AF, Lemcke G (2001) Loss on ignition as a method for estimating organic and
847 carbonate content in sediments: reproducibility and comparability of results. Journal of Paleolimnology
848 25:101–110.

849

850 Hill K (2015) Coastal infrastructure: a typology for the next century of adaptation to sea-level rise.
851 Frontiers in Ecology and the Environment 13 (9):468–476. <https://doi.org/10.2112/07A-0010.1>

852

853 Hood R, Laws EA, Armstrong RA, Bates NR, Brown CW, Carlson CA, Chai F, Doney SC, Falkowski
854 PG, Feely RA, Friedrichs MA, Landry MR, Moore JK, Nelson DM, Richardson TL, Salihoglu B,
855 Schartau M, Toole DA, Wiggert JD (2006) Pelagic functional group modeling: progress, challenges
856 and prospects. Deep Sea Research Part II: Topical Studies in Oceanography 53(5):459–512.
857 <https://doi.org/10.1016/j.dsr2.2006.01.025>

- Horton B, Shennan I, Bradley SL, Cahill N, Kirwan M, Kopp RE, Shaw TA (2018) Predicting marsh vulnerability to sea-level rise using Holocene relative sea-level data. *Nature Communications* 9(1):2697-2690. <https://doi.org/10.1038/s41467-018-05080-0>
- Jørgensen SE, Fath BD (2011a) 10-Structurally dynamic models. In: Sven Erik J, Brian DF (Eds.), *Developments in Environmental Modelling*, vol. 23. Elsevier, Amsterdam, pp. 309–346.
- Kirwan M, Walters DC, Reay WG, Carr JA (2016) Sea level driven marsh expansion in a coupled model of marsh erosion and migration. *Geophys. Res. Lett.* 43: 4366–4373, <https://doi.org/10.1002/2016GL068507>
- Kirwan ML, Megonigal JP (2013) Tidal wetland stability in the face of human impacts and sea-level rise. *Nature* 504:53–60. <https://doi.org/10.1038/nature12856>
- Kirwan ML, Murray AB (2007) A Coupled Geomorphic and Ecological Model of Tidal Marsh Evolution. *Proceedings of the National Academy of Sciences* 104 (15):6118–6122. <https://doi.org/10.1073/pnas.0700958104>
- Kolker AS, Kirwan ML, Goodbred SL, Cochran J K (2010) Global climate changes recorded in coastal wetland sediments: empirical observation linked to theoretical predictions. *Geophys. Res. Lett.* 37, L14706.
- Knutson PL, Brochu RA, Seeling WN, Inskeep M (1982) Wave dampening in *Spartina alterniflora* marshes. *Wetlands* 2:87–104.
- Landis JR, Koch GG (1977) The measurement of observer agreement for categorical data. *Biometrics* 33:159-74. <https://doi.org/10.2307/2529310>
- Legates DR, McCabe Jr GJ (1999) Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation. *Water Resources Research* 35(1):233-241. <https://doi.org/10.1029/1998WR900018>
- Le Roux DY (2012) Spurious inertial oscillations in shallow-water models. *Journal of Computational Physics* 231:7959–7987. <https://doi.org/10.1016/j.jcp.2012.04.052>
- Lesser GR, Roelvink JA, Van Kester J, Stelling GS (2004) Development and validation of a three-dimensional morphological model. *Coastal Engineering*, 51(8-9):883–915.
- Lin J, Kuo AY (2001) Secondary Turbidity Maximum in a Partially Mixed Microtidal Estuary. *Estuaries* 24:707–720. <https://doi.org/10.2307/1352879>
- Liu Q, Anderson E, Zhang YJ, Weinke AD, Knapp KL, Biddanda BA (2018) Modeling Reveals the Role of Coastal Upwelling and Hydrologic Inputs on Biologically Distinct Water Exchanges in a Great Lakes Estuary. *Estuarine, Coastal and Shelf Science* 29:41-55. <https://doi.org/10.1016/j.ecss.2018.05.014>

