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Linear and Nonlinear Responses to Northeasters Coupled with Sea Level Rise: A Tale of Two Bays

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Abstract

This study aimed at dissecting the influence of sea level rise (SLR) on storm responses in two bays in the Gulf of Maine through high-resolution, three-dimensional, hydrodynamic modeling. Saco Bay, an open bay characterized by gentle coastal slopes, provided a contrast to Casco Bay that has steep shorelines and is sheltered by barrier islands and peninsulas. The Finite-Volume Coastal Ocean Model (FVCOM) was implemented for Saco Bay and Casco Bay to simulate the February 1978 northeaster and an April freshwater discharge event in 2007 following the Patriots Day storm. Both events were repeatedly simulated under SLR scenarios ranging from 0 to 7 ft. Modeled storm responses were identified from the 1978 Blizzard simulations and were tracked across SLR scenarios. By comparing changes in inundation, storm currents, and salinity distribution between the two bays, freshwater discharge and bathymetric structure were isolated as two determining factors in how storm responses change with the rising sea level. The steplike bottom relief at the shoreline of Casco Bay sets up nonlinear responses to SLR. In contrast, storm responses in Saco Bay varied significantly with SLR due to alterations in river dynamics attributed to SLR-induced flooding.

Keywords: storm response, sea level rise, Saco Bay and Casco Bay, the Gulf of Maine, simulation, coastal ocean model

1. Introduction

The influence of sea level rise (SLR) on coastal storm responses is highly complex and not well understood. It has been shown that the impact of SLR on storm tide and surge can vary greatly over small spatial scales [1, 2] though the causes of these variations, likely regionally specific, have not been thoroughly explored. Due to the limited understanding of small-scale uncertainties, linear relationships between SLR and storm response patterns are commonly assumed when modeling SLR scenarios for risk management. This study is aimed at investigating the variability of storm responses sensitive to SLR along the coastline of Saco Bay and Casco Bay in the Gulf of Maine through the application of a hydrodynamic coastal ocean model. The coastline across these two bays varies greatly in topography and intertidal characteristics, which has been shown to be a major factor affecting the impact of SLR on storm surge [3]. Furthermore, coastal flooding caused by northeasters

along the New England coastline is a common occurrence during the cool seasons when cyclogenesis is driven by dynamic atmospheric forcing associated with the jet stream. This makes accurate predictions of storm response of great importance to the coastal communities.

During the October–April period, the extratropical storms affecting this domain are characterized by large, synoptic-scale cyclones, heavy precipitation, and strong wind and are accompanied by wave run-up and sea level setup. As a result, northeasters in this region often result in significant damages including loss of life and property, as well as environmental impacts such as beach erosion. The latter is particularly notable in Saco Bay in northern New England, where beach erosion has been a major issue for several decades. Conversely, in the same area, tropical cyclones are often smaller and move faster, resulting in less time for storm surges to develop over these shallow areas [4], and typically transition into extratropical cyclones before landfall. As such, this study will primarily focus on major extratropical storm events. Scarcity of real-time observation data during these storms has led to an increased reliance on numerical model results for storm forecasts along the coastline [4]. Testing the developed hydrodynamic model against these extreme events across varying SLR scenarios will also help ensure the model's capability in modeling future events.

This study was designed to quantify the relationship between sea level rise and coastal storm responses in Saco Bay and Casco Bay. In doing so, improved forecasts can be provided to coastal communities in preparation for future storm events. To accomplish these goals, a predictive storm response model was developed, building upon the Finite-Volume Coastal Ocean Model (FVCOM) [5]. Inputs for this model were derived from the Northeast Coastal Ocean Forecast System (NECOFS, <http://www.smast.umassd.edu:8080/thredds/catalog/models/fvcom/NECOFS/Archive/catalog.html>) and the United States Geological Survey (USGS, <https://waterdata.usgs.gov/nwis>). Validation of the resultant model was carried out with data collected from NOAA buoys and stations, the University of Maine buoy deployments, and the Sustainable Ecological Aquaculture Network (SEANET). Buoy records and tidal station data along with the validated model simulation were used to establish a baseline assessment of the bays. Storm simulations were then analyzed to identify and dissect storm responses to be tracked across a range of sea level rise scenarios.

The present investigation differentiates itself from past studies in three prominent ways. First, no hydrodynamic model study has been conducted over this domain at the high-resolution used herein. By simulating storms with the minimum 10-m resolution nearshore, we can identify very-small-scale features and provide more accurate dynamic inundation and storm response predictions than what is currently available. Additionally, the methodology of tracking modeled storm responses under elevating SLR scenarios has not yet been applied to the Gulf of Maine, a region particularly vulnerable to the impacts of northeasters. Finally, this study provides a comparison of storm responses and SLR vulnerability in two adjacent bays, distinct from each other in geomorphological and hydrodynamic characteristics.

The following section provides a review of studies contributing to the understanding of SLR storm response interactions and includes a brief overview of the Saco and Casco domain and of the storm events being examined. The rest of the paper is organized as follows. The design, configuration, and validation of the model are discussed in Section 3, followed by an analysis in Section 4 to depict the modeled storm responses. Section 5 looks at the modeled responses in the events of sea level rise, including inundation and circulation patterns. Finally, Section 6 provides a summary of the findings revealed by this study.

2. Background

2.1 Prior understanding of interactions between storm responses and SLR

The relationship between SLR and storm response is still not well understood, as was made clear by Woodruff et al. in a review of studies up to 2012 aimed at dissecting the relationship between SLR and flooding caused by tropical cyclones [6]. Of interest in Woodruff's review were two studies mentioned earlier which applied modeling techniques to investigate storm surge in hurricane conditions under SLR scenarios [1, 2]. Smith et al. [1] was the first to show quantitatively that the relationship between SLR and storm surge is not necessarily linear. In areas with high surge under present conditions, the increase in storm surge under the relative sea level rise (RSLR) scenarios remained linear, with RSLR defined as the cumulative change in vertical height of both land and water [7], but the amplification of surge in areas that typically saw low surge heights was increased by a much larger factor under heightened RSLR scenarios. While not explored in depth by the authors, another important conclusion was a potential plateau effect on the relative impact of SLR on storm surge in certain areas.

Interest in researching the impacts of global SLR and risk management has increased significantly since the NOAA 2012 National Climate Assessment (<https://scenarios.globalchange.gov>) wherein 100-year projections of SLR scenarios were produced for the coastal United States. The assessment report acknowledged the uncertainties regarding the relationship between ocean warming, ice sheet and glacier loss, and SLR, and in doing so provided four different SLR projections, with final endpoints ranging from 0.2 to 2.0 m of coastal SLR by 2100. This range formed the basis for the SLR scenarios chosen for many subsequent investigations, including the present Saco and Casco model study. Some recent studies have acknowledged the uncertainties in the 2012 assessment, illustrating the benefits of analyzing the acceleration of flooding, which appeared to be a more precise calculation than measuring acceleration of SLR [3, 8]. These studies assumed zero acceleration of SLR, linearly generalizing the predicted rise to the entire Gulf of Maine.

The most recent modeling efforts of coastal responses to storms have largely focused on risk management and damage estimation under potential SLR scenarios, such as changes in land cover due to increased storm surge resulting from SLR [9]. Passeri et al. offered a good review of such studies looking at changes in coastal structure estimated from secondary SLR impacts, such as increased surge morphing the landscape in shallow areas [10]. The proposed structural impacts of SLR tie back into the efforts to estimate RSLR, as the generalized linear SLR projections did not account for changes in vertical land height or coastal slopes.

Looking specifically at the Saco and Casco domain, groups local to the region have been focusing on the global SLR projections, as RSLR projections, such as those for NYC and Louisiana, are not readily available. Peter Slovinsky of the Maine Geological Survey incorporated the global projections made by these earlier studies into a presentation for the 2015 State of the Bay Conference [11], in which he outlined the steps that coastal communities have been taking in anticipation of future SLR impacts, including ordinance changes, vulnerability assessments, coastal modeling efforts, public outreach, and infrastructure remodeling. He also pointed out how SLR trends in Portland, Maine, such as those discussed by Ezer and Atkinson [3], may indicate accelerated SLR over the past few decades, which would increase the 2100 SLR projections for Portland to be closer to the higher estimates offered by NOAA [12]. At present, focus continues to rest on risk mitigation and community actions in preparation for worst-case scenario future projections. The Saco and Casco storm response study was devised to support this continued effort through

the simulation of two major storm events: The Blizzard of 1978 and the Patriots Day storm in 2007.

2.2 Saco Bay and Casco Bay

Though situated next to each other, Saco Bay and Casco Bay differ significantly in terms of geography (**Figure 1**). Saco Bay is a 10-mile wide embayment containing the Saco Estuary, Goose Fare Brook tidal inlet, and Scarborough marshes that are fed by Nonesuch River. The mean tidal range of the bay is 2.7 m. During a storm study of Saco Bay, bottom current velocities measured at Higgins Beach and a mooring located just offshore of East Grand Beach reached a maximum of 1.09 m/s across six storm events monitored between January 23 and March 7, 2001 [13]. Many of these hydrodynamic features of Saco Bay have been partially explained by the sheltering of the bay from southerly waves by Biddeford Pool in the south and the presence of the Richmond Island headland in the north acting as a barrier to sediment transport [14]. Much of Saco Bay is very shallow and thus highly sensitive to rises in sea level, in contrast to the steeper shores of Casco Bay.

