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Modeling the Impact of Sea-Level Rise on Nearshore Flooding due to Storm Surges

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ABSTRACT

Estimating storm surge impacts in coastal areas has become increasingly important under projected future sea-level rise scenarios. Some conventional flood modeling methods for storm surge are inaccurate due to i) over-simplistic methodology, ii) inadequate spatial resolution, and iii) a lack of validation against observed data. We created and validated a coupled model system consisting of a circulation and phase-averaged wave model (FVCOM-SWAVE) and a nonlinear, phase-resolving, Boussinesq wave model (FUNWAVE-TVD) with very high spatial resolution. We applied the models to the tidal reach of the Thames River, CT, USA, a ~1 km wide channel, ~25 km in length. Most of the channel is between 3 m and 7 m in depth, but a narrow navigation channel is dredged to approximately 12 m. The surrounding coasts are densely developed and are the sites of two important ports. To simulate future flooding when the mean sea level is higher, we used the coupled circulation and wave model of the Long Island Sound (Liu et al., 2020) to prescribe boundary conditions for FUNWAVE-TVD. We compared the model results with the base flood elevation from FEMA Flood Insurance Rate Map (FIRM), the North Atlantic Coast Comprehensive Study (NACCS), and Liu et al. (2020)'s Long Island Sound FVCOM-SWAVE model. The current model system is found to model wave processes of extreme storms more accurately in shallow water regions compared to the empirical equation application of FEMA and coupled circulation-phase averaged model application of NACCS. Extreme storm scenarios under local sea-level rise predictions were also examined using the current model system. This study would benefit coastal risk planning for severe storms under future sea-level rise.

KEY WORDS: annual exceedance probability; return period; flood map; surge predictions

INTRODUCTION

Coastal flooding caused by extreme storms has been a challenging issue that requires current adaptation measures to be updated to account for changing climates. One example of this is Super Storm Sandy, which resulted in 72 deaths and over $50 billion in damages in the US from New Jersey to Rhode Island (Galarneau et al., 2013). Without any actions to address the impacts of climate change, it is estimated that the cost globally could reach $63 billion per year by 2050, even if flood probability remains unchanged (Hallegatte et al., 2013; Prime et al., 2015). Climate change has been causing sea levels to rise, which worsens the impact of storms and hurricanes (Lin et al., 2016; Liu et al., 2020; McInnes et al., 2003; O'Donnell et al., 2016). Liu et al. (2020) and O'Donnell et al. (2016) found that due to sea level rise, storms that have a 1% chance of occurring in a given year (annual exceedance probability- AEP) can now occur with a 3% to 5% AEP in coastal towns in Connecticut. The increasing frequency of severe flooding has made it important to accurately map flood-prone areas and develop criteria for adaptation methods to improve flood resilience.

The City of New London has a developed coastline along the Thames River and the Long Island Sound, which includes various types of shorefront like rocky areas, bluffs, escarpments, and intertidal flats. Many homes, businesses, industries, and critical infrastructures close to the coast are at a lower elevation and more prone to coastal flooding. Past storms like Superstorm Sandy have caused coastal flooding in New London, causing damage to properties and the City received federal assistance (City of New London, 2017). New London is also concerned with the potential long-term impacts of rising sea levels on future flooding conditions.

METHODS

The Finite Volume Community Ocean Model (FVCOM) (Chen et al., 2006; Qi et al., 2009) was used to simulate extreme storm events in the Thames River. FVCOM is an unstructured-grid, 3D primitive equation ocean circulation model. FVCOM-SWAVE, a variant of FVCOM that was coupled to an adapted Simulating Wave Nearshore (SWAN) model (Booij et al., 1999), incorporates the exchange of wave radiation stresses as well as near-bottom and surface shear stresses (Qi et al., 2009; Wu et al., 2011). An unstructured mesh of minimum 5 m resolution along the shoreline (Fig. 1) was created using OceanMesh2D (Roberts et al., 2019). The mesh covers both water and land below 5 m NAVD88. Open boundary forcing include wave and surge water level from Liu et al. (2020). Model topography is from the USGS CoNED topobathemetric data product. For each FVCOM model run, the maximum water elevation and significant wave height were aggregated for each grid point, and were then used to create subgrid-scale flood maps using Kalpana (https://ccht.ccee.ncsu.edu/kalpana/).