- Machiwal D, Jha MK (2015) GIS-based water balance modeling for estimating regional specific yield and distributed recharge in data-scarce hard-rock regions. *Journal of Hydro-Environment Research* 9(4):554–568. <http://dx.doi.org/10.1016%2Fj.jher.2014.07.004>
- Mariotti G, Fagherazzi S, Wiberg PL, McGlathery KJ, Carniello L, Defina A (2010) Influence of storm surges and sea level on shallow tidal basin erosive processes. *J. Geophys. Res.* 115 C11012. <https://doi.org/10.1029/2009JC005892>
- McHugh, M (2012) Interrater reliability: The kappa statistic. *Biochemia Medica* 22(3):276–282. <https://doi.org/10.11613/bm.2012.031>
- Meskini-Vishkaee F, Davatgar N (2018) Evaluation of different predictor models for detailed soil particle-size distribution. *Pedosphere* 28(1):157–164. [https://doi.org/10.1016/S1002-0160\(17\)60422-3](https://doi.org/10.1016/S1002-0160(17)60422-3)
- Mitchell M, Herman J, Bilkovic DM, Hershner C (2017) Marsh persistence under sea-level rise is controlled by multiple, geologically variable stressors. *Ecosystem Health and Sustainability* 3(10), 1379888. <https://doi.org/10.1080/20964129.2017.1396009>
- Mitsch WJ, Gosselink JG (2007) *Wetlands*. 4th edn. John Wiley & Sons.
- Moerman E (2011) Long-term morphological modelling of the Mouth of the Columbia River. Master Thesis in Coastal Engineering. Civil Engineering and Geosciences. Delft University of Technology. Netherlands.
- Mogensen LA, Rogers K (2018) Validation and comparison of a model of the effect of sea-level rise on coastal wetlands. *Scientific Reports* 8:1369.
- Moore KA, Silberhorn GM (1980) James City County Tidal Marsh Inventory. Special Reports in Applied Marine Science and Ocean Engineering No. 188. Virginia Institute of Marine Science, College of William and Mary. <https://doi.org/10.21220/V54H8T>
- Moore KA, Silberhorn GM (1976) Gloucester County Tidal Marsh Inventory. Special Report in Applied Marine Science and Ocean Engineering No. 64. Virginia Institute of Marine Science, College of William and Mary. <https://doi.org/10.21220/V5972B>.
- Morgan PA, Burdick DM, Short FT (2009) The functions and values of fringing salt marshes in Northern New England, USA. *Estuaries and Coasts* 32:483–495. <http://www.jstor.org/stable/40663558>
- Moriasi D, Arnold J, Van Liew M, Bingner R, Harmel D, Veith T (2007) Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the American Society of Agricultural and Biological Engineers* 50(3):885–900. <https://doi.org/10.13031/2013.23153>
- Morris JT, Barber DC, Callaway JC, Chambers R, Hagen SC, Hopkinson CS, Johnson BJ, Megonigal P, Neubauer SC, Troxler T, Wigand C (2016) Contributions of organic and inorganic matter to sediment volume and accretion in tidal wetlands at steady state. *Earth's Future* 4(4):110–121. <https://doi.org/10.1002/2015EF000334>