In this text, Casco Bay is split into northern and southern Casco Bay at the Chebeague Island. As is the case with Saco Bay, the M2 semidiurnal lunar tide is the primary tidal constituent for Casco Bay [14]. The primary freshwater input into the bay is considered as the combined discharge of the Presumpscot and Royal rivers, averaging roughly 40 m³/s [15]. A salinity gradient is also present in the northern Casco Bay due to the input from the Kennebec [16], a river system comprised of the Kennebec and Androscoggin rivers that has been observed to discharge upward of 4000 m³/s of freshwater during the spring.

2.3 Historical storms

Two storm events were chosen for this study. The Blizzard of 1978, herein referred to as the 1978 event, was selected for the peak sea levels recorded at

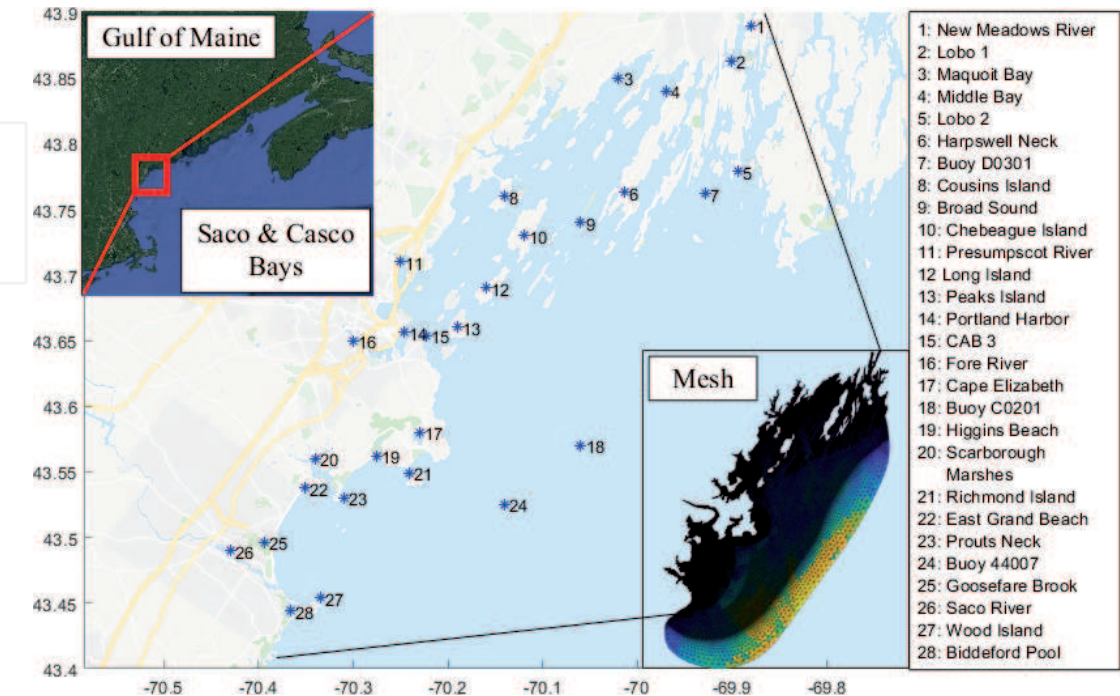


Figure 1. Points of interest in Saco Bay and Casco Bay. In this study, the model domain south of point 17 (Cape Elizabeth) is considered “Saco Bay,” while all points north of 17 are considered to be within “Casco Bay.” The mesh designed for the Saco-Casco model is shown in the bottom right.

Portland Station, identified as a 100-year event. The Patriots Day storm, herein referred to as the 2007 event, was chosen for the peak freshwater discharge that occurred following the storm, offering an opportunity to relate the dynamics of river flooding to SLR.

First identified as an extratropical cyclone on February 5, the 1978 event reached a low pressure of 984 mbar as it retrograded from well off the mid-Atlantic coast to Long Island, moving northward toward the New England coastline [17]. On February 7, northeasterly wind gusts of 83 and 92 mph were reported in Boston and Cape Cod, respectively, along with sustained hurricane force winds [17]. The record surge resulting from the cyclone makes it a focal point for this study, as sea level heights reached their 100-year maximum during this event both in Portland, Maine, and in Boston. Specifically looking at Portland, historical archives report 14.17 ft. (equivalent to 4.32 m) above the MLLW as the peak water level ever recorded [4].

The 2007 event was initially reported on April 15 as a low pressure in the south-eastern United States before it traveled north along the coastline. NOAA records indicate a barometric low of 972 mbar and wind gusts up to 59 mph over Portland [18]. The Portland Harbor tide gauge reported a peak water level of 13.28 ft. during this event [4]. Rainfall totaled 5.6 inches in Portland, Maine. River flooding was severe with near record levels reported for the Presumpscot River. This provides an effective case study of rainfall vs. snowfall effects on bay responses between this storm and the 1978 event, as icing resulted in decreased river flow following the 1978 event, whereas a surge in freshwater discharge resulted from the precipitation during the 2007 event. The National Weather Service (NWS) Storm Events Database (SED) and the National Centers for Environmental Information (NCEI) database also reported that the Patriots Day storm destroyed two homes due to flooding, and significant flooding was reported along with high levels of coastal erosion along the bays' coastlines.

Northeasterly coastal winds associated with the northeaster events were captured by the NECOFS model simulation (**Figure 2**). The storm window of the 2007 event over the Saco and Casco domain was defined as April 16, 01:00, when the upward climb of observed winds at buoy C0201 exceeded the maximum winds prior to the storm, to April 19, 20:00, when winds dropped below the monthly mean winds for April 2007. The NECOFS output wind fields for April 2007 differed

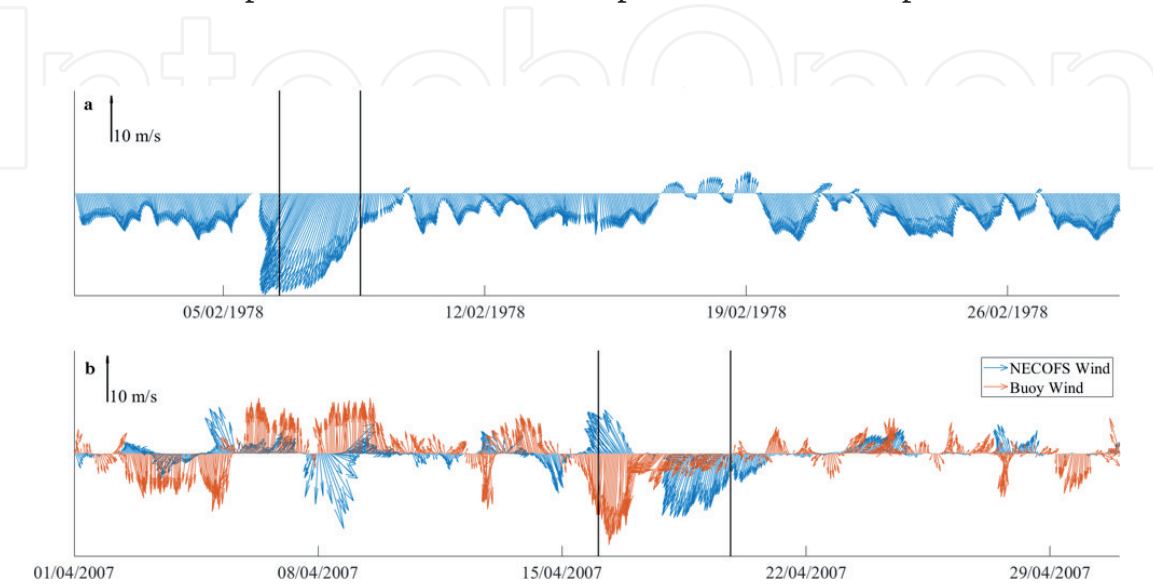


Figure 2. Wind velocities during February 1978 (a) and April 2007 (b) at buoy C0201. Observed winds, available only for the latter period, are shown in red, while NECOFS-predicted winds are shown in blue. Storm windows are indicated by vertical black lines. The black arrow in the top left of each plot indicates velocity scale.

significantly in magnitude and direction from buoy observations. At buoy C0201, NECOFS-modeled storm winds were initially directed in nearly the opposite direction from observed winds, with roughly half the speed. Saco River discharge rates increased rapidly from an estimated minimum of $\sim 60 \text{ m}^3/\text{s}$ to an estimated peak of $\sim 500 \text{ m}^3/\text{s}$ on April 16 at 22:00 and remained high for the remainder of the month due to spring freshet. For the 1978 event, no such observations were available, so its storm window was defined purely from NECOFS wind output as Feb 6, 12:00, to Feb 8, 16:00, when storm winds rose above the maximum February 1978 winds not associated with the storm.

