A Tale of Two Bays: the Development and Applications of the Saco and Casco Modeling Project

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A TALE OF TWO BAYS: THE DEVELOPMENT AND APPLICATIONS OF
THE SACO AND CASCO MODELING PROJECT

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This thesis details the development and application of a finite-volume, hydrodynamic model of Saco and Casco Bays. The primary study conducted herein focused on coupling storm simulations with sea level rise (SLR) to identify vulnerabilities of the two bays. The February 1978 Northeaster and an April freshwater discharge event in 2007 following the Patriot’s Day Storm were modeled by utilizing the Finite-Volume Coastal Ocean Model (FVCOM). 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 step-like bottom relief at the shoreline of Casco Bay set 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. Following the storm response study, variants of the Saco and Casco model were developed to support interdisciplinary research involving biological modeling, policy making, and other resiliency studies. This thesis details the processes involved in producing a modular model design flexible enough to be utilized across a diverse research effort.
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CHAPTER 1
INTRODUCTION

A concerted effort is being made to approach the field of oceanography from an interdisciplinary perspective. Due to the complexity of the connections between physical and biogeochemical attributes of, and anthropogenic factors influencing hydrographic environments, a number of modeling efforts have been initiated to better understand our coastal systems. The present thesis covers the development and application of one such model – a three-dimensional, hydrodynamic model of Saco and Casco Bays in the Gulf of Maine. These two bays have been the focus of many studies over the past few decades due to Saco Bay’s history of erosion and beach recession, and the many industries reliant on Casco Bay for economic stability. Further details regarding these two bays have been provided in Chapter 2.

The model foundation chosen to produce the simulations was built upon the Finite Volume Coastal Ocean Model (FVCOM). We chose this framework due to its ability to simulate three-dimensional dynamics at very high temporal and spatial resolutions, allowing us to analyze small-scale features that are not captured by traditional approaches such as satellite image analysis and two-dimensional surface modeling. Chapter 3 of this thesis details the data that was compiled to develop this model, and the configuration, preparation, and calibration of the model are discussed in Chapter 4.

The storm response study presented in Chapter 5 was proposed in response to resiliency efforts being made to protect the coastline of Maine from storm surge and climate change. Specifically, we chose to investigate the relationships between northeasters and sea level rise using the unique morphologies of the Saco and Casco Bays as contrasting environments in the experimental process. Saco Bay’s open structure and shallow coastal slopes offered an environment that was highly vulnerable to heightened sea levels and external changes in circulation such as offshore storm currents. Casco Bay, due to numerous barrier islands and steeper coastal slopes, presented a far more resilient domain.
While highly different from one another, the two bays are located next to each other along a shared coastline, allowing for the simulation of unique but interrelated dynamics.

Given the differences between the two bays, we expected them to respond differently to the northeasters common in the Gulf of Maine. As such, we chose two historic storms, the Blizzard of 1978 and the Patriot’s Day Storm in 2007, to serve as extreme scenarios with the 1978 event’s record sea levels and the 2007 event’s abnormally high spike in freshwater discharge. These two storms were modeled first to identify individual storm responses, such as alterations to circulation patterns and plume dynamics, then again under sea level rise (SLR) scenarios, increasing in 1 ft increments up to 7 ft of SLR. We hypothesized that heightened sea levels would result in changes to storm responses, forming the root questions as to how and why these interactions between storm responses and SLR occur.

The Saco and Casco model was further developed to provide data for several ongoing studies. While we were analyzing the results from the storm response model runs, we also simulated the full year of 2014 with hourly output. This allowed us to calibrate and stabilize the model, producing meaningful results from which we were able to analyze seasonal trends in the dynamics of the two bays. Following this simulation, we developed a variant of the model to simulate Casco Bay alone. With the limited domain, we were able to complete model runs roughly an order of magnitude faster than with the full Saco and Casco model. Chapter 6 discusses the initial results and calibration metrics gathered from multiple years of simulations produced with the Casco-only model. Furthermore, the Sustainable Ecological Aquaculture Network (SEANET) at the University of Maine, Orono applied data from the Saco and Casco models to multiple projects summarized in Chapter 7. These projects required modifications to the model to accommodate their individual needs, exemplifying the flexibility and usefulness of these modular designs.

As a whole, this thesis is offered to provide insight into the unique dynamics of the Saco and Casco Bays and to illustrate the value in the robust, three-dimensional modeling of shallow water
environments. Chapter 8 provides a summary of the findings across our applications of the Saco and Casco model, along with a retrospective assessment of the model’s capabilities.
CHAPTER 2

SACO AND CASCO BAYS

Though situated next to each other, Saco Bay and Casco Bay differ significantly in terms of geography. Figure 1 depicts points of interest throughout Saco Bay (Figure 1, top) as well as the portion of the triangular mesh built for the model (Figure 1, bottom). Saco Bay is a ten-mile wide embayment containing the Saco Estuary, Goose Fare Brook tidal inlet, and Scarborough marshes that are fed by Nonesuch River. The bay is characterized by shallow coastal slopes and consequently wide intertidal zones, with a mean tidal range of 2.7 m. During a storm study of Saco Bay, bottom current velocities measured at Higgins Beach and a mooring located just offshore of Old Orchid Beach reached a maximum of 1.09 m/s across six storm events monitored between January 23 to March 7, 2001 (Hill et al., 2004). Variations in wave direction and approach have been observed during storms (both tropical and extra-tropical), diverging from the normal southerly-southeasterly approach to a northeasterly trajectory (Hill et al. 2004). NOAA Buoy 44007, located 12 NM Southeast of Portland between Saco and Casco bays, has

Figure 1 – Map of Saco Bay. (a) shows points of interest mentioned throughout the text. (b) shows the subset of the Saco and Casco mesh covering Saco Bay, with 10 m maximum resolution in shallow waters.
been used in the past to classify “storm events” in the region as when significant wave height reported by the buoy exceeded 2 m, with each event ending when wave height settled below 1.25 m (Hill et al. 2004). 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 (Kelley et al., 2005).