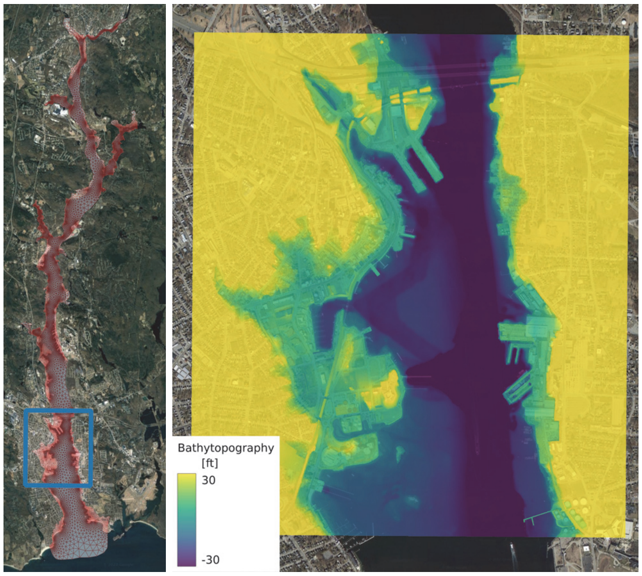

Fig.1 Left panel: FVCOM unstructured mesh of the parent domain covering from the mouth of the Thames River to Norwich, CT. Blue rectangle represents the extent of the FUNWAVE subdomain. Right panel: Bathytopography of the FUNWAVE subdomain covering the downtown area of New London, CT.

For the subdomain covering the downtown New London area where high-resolution flood predictions are required, we used the phaseresolving Boussinesq wave model of FUNWAVE-TVD (version 3.5) (Shi et al., 2012). FUNWAVE-TVD uses a two-way numerical wavemaker for source terms (Wei et al., 1999). The irregular wind-waves are generated by the wavemaker using a finite depth TMA spectrum (Bouws et al., 1985). The wavemaker, with the γ parameter set to 5 and frequency ranged between 0.03-0.3 Hz, was placed 150 m north of the southern boundary in the model domain. Following Westcott (2018), a flattened area with a constant depth comparable to the real depth at the wavemaker was created around the wavemaker (250 m width) to ensure proper wave generation. The bottom friction was specified with a uniform drag coefficient, cd = 0.003. The surge water level and maximum significant wave height forcing for the FUNWAVE domain come from the FVCOM parent domain (Table 1). The surge level was prescribed at the boundaries in a slowly increasing manner, because sheltered basins in our area may not be fully flooded during storms. The model simulates 2 hours, and the water level along the nesting boundary ramps up linearly from 0.5 m below the target surge level to the target surge level during the first hour of simulation, and remains constant at the target surge level during the second hour of simulation. No sponge layer was used to avoid unintended interference with surge water level forcing. The grid resolution is 2.4 m for all model runs. The linear dispersion relation and upper bound frequency (0.3 Hz) we used imply the minimum wavelength in the model is approximately 3.25 m, thus using a grid size of 2.4 m is appropriate. FUNWAVE was run with Cartesian coordinates in meters and model grids were projected to the State Plane Coordinate System.
Annual exceedance probability (AEP) refers to the probability of a flood event occurring in any year. A return interval is the average time between flood events. For example, the return interval of a flood might be 100 years; otherwise expressed as its probability of occurring being 1/100, or a 1% chance in any one year. Using the one-way nested FVCOMFUNWAVE model system, we performed simulations to estimate the effects of coastal waves and wave run-up under storms with 1%, 2%, and 10% AEP considering both the current sea-level and the 2050 sea-level rise projections. Boundary conditions for these future storm scenarios applied to the FVCOM domain are from a larger Long Island Sound model (Liu et al., 2020).