3. The Saco and Casco model

3.1 Model setup

The Saco-Casco model was an implementation of FVCOM that was developed to model complex coastal systems [5]. The finite-volume method takes the advantage of both the finite-element and finite-difference methods. It calculates the transport between elements by evaluating the integral form momentum and mass conservation equations along each element's boundaries [5, 19]. The three-dimensional unstructured grid is specified as the two-dimensional mesh coupled with the terrain-following layers in the sigma coordinate in the vertical. By performing calculations across an unstructured grid, FVCOM allows for high-resolution modeling along complex coastlines that would otherwise be difficult to accurately simulate [5].

The domain defined for the Saco and Casco model covers the coastal waters, including intertidal areas, from Kennebunkport in the south to Sebasco in the north in the Gulf of Maine (see the lower right inset in **Figure 1**). Saco Bay was discretized to the highest resolution of 10 m in areas shallower than 2 meters below the mean sea level, while equivalent depths in Casco Bay were set to 100-m resolution. Resolution in the rest of the domain was determined by depth, expanding to a maximum resolution along the open boundary to match that of NECOFS Gulf of Maine 3 (GOM3) mesh.

The 1/3 arc-second NOAA digital elevation model (DEM) for Portland, Maine [20], was used to specify the bathymetry for Saco Bay and Casco Bay. Through Aquaveo's Surface Modeling Software, the 10-m-resolution DEM was interpolated onto the unstructured triangular mesh developed for this study. Prior to interpolation, the DEM was converted from mean high water (MHW) to MSL to match the rest of the input data for the FVCOM model setup. Additional iterations of the Saco and Casco mesh were developed by integrating LiDAR bathymetry data from the NOAA digital coast system [21]. Specifically, the 2010 USACE NCMP Topobathy and 2014 USACE NAE Topobathy datasets were used, covering the Saco Bay coastline and Scarborough marsh with vertical accuracies of 20 and 10 cm and horizontal accuracies of 75 and 100 cm, respectively.

The Saco, Fore, Presumpscot, and New Meadows rivers were incorporated in the Saco and Casco model mesh. Two USGS gauges in the Saco and Casco domain were used for estimating discharge rates from rivers. Station 01064118 at Westbrook, Maine, for the Presumpscot River provides 15-minute discharge rates and gauge heights recorded from October 2016 and 2007 to present, respectively. Fifteen-minute discharge rates and gauge heights for the Saco River are available from station 01066000 at Cornish, New Hampshire, from October 1989 and 2007 to present, respectively.

Discharge rates for the 2007 event from station 01066000 were applied directly to the model's river forcing for the Saco River. Estimations of freshwater discharge had to be made in all other cases. Regressions were developed between gauge height and discharge rates for stations 01064118 and 01066000 using monthly datasets for February and April in years when both variables were available. Numerous iterations on these relationships were implemented, using a past study on the plume structure of Saco River [22] as a guide to adjust the regression coefficients. The results discussed herein reflect model simulations using the most stable freshwater discharge forcing, with the Saco and Nonesuch rivers using simplified discharge rates of 5.94 and $2.97 \cdot Gh$, respectively, where Gh is the observed gauge height in feet at site 01064118. For the Fore, Presumpscot, and New Meadows rivers, discharge rates were estimated at 2.97 , 1.48 , and $2.97 \cdot Gh$, respectively. Only gauge 01064118 was used for the final 1978 simulations, as the regressions built from gauge 01066000 indicated lower than reasonable estimations. For the 2007 event, Gh for these three rivers was also taken from site 0106600, as site 01064118 has no available data for April 2007 and there was no suitable proxy to capture the freshwater discharge event. As gauge heights for 1978 were unavailable, February 2017 observed gauge heights were used as a proxy, as a northeaster occurred at roughly the same time of the year in 2017 as in 1978.

At the time of writing, estimated hindcast discharge rates have been made available at site 01064118 from October 1975 to present and at site 01066000 from May 1916 to present. In comparing our estimated discharge rates to those presented by USGS, the same trends are depicted. Furthermore, the baseline (0 ft. SLR) model has since been rerun upon release of these datasets, which confirms that no noticeable changes are detected when using the modeled discharge vs. USGS predictions.

The Saco-Casco model was initialized and forced at the open boundary with hourly outputs from NECOFS hindcasts `gom3_197802.nc` and `gom3_200704.nc` (http://www.smast.umassd.edu:8080/thredds/catalog/models/fvcom/NECOFS/Archive/Seaplan_33_Hindcast_v1/catalog.html). The NECOFS, supported by the Northeastern Regional Association of Coastal and Ocean Observing Systems (NERACOOS) to complement the ocean observing system, is an FVCOM-based ocean model covering the domain between Long Island and Nova Scotia [23]. The NECOFS was configured using the third iteration of FVCOM coupled with the SWAN model, using the output from a larger-scale Weather Research and Forecasting (WRF) model for meteorological forcing. Data from the National Data Buoy Center buoys, NOAA C-MAN stations, river discharge statistics, and satellites were collected to support the development and testing of the NECOFS model. The NECOFS hindcasts used a mesh, labeled the GOM3, which has a peak resolution of 0.3–1.0 km in coastal areas, including the full Saco and Casco domain.

3.2 Model validation

In situ observations from multiple sources were used to validate the model. Data from the NOAA-operated tidal stations (<http://tidesandcurrents.noaa.gov/>) were used for the sea surface height and water temperature validation. The University of Maine Physical Oceanography Group initiated the development of the Gulf of Maine Ocean Observing System (GoMOOS) in 2001 [24]. The moored buoys designed for this project were equipped with sensors specific to their installation site in addition to a standard set of instruments allowing for the collection and archive of wind speed and direction, visibility, air temperature, wave parameters, water temperature, and conductivity at 1-m depths and current velocity at 2-m depths [25]. For the Saco and Casco modeling project, data were collected from

the University of Maine Mooring C0201, Maine EPSCoR Mooring D0301 as well as Lobo 1 and Lobo 2 (<http://umaine.edu/epscor/seanet/>), and NOAA National Data Buoy Center Buoy 44007 (<http://www.ndbc.noaa.gov>) (see **Figure 1**). These datasets were used for the validation of additional test runs performed over the deployment periods of the buoys.

Time series validation of selected model output variables was performed. Only one station 8418150 (Portland, Maine) existed within the Saco and Casco domain with water level data for these two historic events. Tidal analyses were conducted using the “UTide” Matlab package to assess the model’s ability at capturing tides and tidal residuals. **Figure 3a** and **d** compares the modeled SSH with the observations at the Portland station. **Figure 3b** and **e** compares the reconstructed tidal signals with UTide, which were removed from the raw signals to calculate the residuals (**Figure 3c** and **f**). After correcting for a constant negative bias of 2 feet detected between buoy records and NECOFS output, the modeled water level was able to capture the observed storm surge for the February 1978 event. However, the storm water level was lower than the observation in the first half of the storm window for the 2007 event. This was likely caused by the weaker predicted storm in the first half of the storm window wind seen in **Figure 2b**.