952 Morris JT, Sundareshwar PV, Nietch CT, Kjerfve B, Cahoon DR (2002) Responses of Coastal
 953 Wetlands to Rising Sea Level. *Ecology* 83(10):2869–2877. [https://doi.org/10.1890/0012-](https://doi.org/10.1890/0012-9658(2002)083[2869:ROCWTR]2.0.CO;2)
 954 9658(2002)083[2869:ROCWTR]2.0.CO;2
 955
 956 Neubauer S, Anderson IC, Constantine JA, Kuehl SA (2002) Sediment deposition and accretion in a
 957 mid-Atlantic (U.S.A.) tidal freshwater marsh. *Estuarine Coastal and Shelf Science* 54:713–727.
 958 <https://doi.org/10.1006/ecss.2001.0854>
 959
 960 NOAA Tides and Currents (2018) Relative Sea Level Trend 8638610 Sewells Point, Virginia.
 961 https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8638610. Accessed 11 November
 962 2018.
 963
 964 NTHMP (2012) Proceedings and results of the 2011 NTHMP model benchmarking workshop.
 965 Boulder: US Department of Commerce/NOAA/NTHMP, NOAA Special Report 436p.
 966
 967 Odink SJ (2019) Long-term marsh growth and retreat in an online coupled hydrodynamic,
 968 morphodynamic and ecological model. Master Thesis In Water Engineering And Management. Faculty
 969 Of Engineering Technology. University Of Twente. The Netherlands.
 970
 971 Pinto L, Fortunato AB, Zhang Y, Oliveira A, Sancho FEP (2012) Development and validation of a
 972 three-dimensional morphodynamic modelling system for non-cohesive sediments. *Ocean Model* 57-
 973 58:1–14. <https://doi.org/10.1016/j.ocemod.2012.08.005>
 974
 975 Poppe LJ, Eliason AH, Fredericks JJ, Rendigs RR, Blackwood D, Polloni CF (2003) Grain-Size
 976 Analysis of Marine Sediments: Methodology and Data Processing. In Open File Report 00-358,
 977 Chapter 1. U.S. Geological Survey. <https://pubs.usgs.gov/of/2000/of00-358/text/chapter1.htm>.
 978 Accessed 12 December 2018.
 979
 980 Rahman A (2015) Cliff Erosion of salt marshes: Experimental evaluation of the effect of vegetation
 981 characteristics and sediment properties on erodibility. Master's thesis in Water Engineering &
 982 Management. University of Twente Enschede, The Netherlands.
 983
 984 Rahmstorf S, Box JE, Feulner G, Mann ME, Robinson A, Rutherford S, Schaffernicht EJ (2015)
 985 Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. *Nature Climate*
 986 *Change* 5:475–480. <https://doi.org/10.1038/nclimate2554>
 987
 988 Raposa K, Ekberg MLC, Burdick D, Ernst NT, Adamowicz SC (2017) Elevation change and the
 989 vulnerability of Rhode Island (USA) salt marshes to sea-level. *Regional Environmental Change*
 990 17:389–397. <https://doi.org/10.1007/s10113-016-1020-5>
 991
 992 Reed DJ (1995) The response of coastal marshes to sea-level rise: survival or submergence? *Earth*
 993 *Surface Processes and Landforms* 20:39–48. <https://doi.org/10.1002/esp.3290200105>
 994
 995 Renard KG, Foster GR, Weesies GA, Porter JP (1991) RUSLE: Revised universal soil loss equation.
 996 *Journal of Soil and Water Conservation* 46:30-33.
 997
 998 Rodrigues M, Oliveira A, Queiroga H, Fortunato AB, Zhang. MY (2009) Three-dimensional modeling
 999 of the lower trophic levels in the Ria de Aveiro (Portugal). *Ecological Modelling* 220(9-10):1274-
 1000 1290.