Table 1. Open boundary conditions for FUNWAVE

Scenario	Hs (m/ft)	Surge (m/ft)
10 year	1.46/4.79	1.77/5.81
50 year	1.9/6.23	2.23/7.32
100 year	2.07/6.79	2.31/7.58
10 year + SLR	1.97/6.46	1.89/6.2
50 year + SLR	2.4/7.87	2.31/7.58
100 year + SLR	2.58/8.46	2.38/7.81

RESULTS AND DISCUSSION

Validation

To validate the water elevation estimates by FVCOM, a simulation of the Superstorm Sandy was performed and results compared with the NOAA tide gauge and data from a high water mark (HWM) location and a storm surge sensor (SSS) deployed by USGS during the superstorm (Fig. 2). Model estimated peak water level is 1.85 m at the HWM location with the observed water height of 1.74 m (both values are above NAVD 88). The modeled water level time series also agree with the observations, with the differences in the peak water level <10 cm.

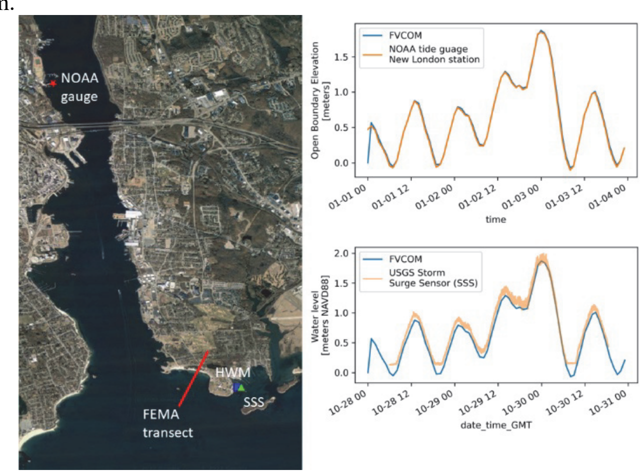

Fig.2 Left: locations of the NOAA tide gauge (red star), the storm surge sensor (green triangle), high water mark (blue square), and the FEMA transect (red line). Right: Time series of the observed and FVCOM-modeled water level during Superstorm Sandy at the NOAA tide gauge and the storm surge sensor locations.

Comparison with FEMA and NACCS

Estimated wave height for a set of return periods made by the North Atlantic Coast Comprehensive Study (NACCS) and FEMA Flood Insurance Study were compared with the same estimates from the present study's FVCOM outputs. Fig. 3 shows that under the 100-year storm scenario, the overall surge water level estimated by FVCOM is lower than that from NACCS, whereas the FVCOM-estimated significant wave height is higher than that from NACCS. The 10- and 50-year scenario results exhibited similar patterns (not shown). The study area's FEMA BFE water levels are comparable with the present FVCOM model's predictions near the Thames River mouth, whereas the FEMA-projected upstream water level is higher (Fig. 4).