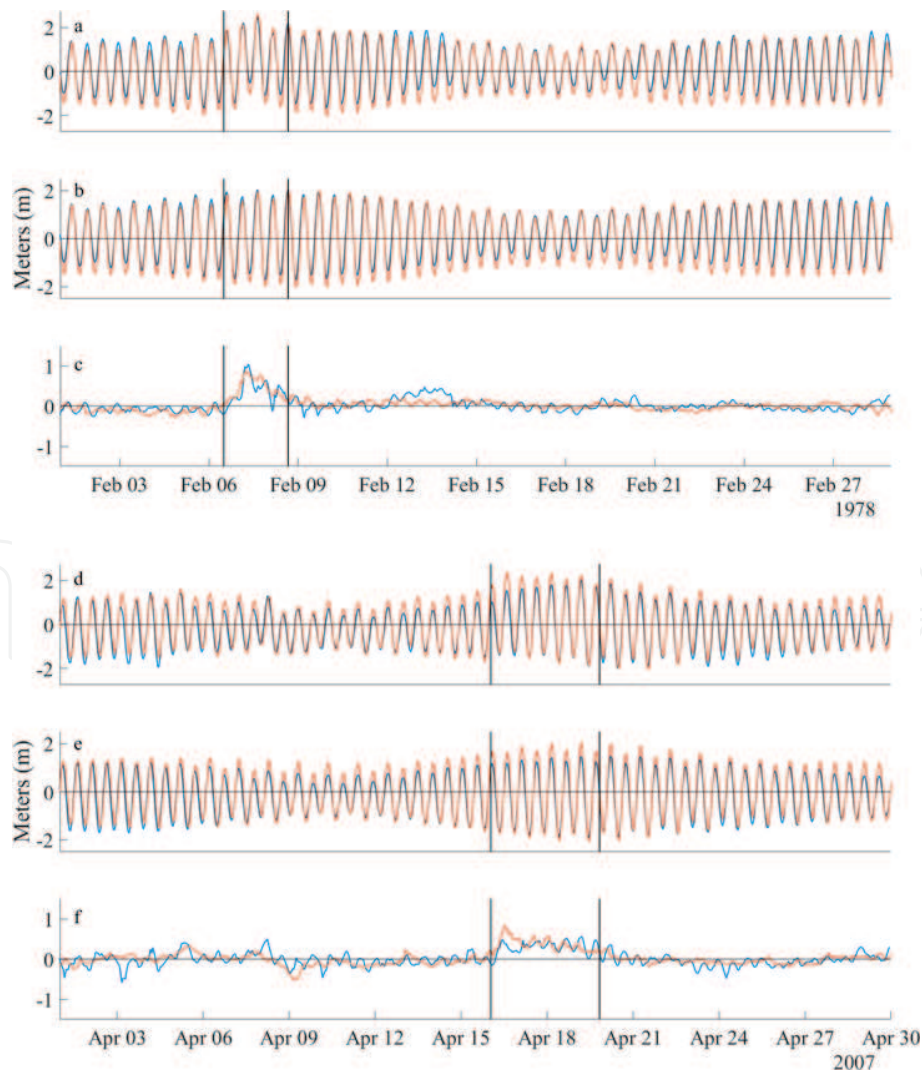


Figure 3. Comparison of the water level for the baseline simulation of the 1978 event (a–c) and the 2007 event (d–f) for the raw signals (a and d), tidal harmonics (b and e), and tidal residuals (c and f). Tidal constituents used in UTide include M2, N2, S2, K1, O1, NU2, and T2. Storm windows are indicated by vertical black lines.

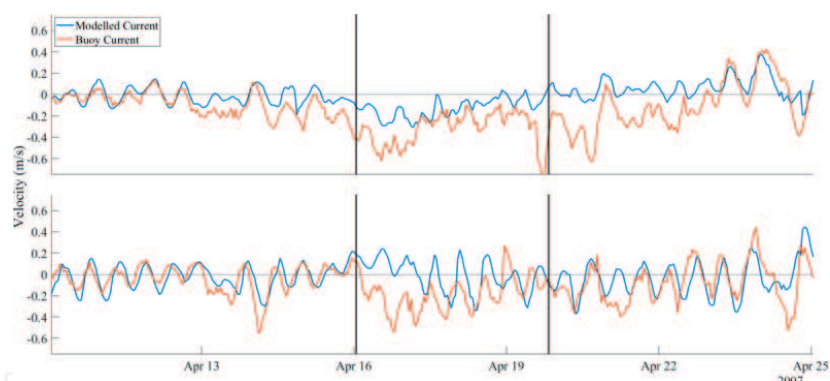


Figure 4. Comparisons of near-surface currents observed at buoy C0201 and modeled current for the April 2007 event. Negative velocities indicate westward (top) or southward (bottom) currents. The storm window is indicated by vertical black lines.

Furthermore, current data was available at buoy C0201 for the 2007 event (**Figure 4**). The increase in westward velocity was revealed by the model, but at about half of the magnitude. The southward tendency was completely missed in the first half of the storm window again due to the errors in NECOFS-predicted wind direction. Discrepancies in modeled current output were examined by modifying the wind forcing. When the model run was repeated using the buoy-observed wind (red vectors in **Figure 2** and spatially uniform), the southward velocity in the first half of the storm window was improved, but the simulated currents deteriorated before and after the storm (not shown). Therefore, in this study we still used the simulations with NECOFS-predicted winds for the consistency between the surface and lateral boundary conditions because the open boundary condition adopted from the NECOFS was produced with the same set of meteorological forcing. As such, the 2007 event cannot be confidently referred to as a “storm scenario” with regards to modeled currents. However, the high discharge rates and availability of discharge data allowed us to utilize the April 2007 model runs as SLR simulations of a freshwater discharge event.

4. Bay response to northeasters

Responses in this study were defined as deviations from the typical circulation patterns seen during non-storm conditions. A storm window (see Section 2.3 above) was chosen for each storm event wherein anomalies were detected and collected for further analysis.

4.1 Casco Bay

Following the path of the storm winds, we first examine the surface currents entering the model domain from the northeast corner of the model’s open boundary. **Figure 5** depicts frames of surface currents during flood and ebb tides prior to and within the 1978 event’s storm window. From this figure, we can see typical flooding and ebbing currents as strong flows in and out of the bay through the Broad Sound and the passage between the Peaks Island and Long Island. Outflow from the New Meadows River is visible in the upper reach of the estuary during ebb tides. As storm winds reached their peak magnitude, the surface current velocities in New Meadows River, measured at the sites of Lobo 1 and Lobo 2, increased sharply in the southward direction during ebb tides, increasing the reach of the New Meadows river plume into Casco Bay. The most apparent change was the

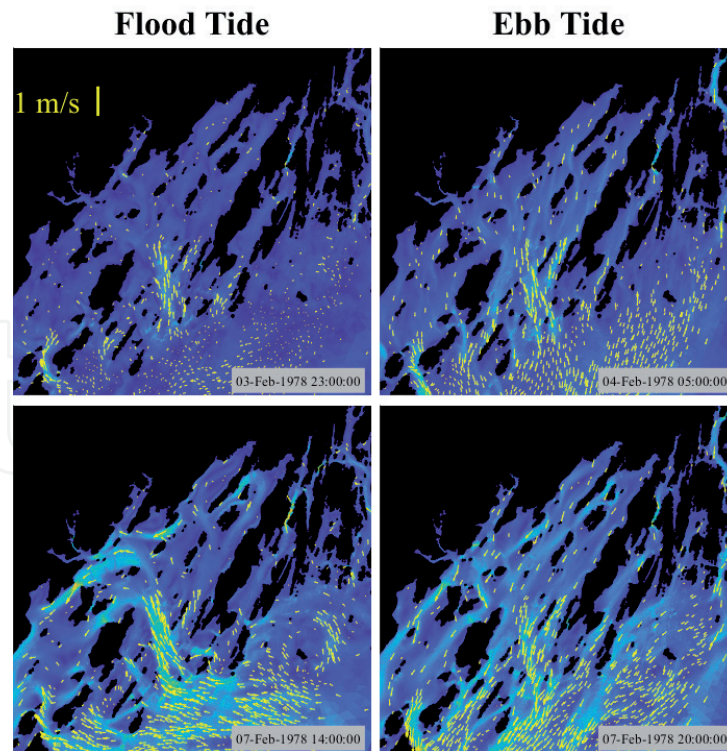


Figure 5. Frames of modeled surface currents in northern Casco Bay for the 1978 event before (top) and during (bottom) the storm window during flood (left) and ebb (right) tides. The yellow arrow in the top left panel indicates velocity scale.

increased northward surface current during flood tides within the storm window, which flowed into the Broad Sound along the east coast of Chebeague Island, circulating counterclockwise around Cousins Island.

Continuing southward (**Figure 6**), the flood tide entered southern Casco Bay mostly through the passage between Long Island and Peaks Island, which circulated counterclockwise to enter Portland Harbor and keep the Fore River plume inside the estuary. During ebb, the Presumpscot River and Fore River plumes joined the outgoing tidal flows to form a strong southward current extending from Portland Harbor to south of Cape Elizabeth. Southward ebbing tidal currents were also strong in the passage between Long Island and Peaks Island. Albeit the flows were strengthened, the general patterns remained during the 1978 events except that the Presumpscot plume was more restricted during flood by the impeding tidal plus storm currents.

Briefly comparing the northern and southern halves of Casco Bay, the more open segment in the north, including Broad Sound and Maquoit Bay and Middle Bay, was less susceptible to storm forcing. The southern Casco Bay showed more noticeable storm responses in Portland Harbor, where the Presumpscot River and Fore River plumes were altered significantly by storm winds.