1001
1002 Roelvink DJA, Reniers AJH (2011) A Guide to Modeling Coastal Morphology. World Scientific
1003 Publishing Company. Series: Advances in Coastal and Ocean Engineering. Book 12.
1004
1005 Roelvink DJA (2006) Coastal morphodynamic evolution techniques. Coastal Engineering 53(2-
1006 3):277–287.
1007
1008 Roland A, Zhang YJ, Wang HV, Meng Y, Teng YC, Maderich V, Brovchenko I, Dutour-Sikiric M,
1009 Zanke U (2012) A fully coupled 3D wave-current interaction model on unstructured grids. Journal of
1010 Geophysical Research 177:1-18. <https://doi.org/10.1029/2012JC007952>
1011
1012 Roland A (2009) Development of WWM II: Spectral wave modeling on unstructured meshes. Ph.D.
1013 thesis, Technical University Darmstadt, Institute of Hydraulic and Water Resources Engineering.
1014
1015 Sallenger AH, Doran KS, Howd PA (2012) Hotspot of accelerated sea-level rise on the Atlantic coast
1016 of North America. Nature Climate Change 2:884-888. <https://doi.org/10.1038/nclimate1597>
1017
1018 Santisteban JI, Mediavilla R, López-Pamo E, Dabrio CJ, Zapata MBR, García MJG, Castaño S,
1019 Martínez-Alfaro PE (2004) Loss on ignition: a qualitative or quantitative method for organic matter
1020 and carbonate mineral content in sediments? Journal of Paleolimnology 32: 287-299.
1021
1022 Schwimmer RA (2001) Rates and processes of marsh shoreline erosion in Rehoboth Bay, Delaware,
1023 USA. Journal of Coastal Research 17(3): 672–683.
1024
1025 Shepard CC, Crain CM, Beck MW (2011) The protective role of coastal marshes: A systematic review
1026 and meta-analysis. PLoS ONE 6:e27374. <https://doi.org/10.1371/journal.pone.0027374>
1027
1028 Silinski, A, Heuner M, Schoelynck J, Puijalon S, Schröder U, Fuchs E et al. (2015) Effects of wind
1029 waves versus ship waves on tidal marsh plants: a flume study on different life stages of *Scirpus*
1030 *maritimus*. PLoS ONE, <https://doi.org/10.1371/journal.pone.0118687>
1031
1032 Singh J, Knapp V, Demissie M (2004) Hydrologic modeling of the Iroquois River watershed using
1033 HSPF and SWAT. ISWS Contract Report CR 2004-08. Illinois State Water Survey.
1034 <http://www.isws.illinois.edu/pubdoc/CR/ISWSCR2004-08.pdf>. Accessed 22 November 2019.
1035
1036 Sisson GM, Shen J, Kim SC, Boon JD, Kuo AY (1997) VIMS three dimensional hydrodynamic-
1037 eutrophication model (HEM-3D): Application of the hydrodynamic model to the York River system.
1038 SRAMSOE Report No. 341. Virginia Institute of Marine Science. Gloucester Point, Va. 123pp.
1039 <https://doi.org/10.21220/V5ZB3N>
1040
1041 Stanev EV, Pein JU, Grashorn S, Zhang Y, Schrum C (2018) Dynamics of the Baltic Sea Straits via
1042 Numerical Simulation of Exchange Flows. Ocean Modelling 131:40-58.
1043 <https://doi.org/10.1016/j.ocemod.2018.08.009>
1044
1045 Stanev EV, Grashorn S, Zhang YJ (2017) Cascading ocean basins: numerical simulations of the
1046 circulation and interbasin exchange in the Azov-Black-Marmara-Mediterranean Seas system. Ocean
1047 Dynamics 67:1-23. <https://doi.org/10.1007/s10236-017-1071-2>