In the Saco and Casco model, the Nonesuch River is used as the sole source of freshwater draining the Scarborough marshes, though it should be noted that there are also smaller rivers, such as the Libby, Dunstan, and Scarborough rivers all contributing to the discharge from Nonesuch River. The choice to use the point labeled as the Nonesuch River in Figure 1 (top) as a proxy for this full river system was made for model stability purposes. Additional adjustments to Saco Bay’s structural definitions made for specific model configurations are further detailed in Chapters 5 through 7.

In contrast to Saco Bay, Casco Bay is characterized by steep coastal slopes and numerous islands throughout. In this text, Casco Bay is split into northern and

Figure 2 – Map of Casco Bay. (a) shows points of interest mentioned throughout the text. (b) shows the subset of the Saco and Casco mesh covering Casco Bay, with 50 m maximum resolution in Portland harbor.
southern Casco Bay at the Chebeague Island. Figure 2 (top) depicts the points of interest in the bay. The Fore, Presumpscot, and New Meadows rivers were included in the full-domain mesh illustrated in Figure 2 (bottom), while additional freshwater discharge nodes including the Royal, Cousins, and Harraseeket rivers were added for the Casco-only mesh developed for further studies. At the time of writing, the Casco-only model is still undergoing iterations for ongoing studies and is detailed further in Chapter 6.

The M2 semi-diurnal lunar tide is the primary tidal constituent for Casco Bay as it is for Saco Bay (Kelley et al., 2005). The step-like nature of the shoreline characteristic of the bay is one of the primary focuses of the study detailed in Chapter 4. This slope structure plays a large role in determining the shape of the intertidal zones in Casco Bay, and changes to those intertidal zones in the face of SLR could pose significant problems for the many industries. The primary freshwater input into the bay is considered as the combined discharge of the Presumpscot and Royal rivers, averaging roughly 40 m$^3$s$^{-1}$ (Janzen et al., 2005). A salinity gradient is also present in the northern Casco Bay due to the input from the Kennebec (Xue and Du, 2010), a river system comprised of the Kennebec and Androscoggin rivers that has been observed to discharge upwards of 4000 m$^3$s$^{-1}$ of freshwater during the spring. In the models, the Kennebec River plume is integrated through boundary conditions prescribed from NECOFS to the northeast segment of the open boundary of the mesh.
CHAPTER 3
DATA

3.1 Bathymetry

The 1/3 arc-second NOAA Digital Elevation Model (DEM) for Portland, Maine (Portland, M. and DOC/NOAA/NESDIS/NCEI, 2019) was used to specify the bathymetry for Saco and Casco bays. LiDAR bathymetry data was also available from the NOAA Digital Coast system (Coast.noaa.gov, 2019). 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 cm and 10 cm, and horizontal accuracies of 75 cm and 100 cm, respectively.

3.2 NERACOOS Model Products

The Saco-Casco model was initialized and forced at the open boundary with hourly outputs produced by the Northeast Coastal Ocean Forecast System’s (NECOFS) hindcast simulations (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 as detailed on the NERACOOS website (http://www2.neracoos.org). 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 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 Gulf of Maine 3 (GOM3), which has a peak resolution of 0.3 to 1.0 km in coastal areas, including the full Saco and Casco domain. As can be seen in Figure 3, the low resolution of coastal reas in the Saco and Casco bays prevents the NECOFS from capturing many of the small-scale features caused by rapid changes in coastal bathymetry. Rivers along the coastlines of Saco and Casco Bays are oversimplified in the GOM3 mesh, composed of only a few triangular elements that do not conform to the actual shape of the rivers.

3.3 USGS River Gauges

Station 01064118 at Westbrook, Maine for the Presumpscot River provides fifteen-minute discharge rates and gauge heights recorded from Oct. 2016 and Oct. 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. Station 01059000 for Androscoggin River was also utilized to help calibrate the Royal, Cousins, and Harraseeket river forcing in...
the Casco-only model runs discussed in Chapter 6. Figure 4 illustrates the large distance between these gauges and the freshwater discharge nodes in the full Saco and Casco mesh, introducing a source of uncertainty in forcing data. As such, scaling factors for river discharge were largely specific to individual model runs.

### 3.4 Portland Tidal Station

The NOAA-operated Portland Tidal Station was used for sea surface height and water temperature validation. The station outputs air and water temperature, elevation, and atmospheric pressure in 6-minute intervals.

### 3.5 Buoys

In response to a demand for a real-time monitoring system in the Gulf of Maine, the University of Maine Physical Oceanography Group

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Figure 4 – USGS River Gauge Map. Map showing the locations of the USGS river gauges and freshwater discharge nodes in the mesh (where Ri is the identifier for river node i).