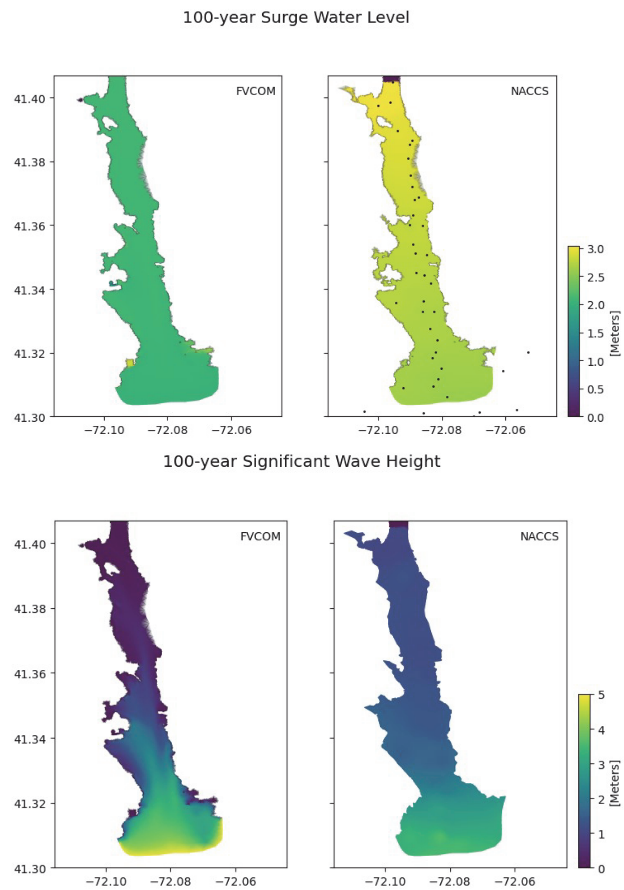

Fig.3 Comparison of the maximum storm surge water level (top 2 panels) and significant wave heights (bottom 2 panels) under the 100-year scenario between FVCOM and NACCS. Black dots in the NACCS plot indicate locations of the NACCS "save points".

Extreme Storm Modeling

Maps of predicted flood extent and flood water depth above ground were created based on the AEP projections, using the nested FVCOMSWAVE and FUNWAVE configuration. A total of 6 scenarios of current floods (10-, 50- and 100-year) and future floods (10-, 50-, and 100-year +20 inches sea level rise) are considered (Fig. 5).

Connecticut is anticipating a rise in sea level up to 0.5 m (20 inches) by 2050 (O'Donnell, 2019). Liu et al. (2020) demonstrated that this increase in sea level will lead to more frequent and severe storms. Specifically, 10% AEP storms are expected to become 30%-50% AEP events, and 1% AEP storms are expected to become 5% AEP events (Fig. 6). The flood maps for the 10% AEP with current sea level and 1% AEP events in 2050 show minimal differences in the extent of flooding. The elevation changes result in similar low-lying areas being flooded during both scenarios. However, the higher likelihood of these events occurring annually indicates that planning efforts should consider implementing protective measures in areas frequently flooded by 10% AEP storms.

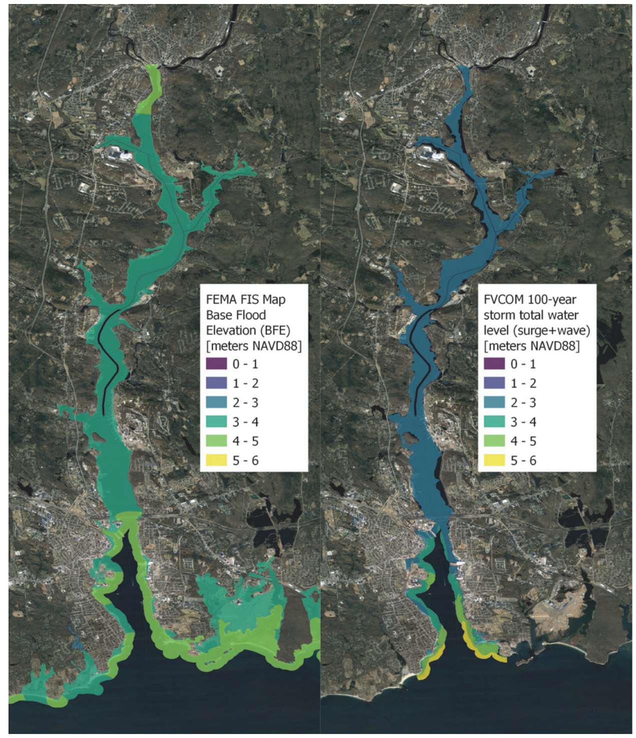

Fig.4 Comparison between the FVCOM-estimated maximum total water elevation (surge + waves) under the 100-year storm scenario and the 100-year base flood elevation (BFE) from the FEMA Flood Insurance Study (FIS).