1048 Styles R, Brown ME, Brutsché KE, Li H, Beck TM, Sánchez A (2016) Long-term morphological
 1049 modeling of barrier island tidal inlets. *Journal of Marine Science and Engineering* 4(65):126-148.
 1050 <https://doi.org/10.3390/jmse4040065>
 1051
 1052 Tang W, Hu J, Zhang H, Wu P, He H (2015) Kappa coefficient: A popular measure of rater
 1053 agreement. *Shanghai Archives of Psychiatry* 27(1):62–67.
 1054
 1055 Temmerman S, Goers G, Wartel S, Meire P (2003b) Spatial and temporal factors controlling short-
 1056 term sedimentation in a salt and freshwater tidal marsh, Scheldt Estuary, Belgium, SW Netherlands,
 1057 *Earth Surf. Processes Landforms* 28:739–755, <https://doi.org/10.1002/esp.495>
 1058
 1059 Titus JG, Anderson KE, Cahoon DR, Gesch DB, Gill SK, Gutierrez BT, Thieler ER, William SJ
 1060 (2009) Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region. U.S. Climate
 1061 Change Science Program and the Subcommittee on Global Change Research. Washington, D.C.
 1062
 1063 Tobias CR, Harvey JW, Anderson IC (2001) Quantifying groundwater discharge through fringing
 1064 wetlands to estuaries: Seasonal variability, methods comparison, and implications for wetland-estuary
 1065 exchange. *Limnology and Oceanography* 46 (3):604–615. <https://doi.org/10.4319/lo.2001.46.3.0604>
 1066
 1067 Umlauf L, Burchard H (2003) A generic length-scale equation for geophysical turbulence models.
 1068 *Journal Marine Research* 6: 235-265. <https://doi.org/10.1357/002224003322005087>
 1069
 1070 USGS (United States Geological Survey) (2011) Bare Earth DEM VA_FEMA_MiddleCounties_2011,
 1071 multiple tiles. U.S. Geological Survey. Access through
 1072 <https://vgin.maps.arcgis.com/home/index.html>. Accessed 9 January 2017.
 1073
 1074 Van Proosdij D, Davidson-Arnott RGD, Ollerhead J (2006) Controls on spatial patterns of sediment
 1075 deposition across a macro-tidal salt marsh surface over single tidal cycles. *Estuarine Coastal Shelf Sci.*
 1076 69:64–86. <https://doi.org/10.1016/j.ecss.2006.04.022>
 1077
 1078 Walters D, Moore LJ, Durán O, Fagherazzi S, Mariotti G (2014) Interactions between barrier islands
 1079 and backbarrier marshes affect island system response to sea level rise: Insights from a coupled
 1080 model. *J. Geophys. Res.* 119:2013–2031
 1081
 1082 Warner JC, Sherwood CR, Signell RP, Harris CK, Arango HG (2008) Development of a three-
 1083 dimensional, regional, coupled wave, current, and sediment-transport model. *Computers &*
 1084 *Geosciences* 34: 1284-1306. <https://doi.org/10.1016/j.cageo.2008.02.012>
 1085
 1086 Viera AJ, Garrett JM (2005) Understanding inter observer agreement: The kappa statistic. *Family*
 1087 *Medicine* 37(5): 360-363.
 1088
 1089 Willmott CJ, Robeson SM, Matsuura K, Ficklin DL (2015) Assessment of three dimensionless
 1090 measures of model performance. *Environmental Modelling and Software* 73:167-174.
 1091 <https://doi.org/10.1016/j.envsoft.2015.08.012>
 1092
 1093 Willmott CJ, Robeson SM, Matsuura K, Ficklin DL (2012) Short Communication: A refined index of
 1094 model performance. *International Journal of Climatology* 32:2088-2094.
 1095 <https://doi.org/10.1002/joc.2419>

1096
1097
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1101
1102
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1120
1121
1122
1123
1124
1125
1126

1127

1128

1129

1130

1131

1132

1133

- Willmott CJ (1982) Some comments on the evaluation of model performance. *Bulletin of the American Meteorological Society* 63:1309–1313. [https://doi.org/10.1175/1520-0477\(1982\)063%3C1309:SCOTEO%3E2.0.CO;2](https://doi.org/10.1175/1520-0477(1982)063%3C1309:SCOTEO%3E2.0.CO;2).
- Ye F, Zhang YJ, Wang H, Friedrichs MA, Irby ID, Ateljevich E, Valle-Levinson A, Wang Z, Huang H, Shen J, Du J (2018) A 3D unstructured-grid model for Chesapeake Bay: importance of bathymetry. *Ocean Modelling* 127:16-39. <https://doi.org/10.1016/j.ocemod.2018.05.002>
- Ye F, Chen Q, Blanckaert K, Ma J (2013) Riparian vegetation dynamics: Insight provided by a process-based model, a statistical model and field data. *Ecohydrology* 6:567–85. <https://doi.org/10.1002/eco.1348>
- Yu HC, Zhang YJ, Yu JCS, Terng C, Sun W, Ye F, Wang HV, Wang Z, Huang H (2017) Simulating multi-scale oceanic processes around Taiwan on unstructured grids. *Ocean Modelling* 112:72-93. <http://doi.org/10.1016/j.ocemod.2017.09.007>
- Zhang Y, Gerds N, Ateljevich E, and Nam K (2019) Simulating vegetation effects on flows in 3D using an unstructured grid model: model development and validation. *Ocean Dynamics* <https://doi.org/10.1007/s10236-019-01333-8>
- Zhang, YJ, Ye F, Stanley EV, Grashorn S (2016) Seamless cross-scale modeling with SCHISM. *Ocean Modelling* 102:64-81. <https://doi.org/10.1016/j.ocemod.2016.05.002>
- Zhang YJ, Ateljevich E, Yu HC, Wu CH, Yu JCS (2015) A new vertical coordinate system for a 3D unstructured-grid model. *Ocean Modelling* 85:16-31. <https://doi.org/10.1016/j.ocemod.2014.10.003>
- Zhang YJ, Baptista AM (2008) SELFE: A semi-implicit Eulerian–Lagrangian finite-element model for cross-scale ocean circulation. *Ocean Modelling* 21(3–4):71-96. <https://doi.org/10.1016/j.ocemod.2007.11.005>