4.2 Saco Bay

Surface currents increased sharply as they continued south of Casco Bay, colliding with the northern coastline of Cape Elizabeth (**Figure 7**). The increase in current velocity was most evident during ebb tides when storm currents and tidal currents aligned but was also visible during flood tides, overpowering the typical tidal currents. Water carried by the southwestward storm currents was directed clockwise around Cape Elizabeth to split to the north and south of Richmond Island. Even though only a small percentage of the water passed to the north of

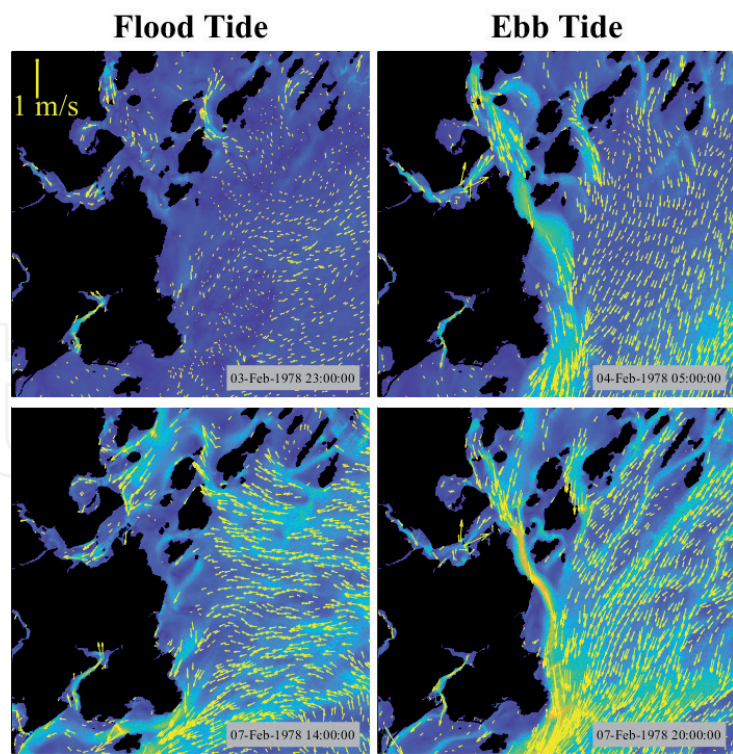


Figure 6.
Similar to Figure 5 but for southern Casco Bay.

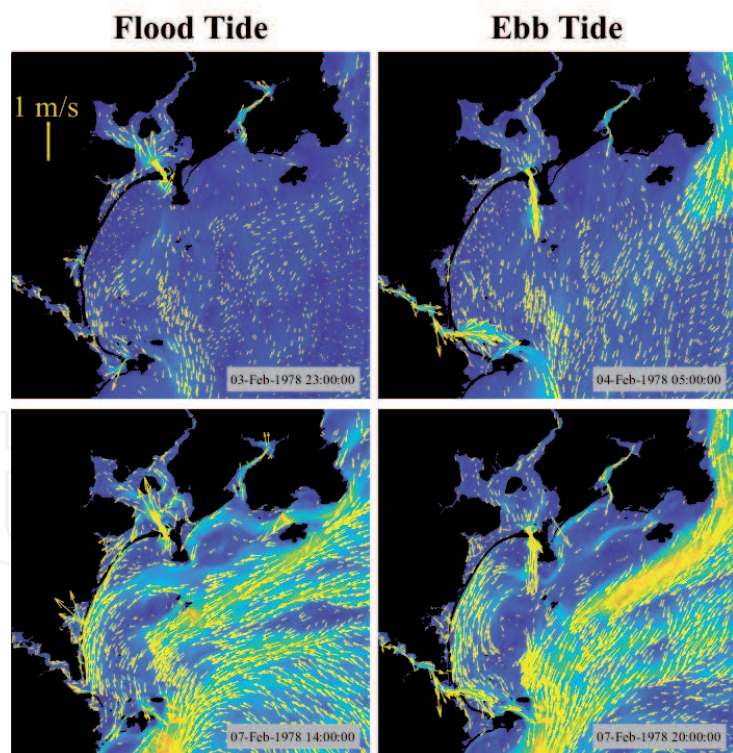


Figure 7.
Similar to Figure 5 but for Saco Bay.

Richmond Island, it was enough to cause a reversal in current velocities there compared to the prestorm flood and ebb tides.

Moving on to Saco Bay itself, under calm conditions, currents formed a clockwise circulation with slow northward flows nearshore and southward flows near the opening. Under storm conditions, circulation in Saco Bay was comprised of a complex relationship between storm winds, tidal currents, and freshwater plume

dynamics. During flood tides, storm currents turning around Cape Elizabeth surged into the bay, generating a persistent southward flow along the Saco Bay shoreline. This southward flow exited the bay primarily through flooded areas in Biddeford Pool, with some merging back with the open-water southward storm currents via a small channel between Biddeford Pool and Wood Island. During ebb tides, the same southward coastal flow was present, but tidal currents increased the velocity of the Saco River and Nonesuch River plumes, which acted as partial barriers against the storm currents from Cape Elizabeth. As flooding in Biddeford Pool decreased, storm currents exiting the bay increased in the channel between Biddeford Pool and Wood Island.

4.3 Comparison of bay responses

It is important to note the diversity of storm responses along the shoreline of the Saco and Casco Bays. Saco Bay was greatly impacted by storm currents extending from the open boundary, resulting in a far more sensitive system. Surface currents during flood tides were heavily dominated by storm currents to result in a reversed flow nearshore, while during ebb tide discharges from the Saco River and Nonesuch River were strong enough to fend off part of the storm currents from the northeast. In contrast, Casco Bay remained largely controlled by normal tidal signals and river discharge rates, except for Portland Harbor, which saw more dramatic responses to storm-induced alterations to the Presumpscot River and Fore River plumes. In northern Casco Bay, the New Meadows estuary experienced minor increases in mixing and a slightly extended reach of the river plume, reducing the incoming reach of tides during peak storm winds. As for deeper waters in each bay, results were as expected; Casco Bay's barrier islands protected it from most open-water storm currents, allowing for tidal currents to remain dominant. In the following section, it will be shown how sensitivity of the bays to these storm currents played a significant role in determining the effects of SLR experienced by each bay.

5. Bay responses to sea level rise

The 1978 and 2007 events were simulated repeatedly under varying sea level rise scenarios. In each run, the open boundary and initial sea surface heights were increased in 1-foot increments from the baseline scenario to a 7-foot scenario to emulate potential water levels. Utilizing the wetting and drying module of FVCOM, mesh cells in Saco Bay and Casco Bay were classified as either "dry," "intertidal," or "wet." The former (latter) were defined as cells in the mesh, which never became wet (dry) throughout the model's runtime. Intertidal areas were cells that alternated between wet and dry.

5.1 Impact of SLR on bay structure

To quantify the impact modeled SLR had on the storm responses, a baseline understanding of how SLR impacted the shapes of Saco Bay and Casco Bay had to be established. As such, inundation maps were generated for the both storm cases under each SLR scenario, where "inundation zone" refers to the subset of the intertidal zone where bathymetric data indicated that the cell had a digital ground relief value above the MHW. **Figure 8** depicts such inundation zone coverage under the baseline (0 ft) and 7-ft. SLR scenarios.

Saco Bay was particularly vulnerable to flooding in response to SLR, specifically in the Scarborough marshes and around the mouth of Saco River. Every beach along