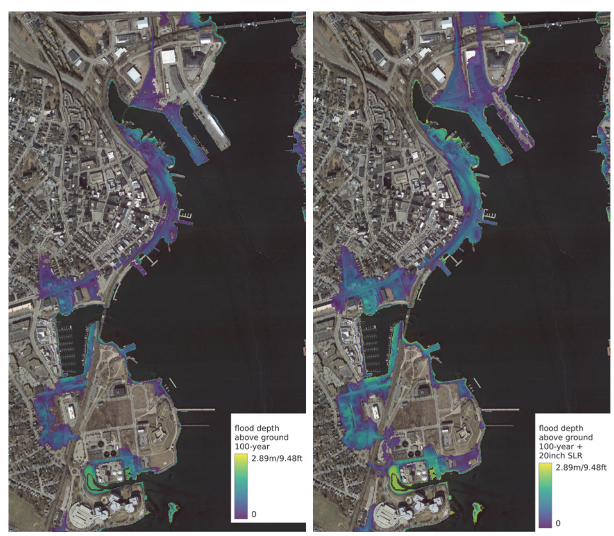

Fig.5 FUNWAVE-estimated maximum flood depth above ground and flood extent for the 1% AEP scenarios of current floods (left panel) and future floods (with 20 inches sea-level rise; right panel).

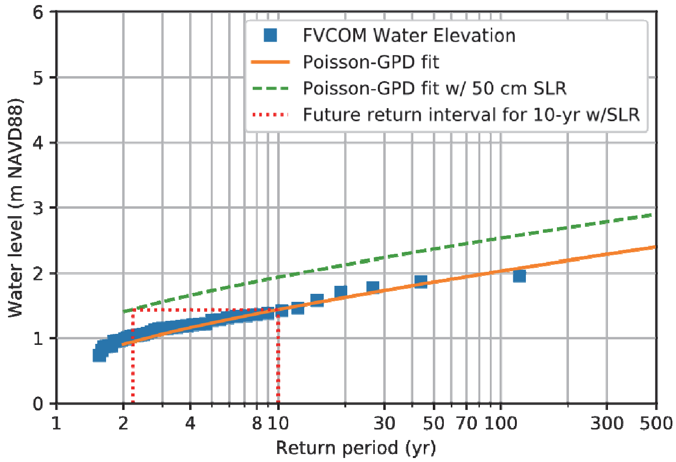

Fig.6 The water level and return period plots for New London are shown both with and without a 20-inch sea-level rise (SLR). The blue squares represent the modeled water levels during 44 extreme storms, while the orange line represents the Poisson-GPD fit of these extreme storm water levels. The green dashed line shows the same fit, but with 50 cm SLR. The red dotted lines illustrate that the water level of a 10-year storm without SLR would be equivalent to that of a 2- to 2.5-year storm with SLR. See (Liu et al., 2020) for more details.

CONCLUSIONS

In this study, we set up a nested nearshore model system to simulate future flooding scenarios with sea-level rise. Results suggest that sea-level rise has a significant impact on the frequency and severity of nearshore flooding due to storm surges. Through the use of high resolution topographical and hydrodynamic data, our model is able to accurately simulate the complex interactions between storm surges and coastal inundation. The results of the modeling efforts suggest that as sea levels continue to rise, the risk of nearshore flooding will increase, potentially leading to significant damage to coastal communities and infrastructure. Model results can also be used to guide adaptation solutions (Liu et al., 2022). Current FEMA and NACCS efforts may not estimate future storm surge scenarios accurately, as they typically use low-resolution data and simplified models (Grilli et al., 2020). Therefore, the methodology and findings of this study can provide valuable insight and support to coastal planning and management decisions that aim to enhance disaster resilience in the face of sea-level rise. The findings of this study highlight the need for continued research and monitoring of sea-level rise and its effects on nearshore flooding, as well as the importance of implementing effective adaptation and risk management strategies to protect coastal communities and infrastructure.

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