Figure 5 – Buoy Map. Map showing the locations of buoys and stations referenced in this study. Buoy C0201 refers to “Buoy C02” in this text.
(PhoG) initiated the development of the Gulf of Maine Ocean Observing System (GoMOOS) in 2001. 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, local visibility such as fog and arctic sea smoke, air temperature, wave parameters, water temperature and conductivity at 1 m depths, and current velocity at 2 m depths (Wallinga, 2003). For the Saco and Casco modeling project, data were collected from Maine EPSCoR Mooring D0301, UMaine Mooring CO2, Maine EPSCoR Lobo 1 and Lobo 2, and NOAA/NDBC Buoy 44007 (Fig. 2). These datasets were used for the validation of additional test runs performed over the deployment periods of the buoys.

3.6 Casco Bay (CAB) 2014 Survey

In 2014, a circulation survey was conducted by NOAA for the Casco Bay area. This survey herein is referred to as the CAB survey. There were 22 locations used to deploy Acoustic Doppler Current Profilers (ADCP) to collect “6-minute data ensembles” over a 1-month period (Kammerer, 2017). Their site map has been reproduced here in Figure 6. The data collected at these sites included current direction and magnitude, temperature, sensor metrics and quality control information. This data was used to calibrate the Saco and Casco models using hourly output from model runs of 2014.

Figure 6 – CAB Survey Map. Casco Bay 2014 survey “Projected Area,” reproduced from Figure 1 of Kammerer, 2017.
CHAPTER 4

THE SACO AND CASCO MODEL

The Saco and Casco model was an implementation of FVCOM that was developed to model complex coastal systems (Chen et al., 2003). The finite-volume method takes 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 (Chen et al., 2003, 20]. 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 (Chen et al., 2003). This chapter details the process of designing and implementing the Saco and Casco FVCOM model.

4.1 Mesh Setup

Through Aquaveo’s Surface Modeling Software, the 10-m resolution Portland DEM was interpolated onto the unstructured triangular mesh developed for this study. Prior to interpolation, the DEM was converted from MHW to MSL to match the rest of the input data for the FVCOM model setup.

Figure 7 – SMS Software Interface. Mesh in development in SMS 10.1. Triangles along the open boundary were created manually to increase the stability of the final FVCOM models.
Additional iterations of the Saco and Casco mesh were developed by integrating NOAA LiDAR data. 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. Figure 7 depicts an example of the SMS interface used to develop the final version of the full Saco and Casco mesh. Saco Bay was discretized to the highest resolution of 10 m in areas shallower than two 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 originally to match that of NECOFS Gulf of Maine 3 (GOM3) mesh. The final version of the Saco and Casco mesh included additional boundary nodes between the GOM3 nesting nodes, allowing for more stable boundary forcing during model runtime. The SMS “Data” options were used to devise a set of equations to dynamically adjust mesh resolution based on region and depth, creating the zonal bands visible in Figure 7, where resolution changes rapidly at the intersection of two such bands.

4.2 FVCOM Input Generation

Preparation of the FVCOM forcing files was performed through MATLAB and Fortran scripts. NECOFS model output and USGS river data was matched by associated datetime metadata and interpolated onto mesh nodes or elements according to FVCOM specifications. This process was automated and optimized for the Advanced Computing Group (ACG) cluster at the University of Maine, Orono. In doing so, it became possible to prepare hourly forcing for a year of simulated time in less than a day, removing the preexisting bottleneck of model preparation time. Points of potential human error were minimized by the creation of a configuration script that managed the rest of the system; only one small section of MATLAB code would need to be edited to apply this batch input file generation process to any new model setup or domain. While the final iteration of the Saco and Casco model utilized FVCOM 4.1, which used standard NETCDF file formats for defining inputs, earlier variants of the Saco
and Casco model utilized FVCOM 2.7, which required specifically formatted custom file types for forcing data. To accomplish this in the automated file preparation MATLAB system, MATLAB scripts were written that generated, compiled, and ran Fortran scripts as intermediary processes to generate the necessary forcing files.

### 4.3 Freshwater Forcing

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 for the storm response study in Chapter 5. 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 where both variables were available. Numerous iterations on these relationships were implemented, using a past study on the plume structure of Saco River (Tilburg et al., 2011) as a guide to adjust the regression coefficients. The experimental results discussed in Chapter 5 reflect model simulations using the most stable freshwater discharge forcing, with the Saco and Nonesuch rivers using simplified discharge rates of 5.94*Gh and 2.97*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*Gh, 1.48*Gh, and 2.97*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 1016600, 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 year in 2017 as in 1978.

At the time of writing, estimated hindcast discharge rates have been made available at site 01064118 from Oct. 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 re-run upon release of these datasets, which confirms that no noticeable changes are detected when using the modeled discharge vs USGS predictions.

4.4 Model Validation

In situ observations from multiple sources were used to validate the model. Data from the NOAA-operated tidal stations (http://tidesand currents.noaa.gov/) were used for the sea surface height and water temperature validation. PhoG initiated the

Figure 8 – Water Level Comparisons. 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.
development of the Gulf of Maine Ocean Observing System (GoMOOS) in 2001 (Pettigrew et al., 2001-2008). 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 (Wallinga et al., 2003). For the Saco and Casco modeling project, data were collected from the University of Maine Mooring C02, Maine EPSCoR Mooring D0301 as well as Lobo 1 and 2 (http://umaine.edu/epscor/ seanet/), and NOAA National Data Buoy Center Buoy 44007 (http://www.ndbc.noaa.gov) (see Figure 5). These datasets were used for the validation of additional test runs performed over the deployment periods of the buoys.

Time series validation of select 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 8a and 8d compare the modeled SSH to observations at the Portland station. Figure 8b and 8e compare the reconstructed tidal signals from
UTide, which were removed from the raw signals to calculate the residuals (Figure 8c and 8f). After correcting for a constant negative bias of two 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 discussed in Chapter 5.