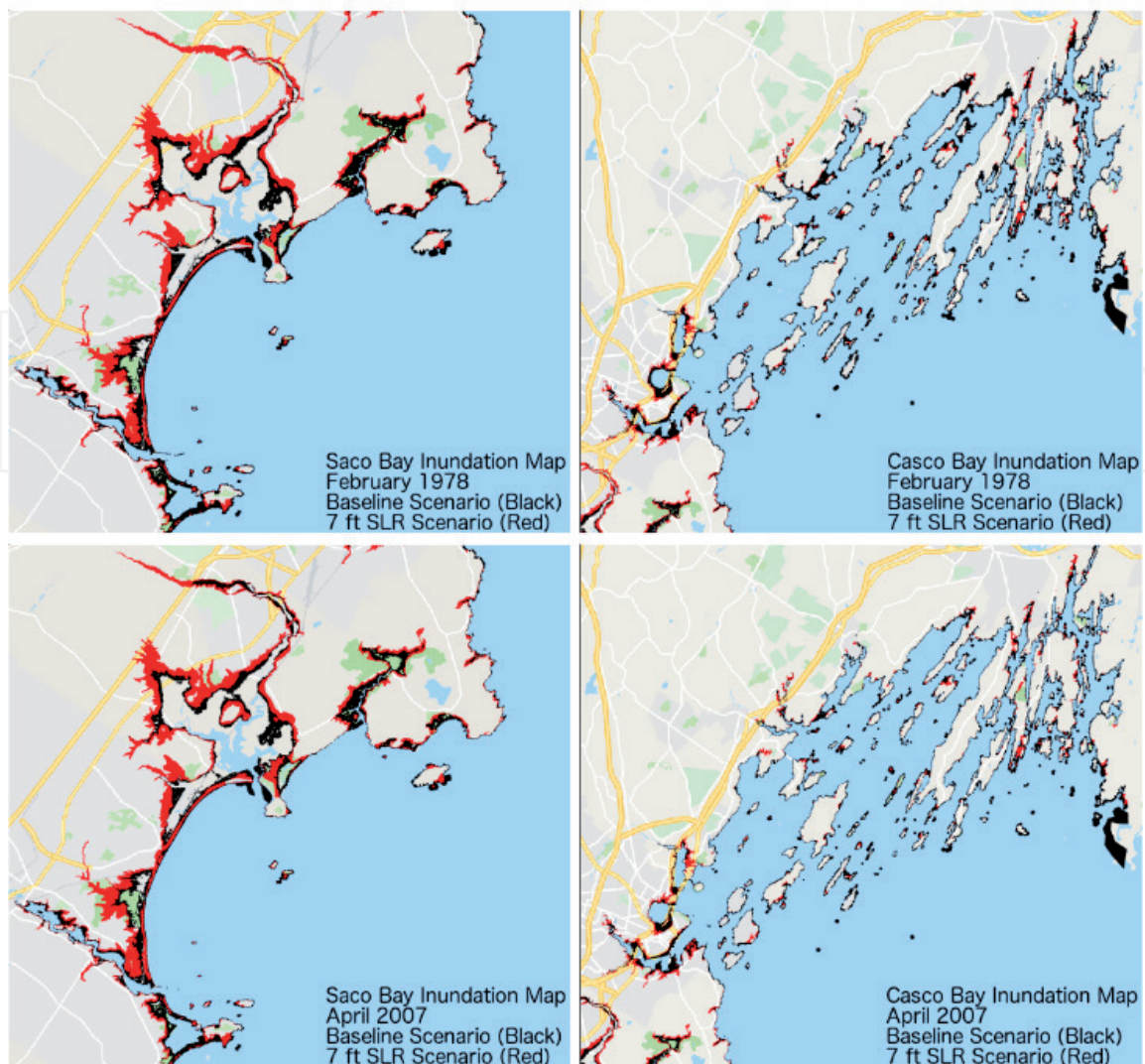


Figure 8.
Inundation maps for the Saco Bay and Casco Bay. Baseline scenario flooding (black) is overlaid by flooding measured in the modeled 7-ft. SLR scenario (red). Inundation cells were identified as the modeled intertidal zone above 0 m MHW.

the bay was completely flooded by 7 ft. of SLR in both storm events, along with the marshes and communities around Goosefare Brook. In contrast, Casco Bay saw less change in inundation zone coverage (relative to the size of the bay) between the baseline and 7-ft. SLR scenarios, primarily isolated to the localized flooding around Portland, where storm-induced flooding spread most noticeably around the mouths of the Fore River and Presumpscot River. The trends of inundation zone expansion can be seen in **Figure 9**, along with the trends of each cell type (dry, wet, and intertidal) against SLR.

It was expected that the inland expansion of the intertidal zone during the 2007 event would mirror that of the 1978 event with a 1-foot “lag” in SLR scenario, as the peak sea level during the 2007 event was roughly 1 foot lower than that of the 1978 event. This lag is clearly visible in the inundation and dry cell trends in both Saco Bay and Casco Bay. Looking closer at the inundation and dry cells, both bays saw a net increase of roughly 20 km² in inundation zone coverage from the baseline scenario to the 7-ft. SLR scenario, reflecting an identical drop in dry cell coverage. This 20-km² change corresponded to an 18.2% reduction in Casco Bay’s dry cell coverage versus a 57.1% reduction in Saco Bay’s dry cell coverage. Furthermore, these reductions were not the result of continuously linear trends.

Casco Bay saw a linear drop in dry cell coverage from the baseline to 4-ft. SLR scenario for the 1978 event (baseline to 5-ft. SLR for the 2007 event), before

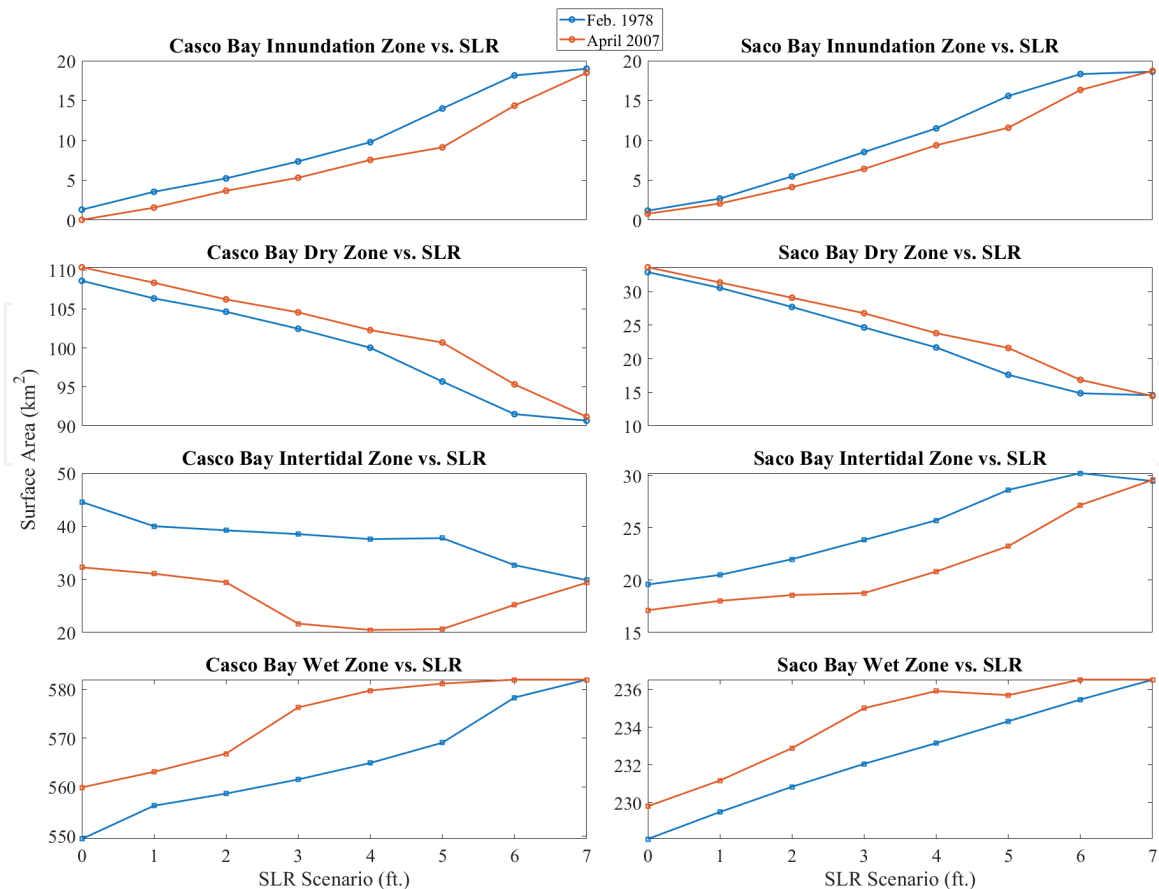


Figure 9.

Cell-state distribution from the FVCOM wetting/drying module vs. SLR during the 1978 and 2007 events in Saco Bay and Casco Bay. Mesh limits were reached in the 7-ft. SLR scenario, causing the zonal distributions in both events to converge.

dropping at a significantly higher rate until the mesh limitations were reached in the 6-ft. SLR scenario (7-ft. SLR for the 2007 event). This “drop off” point was a result of the peak sea level exceeding roughly 13 ft. above MSL, at which point many of the steep coastal slopes in Casco Bay, mainly around Portland Harbor, were overcome, yielding significantly increased flooding. In contrast, Saco Bay’s inundation increased at a slightly exponential rate before slowing down following the 4-ft. SLR scenario (5-ft. SLR scenario for the 2007 event).

The intertidal and wet cells of each bay saw far more complex changes in response to SLR. In Casco Bay, there was a significant difference in behavior of the intertidal zone during the 1978 event when compared to the 2007 event. In the 1978 event, after an initial drop of ~5 km², the intertidal zone in Casco Bay saw very little change in size until the 5-ft. SLR scenario, at which point the intertidal zone decreased in size by roughly 5 km² per 1 ft. of SLR. These drops in intertidal zone coverage were reflected by spikes in wet cell coverage in the 1-ft. SLR and 6-ft. SLR scenarios, resulting from low tides rising above 7.25 and 12.25 ft. above MSL, respectively. For the 2007 event, the wet zone expanded greatly between 2- and 3-ft. SLR, which was accompanied by a sharp decrease in the intertidal zone. The intertidal areas stayed mostly the same between 3- and 5-ft. SLR despite the slight increase of wet zone, which was compensated by the decrease of dry zone. However, between 5- and 7-ft. SLR, the intertidal area expanded largely at the expense of contracting dry zone.