APPENDICES

Appendix A - TMM Physical Formulation – Governing equations:

SCHISM solves the 3D Reynolds-averaged Navier-Stokes equation in its hydrostatic form:

$$\text{Momentum equation: } \frac{D\mathbf{u}}{Dt} = \frac{\partial}{\partial z} \left(\nu \frac{\partial \mathbf{u}}{\partial z} \right) - g \nabla \eta + \mathbf{F}$$

Continuity equation in 3D and 2D depth-integrated forms:

$$\nabla \cdot \mathbf{u} + \frac{\partial w}{\partial z} = 0$$

$$\frac{\partial \eta}{\partial t} + \nabla \cdot \int_{-h}^{\eta} \mathbf{u} dz = 0$$

Transport equation:

$$\frac{\partial C}{\partial t} + \nabla \cdot (\mathbf{u}C) = \frac{\partial}{\partial z} \left(\kappa \frac{\partial C}{\partial z} \right) + F_h,$$

Equation of state:

$$\rho = \rho(S, T, p)$$

where

$$\nabla \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y} \right)$$

D/Dt	material derivative (s^{-1})
(x, y)	horizontal Cartesian coordinates (m)
z	vertical coordinate, positive upward (m)
t	time (s)
$\eta(x, y, t)$	free-surface elevation (m)
$h(x, y)$	bathymetric depth (m)
$\mathbf{u}(x, y, z, t)$	horizontal velocity, with Cartesian components (u, v)
w	vertical velocity
$\mathbf{F}$	other forcing terms in momentum (baroclinic gradient ($-\frac{g}{\rho_0} \int_z^{\eta} \nabla \rho d\zeta$), horizontal viscosity, Coriolis, earth tidal potential, atmospheric pressure, radiation stress)
g	acceleration of gravity, in (ms^{-2})
C	tracer concentration (e.g., salinity, temperature, sediment, etc.)
ν	vertical eddy viscosity, in (m^2s^{-1})
κ	vertical eddy diffusivity, for tracers, in (m^2s^{-1})
F_h	horizontal diffusion and mass sources/sinks

As previously stated, a simpler 2D barotropic configuration was used in this study.

1170

1171 ***Appendix B - TMM Numerical Formulation: Geometry and Discretization***

1172 SCHISM-TMM is a finite-element model that uses a flexible unstructured grid (UG). For the
1173 horizontal grid, hybrid triangular-quadrangular (quads) elements are employed to take advantage of the
1174 superior boundary-fitting capability of triangles as well as efficiency/accuracy of quads in representing
1175 certain features (e.g., channels) as needed.