Furthermore, current data was available at buoy C02 for the 2007 event (Figure 9). 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 modelled 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 modelled 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. Following calibrations made to stabilize the storm response models, additional scenarios were simulated for various independent projects. Calibrations specific to Casco-only mesh will be further discussed in Chapter 6.
CHAPTER 5

STORM RESPONSES COUPLED WITH SEA LEVEL RISE

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 (Smith et al., 2010; Lin et al., 2012) 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 and Casco bays 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 (Ezer and Atkinson, 2014). 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 extra-tropical 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 (Cannon, 2007), 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 (Cannon, 2007). 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 and Casco bays. 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) (Chen et al., 2003). Inputs for this model were derived from the NECOFS 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, 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 investigation presented in this chapter 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.
5.1 Background

5.1.1 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 Portland Station, identified as a 100-year event. The Patriot’s 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 extra-tropical cyclone on February 5th, the 1978 event reached a low pressure of 984 mbar as it retrograded from well off the Mid Atlantic coast to Long Island, moving northwards towards the New England coastline (Brown and Olson, 1978). On February 7th, northeasterly wind gusts of 83 mph and 92 mph were reported in Boston and Cape Cod, respectively, along with sustained hurricane-force winds (Brown and Olson, 1978). The record surge resulting from the cyclone makes it a focal point for this study, as sea level heights reached their 100-year maximum

Figure 10 – Storm Wind Comparisons. Wind velocities during February 1978 (a) and April 2007 (b) at buoy CO2. 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.
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 (Cannon, 2007).

The 2007 event was initially reported on April 15th as a low-pressure in the southeastern United States before it travelled north along the coastline. NOAA records indicate a barometric low of 972 mbar and wind gusts up to 59 mph over Portland (Zou and Xie, 2016). The Portland Harbor tide gauge reported a peak water level of 13.28 ft during this event (Cannon, 2007). 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 Patriot’s 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 partially captured by the NECOFS model simulation (Figure 10). 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 C02 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 significantly in magnitude and direction from buoy observations. At buoys C02, NECOFS-modelled 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 roughly 60 m$^3$s$^{-1}$ to an estimated peak of roughly 500 m$^3$s$^{-1}$ 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 NEOFS 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.

5.1.2 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 through 2012 aimed at dissecting the relationship between SLR and flooding caused by tropical cyclones (Woodruff et al., 2013). Of interest in Woodruff’s review were two studies mentioned earlier which applied modelling 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 (Cahoon, 2015), 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 U. S. 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 m 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 (Ezer and Atkinson, 2014; Zervas, 2009). These studies assumed zero acceleration of SLR, linearly generalizing the predicted rise to the entire Gulf of Maine.

The most recent modelling 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 (Ferreira, 2014). 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 (Passeri et al., 2015). 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 Maine Geological Survey incorporated the global projections made by these earlier studies into a presentation for the 2015 State of the Bay Conference (Slovinsky, 2015), 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 (Ezer and Atkinson, 2014), 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 (Parris et al.). 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 Patriot’s Day Storm in 2007.
5.2 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.

5.2.1 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 11 depicts frames of surface currents during ebb and flood tides before and during after the 1978 event. From this figure, we can see typical flooding and ebbing currents as strong flows into and out of the bay through the Broad Sound and the passage between the Peaks and Long islands. Outflow from the New Meadows River is visible in the upper reach of the estuary during ebb.

Figure 11 – Frames of Surface Currents in Northern Casco Bay. 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.
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 increased northward surface current during flood tides within the storm window, which flew into the Broad Sound along the east coast of Chebeague Island, circulating counterclockwise around Cousins Island.

Continuing southward (Figure 12), the flood tide entered southern Casco Bay mostly through the passage between Long and Peaks islands, which circulated counterclockwise to enter Portland Harbor and keep the Fore River plume inside the estuary. During ebb, the Presumpscot 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 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 the Maquoit and Middle Bays, was less susceptible to storm forcing. The southern Casco Bay showed more noticeable storm responses in Portland Harbor, where the Presumpscot and Fore river plumes were altered significantly by storm winds.

5.2.2 Saco Bay

Surface currents increased sharply as they continued south of Casco Bay, colliding with the northern coastline of Cape Elizabeth (Figure 13). 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 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 in Saco Bay 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 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.

5.2.3 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
and Nonesuch rivers 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 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.

5.3 Bay Response 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 one-foot increments from the baseline scenario to a seven-foot scenario to emulate potential water levels. Utilizing the wetting and drying module of FVCOM, mesh cells in Saco and Casco bays were classified as either “dry,” “intertidal,” or “wet”. The former (latter) were defined as cells in the mesh, which never became wet (dry), respectively, throughout the model’s runtime. Intertidal areas were cells that alternated between wet and dry.

5.3.1 Impact of SLR on Bay Structure

To quantify the impact SLR had on the storm responses, a baseline understanding of how SLR impacted the shapes of Saco and Casco bays 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 the cell had a digital ground relief value above the Mean High Water (MHW). Figure 14 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 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 and Presumpscot rivers. The trends of inundation zone expansion can be seen in Figure 15, 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 one foot “lag” in SLR scenario, as the peak sea level during the 2007 event was roughly one foot lower than that of the 1978 event. This lag is clearly visible in the inundation and dry cell trends in both the Saco and Casco Bays. Looking closer at the inundation and dry cells, both bays saw a net increase of roughly 20 km$^2$ in inundation zone coverage from the baseline scenario to the 7 ft SLR scenario, reflecting an identical drop in dry cell coverage. This 20 km$^2$ 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 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

Figure 15 – Wetting and Drying Cell State Distributions. Cell state distribution from the FVCOM wetting/drying module vs. SLR during the 1978 and 2007 events in the Saco and Casco Bays. Mesh limits began to be reached in the 7 ft SLR scenario, causing the zonal distributions in both events to converge.