This complex relationship can be better visualized in **Figure 10**. As Casco Bay’s coastal slopes are largely characterized by short steps formed by tall shelves, the lower tidal ranges of the 2007 event resulted in low tides being constrained by these

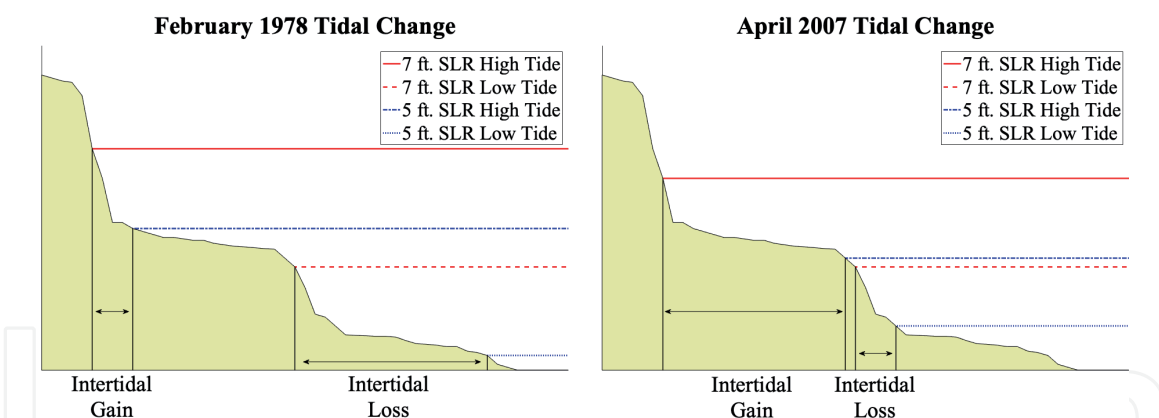


Figure 10.
 Sketch of intertidal zones of Casco Bay under the 5- and 7-ft. SLR scenarios. Due to larger tidal ranges in the 1978 event, there was a net loss in intertidal zone coverage, in contrast to a net gain between these scenarios for the 2007 event.

stairs, limiting the change in wet cell coverage across SLR scenarios. In simulations of the 2007 event, the change in wet cell coverage plateaued after the 3-ft. SLR scenario, while dry cell coverage decreased steeply following the 5-ft. SLR scenario, yielding an overall increase in intertidal zone coverage between the 5- and 7-ft. SLR scenarios. In contrast, simulations of the 1978 event yielded far lower low tides, allowing wet cell coverage to increase following the 5-ft. SLR scenario, resulting in a decrease in intertidal zone coverage.

In Saco Bay, wet cell coverage simply increased linearly alongside SLR for the 1978 event, and the intertidal zone also expanded allowed by the much faster rate of decrease of the dry cell coverage. However, the behavior of the wet cell coverage was more dynamic during the 2007 event, largely explained by the relationship between freshwater discharge and sea level around the Scarborough marshes and Nonesuch River. Referring quickly back to the inundation maps (**Figure 8**), one key distinction between the 1978 and 2007 events was that even though the 2007 had lower peak sea level at Portland, the baseline scenario flooding around the Nonesuch River was higher during the 2007 event than that of the 1978 event, suggesting a positive relationship between discharge from the Nonesuch River and localized flooding along the river's edge. Another anomalous behavior occurred after the 4-ft. SLR scenario, where wet cell coverage in the 2007 event slightly decreased by $\sim 1 \text{ km}^2$, contrary to any expected results. This small drop occurred in the Nonesuch River and is likely attributed to a decrease in minimum sea level in the Nonesuch River following an expansion of the channel between Prouts Neck and East Grand Beach during high tides. To explain further, to stabilize the FVCOM model, a limit of 1.5 m/s had to be placed on currents flowing along this channel, which resulted in elevated sea levels during low tide in the Scarborough marshes and Nonesuch River, as the water was unable to empty out from the marsh during ebb. Once the channel was widened following the 4-ft. SLR scenario, the total volume of water carried under the limited currents was increased enough to lower minimum local water level during low tide. The complexity of the relationship between SLR, estuarine dynamics, and intertidal zone structure highlighted by these results further underscores the limitations of generalized predictions on the effects of SLR on a coastline.

5.2 Impact of SLR on bay circulation

Given the dynamic changes SLR yielded on the structure of the two bays, it was reasonable to expect consequential changes in nearshore circulation. Looking first at the storm currents themselves, **Figure 11** depicts the rate of change of vertically

averaged mean current speed at points of interest for each storm across SLR scenarios. Temporal means of currents at all 24 sigma layers were taken within the storm windows and then averaged to produce the values reflected in these plots. Negligible changes to storm currents were witnessed in northern Casco Bay with the exception of a slight increase in slow storm currents at Buoy D0301 during the 2007 event (**Figure 11d**), so the other five chosen points of interest reflect impacts of SLR on storm currents affecting the four freshwater plumes in southern Casco Bay and Saco Bay.

Starting in Portland Harbor (**Figure 11a**), storm currents consistently increased alongside SLR in both storm events, albeit at different rates. The CAB 3 site was chosen to observe trends in both the Presumpscot River and Fore River plumes, as the southward flux of freshwater into the bay from Portland Harbor was located in this channel (**Figure 6**). The 1978 event, while yielding far less freshwater discharge than the 2007 event, saw greater southward storm currents at the CAB 3 site throughout the storm window due to extreme wind speeds. These currents initially decreased in response to the localized increase in flooding around Portland Harbor from the baseline to the 1-ft. SLR scenario, as was discussed earlier (**Figure 9**). Following this drop, as Casco Bay's coastline resisted additional flooding, storm currents began to increase with the higher volumes of water directed through this channel in higher SLR scenarios, though this effect was nonlinear and plateaued quickly. The storm currents at the CAB 3 site in the 2007 event saw a smaller, more linear rise alongside SLR, as storm currents were largely dominated by high discharge rates which remained constant in the SLR simulations.

Moving southward, the storm currents turning around Cape Elizabeth saw a proportionate rise in velocity across SLR (**Figure 11b**), pulling greater volumes of freshwater out of Portland Harbor. This increase in current speed was mostly linear and consistent from the 1- to 7-ft. SLR scenarios for the 1978 event, matching the linear rise from the 3- and 7-ft. scenarios in the April 2007 event. Further offshore to the southeast of Cape Elizabeth at the site of buoy 44007 (**Figure 11c**), the 1978 storm currents saw a more complex response to SLR, while the 2007 event saw no changes at all. The minor (<0.01 m/s) change in current speed from 0- to 4-ft. of SLR in the 1978 event was identified as a small response to the sudden drop in current speed from Portland Harbor following the initial flooding in southern Casco Bay. The increase in storm currents at site 44007 from 4- to 6-ft. of SLR resulted from an increase in southward currents between the barrier islands throughout Casco Bay. This rise was followed by a plateau effect as these islands began to flood, decreasing the effect of SLR on currents within the channels. Following the storm currents into Saco Bay, SLR had a much stronger effect on the dynamics of the Saco River (**Figure 11e**) and the Nonesuch/Scarborough River (**Figure 11f**).

Saco River behaved as expected as SLR increased. The sides of the river flooded rapidly as sea levels rose, resulting in drops in the current speed exiting the mouth of the river. Interestingly, during the low-discharge 1978 event, this drop was largely linear following a small initial spike of 0.01 cm/s, while the 2007 event saw an exponential decay in storm currents as SLR increased, suggesting a nonlinear relationship between river discharge and SLR as factors influencing estuarine storm currents. Nonesuch river, which is renamed to Scarborough River as it enters the Scarborough marshes along the western shore of Prouts Neck (see **Figure 1**), saw the most dynamic changes in response to SLR.

Prouts neck and the beaches around the mouth of the Scarborough River proved to be the most resilient land to flooding in Saco Bay, resulting in few changes to the structure of the river until SLR increased from 3 to 4 ft. for the 1978 event (4 to 5 ft. for the 2007 event). Because of this delayed response, water built up in the Scarborough marshes as SLR increased, negating any potential expected drop in

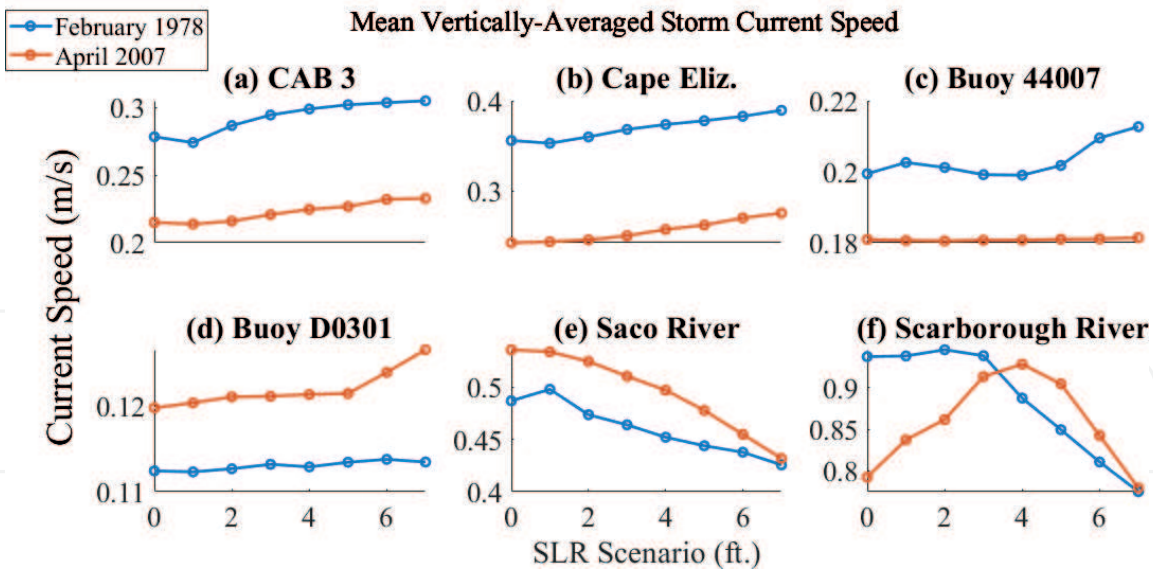


Figure 11. Vertically averaged mean current speed vs. SLR within the storm windows at selected sites (see **Figure 1** for locations) for the 1978 and 2007 events. Temporal averages throughout either storm window reflect the impact of SLR on storm-induced plume dynamics.

current speeds in the 1978 event and resulting in an increase in current speeds aligning with heightened discharge in the 2007 event. Once these shores started to flood, current speed decreased rapidly with SLR, as the constriction point for discharge from the Nonesuch River widened greatly. To fully explain how these differences in storm current response to SLR impacted circulation in the bays, one must look at the resultant changes to plume dynamics following either storm.