1176 The basic 3D computational unit in SCHISM is a triangular prism (Figure 13) or quad prism.
1177 Surface elevations (η) are defined at the nodes, and the horizontal velocities (u, v) are defined at the
1178 side centers and whole levels. The vertical velocity (w) is defined at the element centers and whole
1179 levels, and the tracer concentration (C) is defined at prism center, as it is solved with a finite volume
1180 method. The conformal and non-conformal linear shape functions (Le Roux 2012) are used for
1181 elevations and velocities respectively.

1182 ***Boundary Conditions.*** The differential equations previously described require initial conditions
1183 (I.C.) and boundary conditions (B.C.). Generally, all state variables (η, u, C) are specified at $t=0$ as I.C. In
1184 addition, some variables are specified at all open lateral boundary segments (e.g. open ocean, rivers, etc.).
1185 At the sea-surface interface, SCHISM enforces the balance between the internal Reynolds stress and the
1186 applied shear stress:

$$1187 \quad \nu \frac{\partial \mathbf{u}}{\partial z} = \boldsymbol{\tau}_w, \quad z = \eta$$

1188 Since the bottom boundary layer is typically not well resolved in ocean models, the no-slip condition at
1189 the sea or river bottom ($u = w = 0$) is replaced by a balance between the internal Reynolds stress and
1190 the bottom frictional stress,

$$1191 \quad \nu \frac{\partial \mathbf{u}}{\partial z} = \boldsymbol{\tau}_b, \text{ at } z = -h.$$

1192 For a turbulent boundary layer, the bottom stress is defined as:

$$1193 \quad \boldsymbol{\tau}_b = C_D |\mathbf{u}_b| \mathbf{u}_b$$

1194 where $\mathbf{u}_b$ is the near bottom velocity.

1195 **Turbulence closure.** The momentum equation and transport equation are not closed and must
 1196 be supplemented by turbulence closure equations for the viscosity/diffusivity. SCHISM uses the
 1197 Generic Length-Scale (GLS) model of Umlauf and Burchard (2003) with proper I.C. and B.C. for each
 1198 differential equation.

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1201 **Appendix C. Main Equations for Supporting Models**

1202 **Suspended Sediment Transport.** Suspended sediment concentrations are computed as follows
 1203 (Pinto et al. 2012):

$$1204 \quad \frac{\partial c_j}{\partial t} + \nabla_h \cdot (\mathbf{u}c_j) + \frac{\partial[(w - w_{sj})c_j]}{\partial z} = \frac{\partial}{\partial z} \left(\kappa \frac{\partial c_j}{\partial z} \right) + F_h$$

1205 c_j - volume concentration of suspended sediment in class j

1206 $\mathbf{u}$ - horizontal velocity

1207 κ - eddy diffusivity

1208 w_{sj} - settling velocity

1209 F_h - horizontal mixing

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1211 **Spectral Wave Model (WWM-III).** Governing equation for wave action is defined as (Ronald et al. 2012):

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$$1216 \quad \underbrace{\frac{\partial}{\partial t} N}_{\text{Change in Time}} + \underbrace{\nabla_x (XN)}_{\text{Advection in horizontal space}} + \underbrace{\frac{\partial}{\partial \sigma} (\theta N) \frac{\partial}{\partial \theta} (\sigma N)}_{\text{Advection in spectral space}} = \underbrace{S_{tot}}_{\text{Total Source Term}}$$

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Where:

$$N_{(t,X,\sigma,\theta)} = \frac{E_{(t,X,\sigma,\theta)}}{\sigma}$$

E = variance density of the sea level elevations

σ = relative wave frequency

θ = wave direction

X = Cartesian coordinate vector (x, y) in the geographical space

1231 **Appendix D. Equations for statistical performance measures**
 1232

1233 Kappa Statistic (K)
$$K = \frac{N \sum_{i=1}^k x_{ii} - \sum_{i=1}^k (x_{i+} \times x_{+i})}{N^2 - \sum_{i=1}^k (x_{i+} \times x_{+i})}$$