Figure 16 – Sketch of Casco Bay Coastal Shelf. Sketch of intertidal zones characteristic of Casco Bay under the 5 ft 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.
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 km$^2$, 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 km$^2$ 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 ft and 12.25 ft above MSL, respectively. For the 2007 event, the wet zone expanded greatly between 2ft and 3ft SLR, which is accompanied by a sharp decrease in the intertidal zone. The intertidal areas stayed mostly the same between 3ft and 5ft SLR despite the slight increase of wet zone, which was compensated by the decrease of dry zone. However, between 5ft and 7ft SLR, the intertidal area expanded largely at the expense of contracting dry zone.

This complex relationship can be better visualized in Figure 16. 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 stairs, limiting the change in wet cell coverage across SLR scenarios. During 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 ft and 7 ft SLR scenarios. In contrast, 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 14), one key distinction between the 1978 event and 2007 event 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 ~1 km², 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⁻¹ 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.

5.3.2 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 17 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, 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 17d), 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 17a), 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 and Fore river plumes, as the southward flux of freshwater into the bay from Portland
Harbor was located in this channel (Figure 12). 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 15). 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 affect was nonlinear and plateaued quickly. The storm currents at the

Figure 17 – Mean Vertically-Averaged Storm Current Speed. Vertically-averaged mean current speed vs.
SLR within the storm windows at selected sites (see Figure 1) for the 1978 and 2007 events. Temporal
averages throughout either storm window reflect the impact of SLR on storm-induced plume dynamics.
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 17b), pulling greater volumes of freshwater out of Portland Harbor. This increase in current speed was mostly linear and consistent from the 1 ft to 7 ft SLR scenarios for the 1978 event, matching the linear rise from the 3 ft and 7 ft scenarios in the April 2007 event. Further offshore to the southeast of Cape Elizabeth at the site of buoy 44007 (Figure 17c), the 1978 storm currents saw a more complex response to SLR, while the 2007 event saw no changes at all. The minor (<.01 m s⁻¹) change in current speed from 0 ft 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 ft 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 17e) and the Nonesuch/Scarborough River (Figure 17f).

Saco River behaved as expected as SLR increased. The sides of the river flooded rapidly as sea levels rose, resulting in drop in current speeds exiting the mouth of the river. Interestingly, during the low-discharge 1978 event, this drop was largely linear following a small initial spike of .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 10), 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 ft to 4 ft for the 1978 event (4 ft 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 currents in the 1978 event, and resulting in an increase in currents 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 18 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 and Presumpscot rivers resulted in further extensions of the combined Fore and Presumpscot river plumes northeastward towards Broad Sound, and southward
around Cape Elizabeth for the 1978 event in the 7ft 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 and Nonesuch Rivers. 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 under predicts 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 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 towards Wood Island and Biddeford Pool decreased (Figure 17e), hence the higher minimum
salinity for the 2007 event at 7ft SLR.
5.4 Conclusions

This study aimed at evaluating the impact SLR would have on responses to major storm events in Saco and Casco Bays in the western Gulf of Maine. A hydrodynamic model was developed to simulate the Blizzard of 1978 and the Patriot’s 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 in where river plumes were directed.

The modelled storm responses in Saco and Casco bays 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 impacts 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 shape 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.
CHAPTER 6

ANNUAL SIMULATIONS

In addition to the storm response study, the Saco and Casco model was calibrated to simulate the full year of 2014, and a variant of the model including only Casco Bay was utilized to simulate 2004 and 2014 and is currently being utilized to simulate additional years at the time of writing. The year 2014 was chosen as it aligned with the availability of cruise data throughout Casco Bay, allowing us to better gauge the model’s accuracy and make adjustments as needed. Results from the 2014 simulation were factored into calibration measures taken to yield the final storm simulations shown in Chapter 5. Furthermore, several ongoing studies have requested customized model output for various purposes, with two such projects summarized in Chapter 7. Results from the 2004 and 2014 Casco-only simulations utilized by these projects are provided below, with a brief summary of noteworthy observations made during the model calibration stages.

6.1 Annual Simulation Model Configuration

The Saco and Casco model was used to conduct year-long simulations under a “hot start” configuration to gauge stability and accuracy over longer model runs. Under the hot start process, each month of a given year was run separately, with each month after January using the last hour of the previous month’s simulation to specify initial conditions. For the sake of efficiency and isolation of potential errors, each year was setup to run January under cold-start configurations, where initial conditions were prescribed manually by the interpolation of NECOFS output and translation of USGS river gauge data to freshwater input forcing. Pre-emptive error checking was performed using the Portland tidal station, along with buoy data and meteorological observations when available to assess the accuracy of the NECOFS products prior to interpolation. This setup allowed for the production of hourly output across the entire year. In alignment with the requirements presented for these annual
simulations, a secondary mesh was developed, excluding Saco Bay in exchange for a higher nearshore-resolution through Casco Bay. The final iteration of the Casco mesh is depicted in Figure 19, showing the adjusted domain of the mesh, with resolutions of 50 m nearshore around Portland, 100 m nearshore elsewhere, and 500 m maximum along the open boundary consisting of 69 boundary nodes.