Figure 12 was created to show the change in minimum surface salinity (ΔS) between the baseline and 7-ft. SLR scenarios. By plotting minimum surface salinities, we were able to analyze the maximum reach of each river plume and how that reach was affected by SLR. In Casco Bay, the increase in mean storm currents exiting the Fore River and Presumpscot River resulted in further extensions of the combined Fore River and Presumpscot River plumes northeastward toward Broad Sound and southward around Cape Elizabeth for the 1978 event in the 7-ft. SLR simulation. For the 2007 event, flux out of these two rivers due to river discharge decreased dramatically with SLR, as the widened rivers allowed storm currents to dominate freshwater discharge. The end result was a net increase in salinities throughout the Portland Harbor area, as the offshore water was mixed higher up the rivers by storm winds under heightened SLR scenarios.

Saco Bay saw even greater variations in minimum salinity in response to SLR between the two storms, attributable mostly to the icing vs. flooding states of the Saco River and Nonesuch River. For the 1978 event, the inundation zones present in higher SLR scenarios were comprised primarily of offshore high-salinity waters, resulting in a net increase in salinity for the floodwater across the beaches of Saco Bay and large parts of Scarborough marshes except in the Nonesuch River plume. The resiliency of the modeled Nonesuch River was largely influenced in these simulations by mesh limitations; due to an instability issue with FVCOM, the mesh boundaries had to be restricted to 2 m above MSL around this river. Because of this limitation, the model likely underpredicted the full-range up-river mixing of higher-salinity waters into the Nonesuch River.

The stronger river discharge estimated for the April 2007 event resulted in plume water around Prouts Neck, more so in the higher SLR scenarios, as flooding allowed plume waters to flow southward to the eastern shore of Prouts Neck. Interestingly, despite the freshwater discharge from the Saco River being higher in

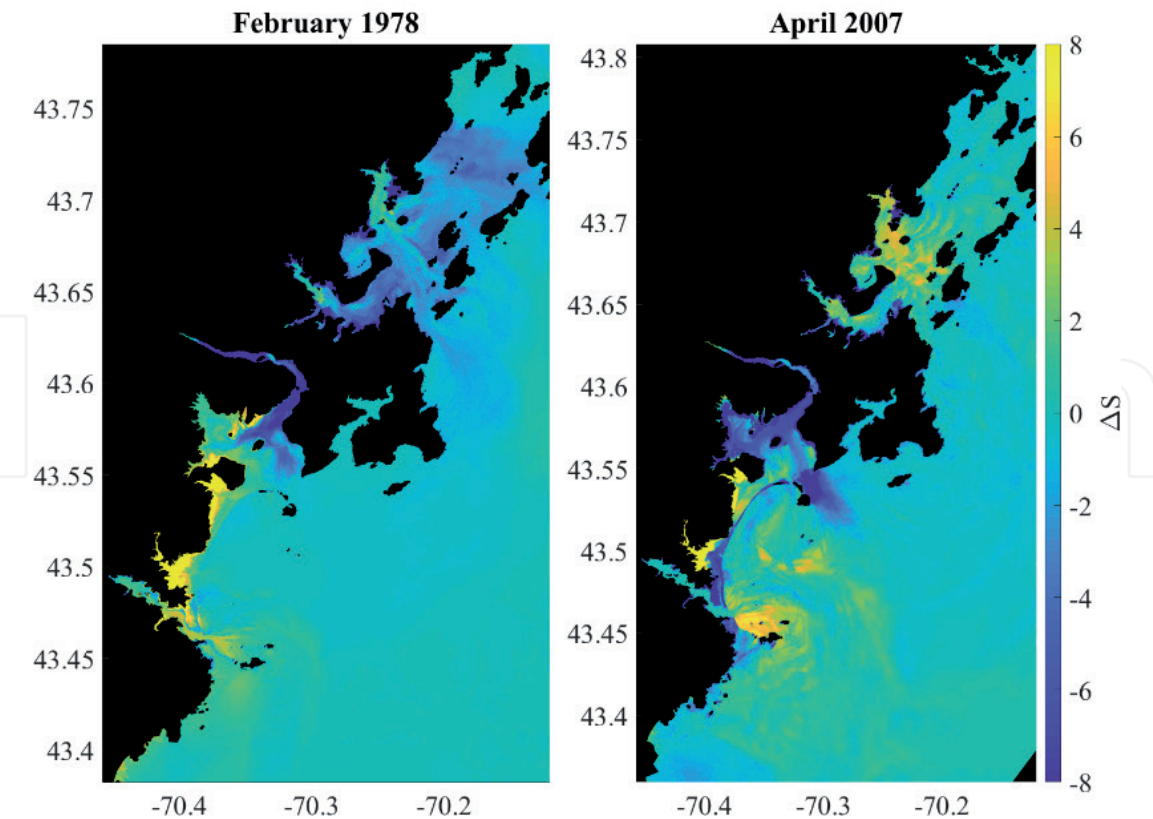


Figure 12.
Map of changes in minimum salinity in response to SLR during the storm windows for the 1978 and 2007 events. Darker colors indicate a decrease in minimum salinity, implying a greater concentration of freshwater with the 7-ft. SLR than the baseline simulation.

the 2007 event than in the 1978 event, the waters just north of Biddeford Pool and around Wood Island saw a large increase in minimum salinity as SLR increased. The reason for this change was the increased SLR resulted in a more northward shift of the Saco River plume that flooded around the mouth of Saco River and the beaches to the north, while the eastward current velocities directed toward Wood Island and Biddeford Pool decreased (**Figure 11e**), hence the higher minimum salinity for the 2007 event at 7-ft. SLR.

6. Conclusions

This study aimed at evaluating the impact SLR would have on responses to major storm events in Saco Bay and Casco Bay in the western Gulf of Maine. A hydrodynamic model was developed to simulate the Blizzard of 1978 and the Patriots Day storm in 2007 under varying SLR scenarios to identify and track modeled storm responses. Inundation maps generated from the model results indicated a nonlinear relationship between SLR and inundation zone coverages, as the diverse slopes of the shoreline played the dominant role in determining the rate of change in inundation. Additionally, shifting circulation patterns and morphing of intertidal zones in response to SLR caused changes where river plumes were directed.

The modeled storm responses in Saco Bay and Casco Bay were primarily influenced by freshwater discharge, storm winds, and coastal structure. The percentage of inundated area changed significantly in Saco Bay under increased SLR scenarios and to a lesser degree in Casco Bay. While total inundated surface area increased in response to increased SLR, the results presented in this model study show that inundation maps generated simply from bathymetry alone do not fully capture the complexities of how SLR will impact the structure of a coastline, since they are

unable to reflect changes in circulation due to such factors as freshwater discharge. Consequently, the relationship between SLR and storm responses adopts the complex interactions between freshwater forcing, wind-induced circulation, and coastal morphology, as the dynamic structural changes experienced by the bays impact the severity of storm responses in a major way.

Many of the past studies reviewed in this paper utilized point-sourced tidal data to generalize the impact of SLR over large areas, but the results of the Saco and Casco model study suggest that there is too much variability in coastal responses to SLR to make such generalizations. Through this study, we have shown how generalizations regarding SLR miss out on the small-scale alterations in coastal structure visible in higher-resolution hydrodynamic modeling. By applying high-resolution 3D modeling techniques to this storm response study, we were able to analyze how morphological changes to a coastline induced by SLR have a direct impact on shallow water circulation and river plumes. In turn, the interactions between river plumes and storm winds were altered, producing dynamic changes in the pattern and magnitude of storm currents.

In effect, this study serves to illustrate that to properly forecast how any estuary will respond to storms under projected sea levels, it will be necessary to incorporate more complex, high-resolution, 3D hydrodynamic models than have been applied in the past. Future studies would also need to simulate more complex shallow water dynamics, such as proper wave propagation along the shoreline, to fully analyze how flood zones would change in response to SLR-induced changes in circulation patterns.

Acknowledgements

This study was supported by the National Science Foundation Award #IIA-1355457 to Maine EPSCoR at the University of Maine, Orono, and NOAA grants NA16NOS4730013 and NA13OAR4830233 to the University of Maine. Computations were done using the clusters of the Advanced Computing Group at the University of Maine.

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