Mean Absolute Error (MAE)
$$MAE = \frac{1}{n} \sum_{i=1}^n |P_i - O_i|$$

Willmott Modified Index of Agreement (dr)
$$d_r = \begin{cases} 1 - \frac{\sum_{i=1}^n |P_i - O_i|}{c \sum_{i=1}^n |O_i - \bar{O}|}, & \text{when} \\ \sum_{i=0}^n |P_i - O_i| \leq c \sum_{i=0}^n |O_i - \bar{O}| \\ \frac{c \sum_{i=1}^n |O_i - \bar{O}|}{\sum_{i=1}^n |P_i - O_i|} - 1, & \text{when} \\ \sum_{i=0}^n |P_i - O_i| > c \sum_{i=0}^n |O_i - \bar{O}| \end{cases}$$

$$c=2$$

Nash_Sutcliffe Efficiency (NSE)
$$NSE = 1 - \frac{\sum_{i=1}^n (O_i - P_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2}$$

Observations Standard Deviation Ratio (RSR)
$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\left[\sqrt{\sum_{i=1}^n (O_i - P_i)^2} \right]}{\left[\sqrt{\sum_{i=0}^n (O_i - \bar{O})^2} \right]}$$

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Fig. 1 Diagram of vertical and horizontal marsh responses to sea-level rise

Symbols courtesy of the Integration and Application Network (ian.umces.edu/symbols/), University of Maryland Center for Environmental Science

Fig. 2 SCHISM modeling system. The dashed box indicates the TMM and key supporting components. The hydrostatic core serves as the pillar of the system to provide hydrodynamic variables to other models as well as to facilitate exchange of variables between models in a parallel software environment

Fig. 3 a) York River system; b) Carter Creek and c) Taskinas Creek: study areas in the York River. Bright green areas represent tidal marshes. Background Image: VBMP2017/VBMP2017_WGS - Virginia Geographic Information Network (VGIN)

Fig. 4 Locations of marsh near surface (upper eight cm) sediment cores sampled in a) Carter Creek (33 cores) and b) Taskinas Creek (27 cores). Background Image: VBMP2017/VBMP2017_ WGS - Virginia Geographic Information Network (VGIN)

Fig. 5 a) Unstructured TMM grid used for Carter Creek marshes; b) The marsh layer (in green) is displayed on top of the grid (in yellow). Upland adjacent to the marsh is highly resolved to more accurately capture marsh transgression. Background Image: VBMP2017/VBMP2017_ WGS - Virginia Geographic Information Network (VGIN)

Fig. 6 a) Unstructured TMM grid used for Taskinas Creek marshes; b) The marsh layer (in green) is displayed on top of the grid (in yellow). Upland adjacent to the marsh is highly resolved to more accurately capture marsh transgression. Background Image: VBMP2017/VBMP2017_ WGS - Virginia Geographic Information Network (VGIN)

Fig. 7 Marsh boundary evolution output for Carter Creek – Hindcast outputs: changes in marsh boundary after 40 years of simulation with a sea-level rise of 4 mm/yr. Background image: VBMP2017/VBMP2017_WGS - Virginia Geographic Information Network (VGIN)

Fig. 8 Marsh boundary evolution output for Taskinas Creek – Hindcast outputs: changes in marsh boundary after 40 years of simulation with a sea-level rise of 4 mm/yr. Background image: VBMP2017/VBMP2017_WGS - Virginia Geographic Information Network (VGIN)

Fig. 9 Points used to generate the error matrices in a) Carter Creek (100 points) and Taskinas Creek (100 points). Points were generated using ArcGIS point generator. Background image: VBMP2017/VBMP2017_Infrared_WGS - Virginia Geographic Information Network (VGIN)

Fig. 10 Aerial drone photos of Taskinas Creek – a) it displays different soil conditions around marsh channels; b) localized depressions can be seen close to the upland edge (red box); c) it shows marsh areas affected by the presence of tree canopies

Fig. 11 Basic 3D computational unit (triangular element) in SCHISM. The elevation (η) is defined at node (vertex) of a triangular element, horizontal velocity (u, v) at side center and whole levels, vertical velocity (w) at element centroid and whole level, and tracers (C) at the prism center