With regards to boundary conditions and freshwater discharge, the same sources used for the storm response study were utilized here. For river forcing, the model setup was configured to pull temperature data from USGS site 01038000 and extrapolate those observations to the six included rivers: Fore, Presumpscot, Royal, Harraseeket, Cousins and New Meadows. Observed discharge rates from USGS sites 01064118 and 01059000 were used to estimate discharge for the freshwater discharge nodes marked on Figure 19, above. The same approach for extrapolating river discharge described in section 4.3 was applied to the annual simulations, with various scaling coefficients used across several configurations for each year.
6.2 Water Temperatures

As previously mentioned, the year 2014 was chosen as it aligned with the CAB survey conducted for Casco Bay, providing a large amount of comparative data to be used for validation and additional calibration. Figure 20 depicts comparisons of temperatures produced by the model vs. observations at survey locations (see Figure 19 for CAB sites). Sites 1-7, located in and around Portland Harbor, showed a high level of agreement between the observed and modeled temperatures, though the model did not pick up on a rapid drop in temperatures at sites 4-6 associated with discharge from the Fore and Presumpscot rivers in mid-July. Offshore temperatures were consistently overpredicted by the model during the summer months, propagating into Casco Bay between the Long, Peaks, and Cousins islands as evidenced by observations at CAB sites 9-15. In addition to the CAB sites, model results were compared to Portland Station’s temperature observations (Figures 21 & 22).

![Figure 20 – CAB 2014 Sampled Temperature Comparisons](image)

Validation of water temperatures as depths with CAB cruise observations. Modeled surface temperatures were consistently more accurate than temperatures at greater depths though most errors were related to a drop in observed temperatures in mid-July that was not captured by the model. This disagreement is most visible in CAB sites 9, 10, 13, and 14.
As depicted in Figure 21, Portland water temperatures in 2014 were consistently overpredicted by the model during the winter months with a positive bias of up to 5°C, and slightly underpredicted between July and November. Curiously, the CAB site 6, located at the same coordinates as Portland Station, also recorded lower temperatures than the station, aligning more closely with the modeled results. The cause for this disagreement is currently uncertain, though it is likely attributed to differences in sensor depths in a location where two interacting river plumes can cause significant small-scale variations. Regardless, the model clearly produced the expected seasonal variations, though additional calibration should be performed for future simulations of winter months to account for the positive temperature bias.

Following the identification of the high temperature bias observed in the Saco and Casco model for 2014, modifications were made to the FVCOM source code to restrict rapid change of temperatures in shallow waters. This provided us with slightly more control over modeled water temperatures,
resulting in the 2004 signals depicted in Figure 22. However, all attempts to completely alleviate the
model’s tendency to overestimate minimum temperatures and underestimate maximum temperatures
resulted in instabilities, oftentimes preventing the model from completing a simulation.

![Portland Station Temperature Comparison (2004)](image)

Figure 22 – Portland Station Temperature Comparison (2004). Similar to figure 21, but for 2004.

6.3 Surface Salinity

The only salinity data available for calibrating the full-year model runs was at Buoy C02, roughly
5 miles south-southeast of the nearest boundary node on the Casco-only mesh (Figure 19). While this
distance is too great to use for point validation, we can compare seasonal trends in the observed buoy
records to boundary forcing interpolated from the NECOFS model. While this does not reflect the Casco
Bay model’s functionality, it provides insight into the validity of the boundary conditions used to force
Figure 23 – Buoy C02 Salinity Comparison. Comparison of salinities at 20 m depth measured at Buoy C02 vs. boundary condition salinities used at open boundary node 20 for forcing.

Figure 24 Boundary Node Salinity (2014). Modeled boundary salinity for 2014. Note that year-round, boundary salinity was lower in 2014 than in 2004 (Figure 23). Fitted curve with 95% confidence interval (top) is included to more clearly illustrate seasonal trend present in the raw signal (bottom).
identical seasonal trends are apparent. In fact, even using a node much closer to shore, such as CAB site 15, which is influenced more heavily by freshwater discharge, there is a clear peak in salinities in February, which drop off from March to June then remain steady for the remainder of the year. While no observation data is available for 2014, the modeled salinities for 2014 (Figure 24) depicted similar seasonal trends, including lower salinities than in 2004, corresponding to higher freshwater discharge (Figure 25). In contrast to 2014, 2004 river discharge rates were lowest from July to September at USGS sites 01059000 and 01066000, resulting in small shifts to seasonal salinity trends in Casco Bay when comparing the two years. The additional ongoing simulations of 2005-2013 will be needed to further explore this trend in greater depth, and additional validation data would be needed to assess the validity of the modeled behaviors. As a whole, the primary takeaway from analyzing modeled salinities in these annual runs is that known seasonal trends are captured well by the model, and interact properly with freshwater mechanisms, yielding a product that provides value to ongoing studies.

![Image](image.png)

Figure 25 – USGS Verified Freshwater Discharge. Depiction of freshwater discharge measured at gauges 01066000 and 01059000 for 2004 (top) and 2014 (bottom).
6.4 Water Levels

Figure 26 depicts comparisons of modeled vs observed sea surface height at Portland station. Daily averages of the raw sea level signals (Figure 26, top) illustrate seasonal variations in both signals, where summer months produce lower tidal ranges with fewer storm-related events. Tidal reconstructions of both the observed and modeled sea levels (Figure 26, middle), showed slight disagreements that were consistent throughout continuous model runs. That is, for the entire 2004 simulation, modeled tidal signals were slightly higher than observed, and slightly lower than observed throughout the 2014 simulation. Water levels at the Portland Station are slightly lower in January and February than the rest of the year, though this difference is often less than half a meter, leading to the minor incline of the daily averages of tidal reconstructions in Figure 26. Once the tidal reconstructions were removed from the raw signals, the resultant residual sea level signals (Figure 26, bottom) showed similar patterns between the modeled and observed signals, with no clear biases detected. Large

![Figure 26](image)

Figure 26 – Tidal Analysis of 2004 and 2014. Comparison of tidal analyses between modeled and observed sea level signals for 2004 (left) and 2014 (right). Raw signals (top) reflect the raw observed and modeled water levels with reference to MSL. Tidal reconstructions (middle) were generated using the UTide package for MATLAB. Residuals (bottom) were the remaining elevation signals once the tidal reconstructions were removed from the raw signals.
“spikes” in the residual signals associated with storm events were captured by both the model and observation data, allowing for such studies as the storm response study covered in Chapter 5.

6.5 Circulation

The Casco Bay 2014 cruise recorded current magnitude and direction at multiple depths at each testing site. Figures 27 and 28 depict a sample of the comparisons of modeled currents to cruise records for CAB site 11, just north of Peaks Island. The rest of the cruise data comparisons have been compiled into a table in Appendix II. The final version of the Casco Bay model performed well, producing tidal currents in line with observations. The greatest errors were detected in complex channels, such as at CAB site 15, located just south of Cousins Island. While tidal signals were still aligned at site 15, southward surface current magnitude was consistently underpredicted by the model. The cause of this error is uncertain, though we suspect it to be attributable to an underestimation of freshwater.

Figure 27 – CAB 2014 Sampled Eastward Current Comparisons. Comparison of eastward current velocities are varying depths for cruise site 11. Modeled currents are shown by thick, blue lines over the cruise surveyed currents shown by thinner, orange lines.
discharge, specifically from the Royal and Cousins rivers. Additional field testing to acquire validation data for these rivers would be required to pursue further investigation into these errors.

Figure 28 – CAB 2014 Sampled Northward Current Comparisons. Similar to Figure 27, but for northward current velocities.
CHAPTER 7

SEANET USE CASES

The SEANET organization at the University of Maine initiated a number of projects utilizing the model products offered by the Saco and Casco modeling project. Detailed below are a couple of examples of such projects.

7.1 Modeling Optimal Habitat of Major Aquaculture along the Coast of Maine

Andrew Goode, a PhD candidate at the time of writing, utilized model output for Casco Bay “to characterize the size and seasonality of suitable aquaculture habitat for three predominant aquaculture species in Maine; the eastern oyster (Crassostrea virginica), the Atlantic deep-sea scallop (Placopecten magellanicus), and sugar kelp (Saccharina latissimi)” (Andrew Goode, personal communication, May 2, 2019). This project required high-resolution model output in estuaries along the coastline of Casco Bay. To meet these requirements, a sub-mesh of the Saco and Casco mesh grid was developed (Figure 19). As this subdomain did not present the computational restrictions required to simulate Saco Bay, the model could be tuned to run far more efficiently, leading to multiple years of model data being prepared for Goode’s project. With multiple years of hindcast data available, Goode’s aim was to be able “to describe the fluctuation of these habitats over the past decade.” As was the case in the Saco and Casco storm response study, the goal of Goode’s application of the model output was to provide assistance to aquaculturists in decision making ahead of forecast climate change.

7.2 Policy Making – Leasing Decisions

Melissa Kimble, another SEANET graduate student, is utilizing the Saco and Casco model to gauge the viability for aquaculture in specific estuaries (Melissa Kimble, personal communication, May 5, 2019). Modeling efforts were proposed for this project to investigate the relationships between
biophysical variables. In doing so, they believe more informed decision making could be made regarding the leasing of specific aquaculture species. Furthermore, they plan to establish standard proxies to use when specific environmental variables are not available, such as using temperature to estimate salinity profiles around a river mouth. The main benefit of utilizing the Saco and Casco model for this study is the high spatial and temporal resolutions available; satellite measurements used in the past average variables over large spatial scales, introducing significant error in gauging environmental conditions in shallow coastal areas such as the estuaries in question.
CHAPTER 8

SUMMARY

The Saco and Casco FVCOM model was originally proposed to serve as a versatile tool across a number of studies. The end product produced from this project was a stable, flexible model which we applied to a case study investigating the relationship between storm conditions and projected sea level rise. In doing so, we were able to illustrate how the structure of a coastline, along with freshwater mechanics, changes dynamically with response to SLR in ways unique to the coastline under investigation. In consequence, we have shown how accurately predicting future trends in bay behaviors during a storm will require the simulation of similar high-resolution complex models to identify small-scale features that could have a big impact on circulation patterns. The value of being able to simulate coastal hydrodynamics under forecast conditions must not be understated, as even small changes, as evidenced in this study, can yield major impacts on the resiliency of coastal communities.

The Saco and Casco model is continuing to undergo iterative development to meet the needs of ongoing research projects. In addition to the use cases identified in Chapter 7, requests have been made to utilize variants of this model to gauge the potential impact of increased sea levels on residential areas throughout Casco Bay. However, the FVCOM model is not without its flaws. As mentioned earlier, FVCOM can struggle when simulating very shallow waters, producing erroneous temperature calculations and instability issues. Moving forward, future studies will need to address these shortcomings. Alternative three-dimensional modeling frameworks should also be considered in a comparative study, such as an evaluation of the capabilities of FVCOM vs. the Semi-implicit Cross-scale Hydroscience Integrated System Model (SCHISM), which may fare better in certain applications. The Saco and Casco model specifically lacked the ability to simulate icing mechanics and wave physics, and as such made numerous assumptions limiting its reliability when taking practical action involved in resiliency efforts in the face of climate change. It is our intention through the Saco and Casco Modeling
Project to illustrate the benefits of regional high-resolution modeling, while highlighting its shortcomings in the hope that future modeling efforts will continue to improve upon the flexibility and capabilities of coastal hydrodynamic simulations as climate change becomes an increasingly more immediate threat.


Kelley JT, Barber DC, Belknap DF, FitzGerald DM, van Heteren S, Dickson SM. Sand budgets at geological, historical and contemporary time scales for a developed beach system, Saco Bay, Maine, USA. Marine Geology. 2005 Jan;214(1-3):117-42.


Zervas CE. Sea level variations of the United States, 1854-2006. 2009


APPENDIX I

EXTERNAL DATA SOURCES AND MATLAB PACKAGES

A suite of MATLAB scripts was developed to streamline and automate the process of preparing input files for FVCOM. To accomplish this, several externally license MATLAB packages were integrated and are listed below for future reference. Additionally, URLs accessed throughout this study for data used in the generation of forcing files are provided.

I.1 Northeast Coastal Ocean Forecast System (NECOFS)

The NECOFS was utilized to provide boundary and initial conditions for the following variables:

- “Zeta” (Sea surface height referenced to MSL)
- Water temperature
- Salinity
- Wind speed / wind stress
- Net heat flux
- Shortwave radiation

The “Seaplan 33 Hindcast V1” NECOFS catalog was used to access conditions for hindcast data:

http://www.smast.umassd.edu:8080/thredds/dodsC/models/fvcom/NECOFS/Archive/Seaplan_33_Hindcast_v1/

The NECOFS Forecast catalog was used for experimental simulations utilizing wave integration to provide high-resolution 3-day forecast model runs. These experiments were eventually abandoned due to the unreliability of the model setup, but may be revisited in the future:

http://www.smast.umassd.edu:8080/thredds/dodsC/models/fvcom/NECOFS/Forecasts/catalog.html
I.2 United States Geographical Survey (USGS)

USGS sites 01064118, 01066000, and 01059000 provided gage height and discharge data used to calibrate freshwater input nodes in the Saco and Casco models. Temperatures from USGS site 01038000 were utilized for annual model runs using the Casco-only mesh.

Links:
- Site 01064118: https://waterdata.usgs.gov/nwis/inventory?agency_code=USGS&site_no=01064118
- Site 01066000: https://waterdata.usgs.gov/nwis/inventory?agency_code=USGS&site_no=01066000
- Site 01059000: https://waterdata.usgs.gov/nwis/inventory?agency_code=USGS&site_no=01059000
- Site 01038000: https://waterdata.usgs.gov/nwis/inventory?agency_code=USGS&site_no=01038000

I.3 MEXCDF

Created by John Evans, the mexcdf library allowed for efficient manipulation of netcdf files:

https://sourceforge.net/projects/mexcdf/

I.4 UTide

Published by Daniel Codiga on Mathworks’ File Exchange, UTide allowed for the tidal analyses discussed in this study:

APPENDIX II

COMPARISONS OF MODELED VS. OBSERVED CURRENTS FOR CAB CRUISE SITES

The following table details additional validation that was performed for the Casco-only simulations of 2014. The table is separated by CAB survey site using the following key, where subscript “m” indicates modeled results, and subscript “c” indicates observations made by the CAB survey. All velocity values are reported in m s\(^{-1}\) and depths are reported in m.

LON – Longitude of CAB site N

LAT – Latitude of CAB site N

H\(_{M}\) – Depth at model sigma layer (M) or observation depth (C)

C\(_{\text{max},i}\) – Maximum current speed modeled (M) or observed (C) at a given site and depth

U\(_{\text{rmse}}\) – Root mean squared error (RMSE) of modeled vs observed Eastward currents

V\(_{\text{rmse}}\) – RMSE of modeled vs observed Northward currents

C\(_{\text{rmse}}\) – RMSE of modeled vs observed resultant current speed vector

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APPENDIX III

AVAILABILITY OF MODEL PRODUCTS

All data generated by the Saco and Casco model utilized for this thesis and for ongoing products has been made publicly available. At the time of writing, these model products can be accessed through the THREDDS server linked below. As a disclaimer, the raw data available through this server is provided as-is, and the URL may change after completion of this text. Please utilize the README.txt file located in the root directory of the THREDDS server to check for future updates and further information.

University of Maine THREDDS Server:

http://viz.acg.maine.edu:8080/thredds/catalog/fvcom/saco-casco/catalog.html
BIOGRAPHY OF THE AUTHOR

Stephen Moore was born in Silver Spring, MD on March 28, 1992. He graduated from Urbana High School with an International Baccalaureate diploma in 2010. He attended the University of Maryland, Baltimore County (UMBC) from 2010 to 2015, earning both a B.S. in Computer Engineering and a B.A. in Mathematics, with a short sidetrack to Swansea University in Swansea, Wales for the 2012-2013 academic year, where he studied electrical engineering and history. He earned a Fulbright grant following graduation from UMBC in 2015, under which he taught English in the context of computer science and mathematics at Politechnika Poznańska, a university in Poznań, Poland, until May 2016. Stephen is a candidate for the Master of Science degree in Oceanography from the University of Maine in August 2019.