THE UNIVERSITY OF MAINE 1865

1st International Workshop on Waves, Storm Surges and Coastal Hazards

An integrated multi-scale model system for coastal flooding forecasts at Northeastern United States

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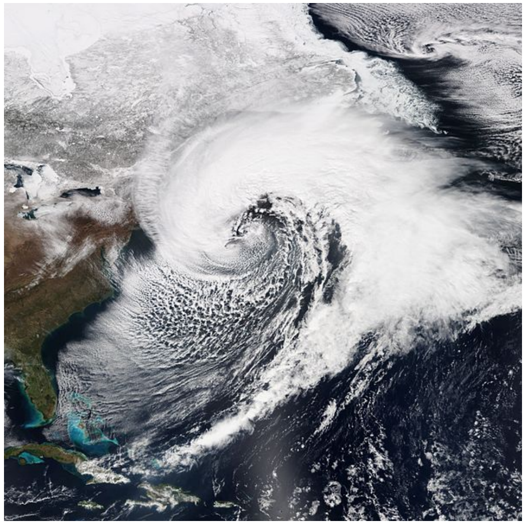
Storms and Coastal Flooding

❑ ***Coastal flooding is a significant socioeconomic hazard***

"The aggregated loss due to storm surge and wave damage in US coastal areas reached approximately 400 billion dollars for major storm events between 1980 and 2012" (The US Billion-dollar Weather/Climate Disaster report by NCDC/NOAA)



Sea level rise

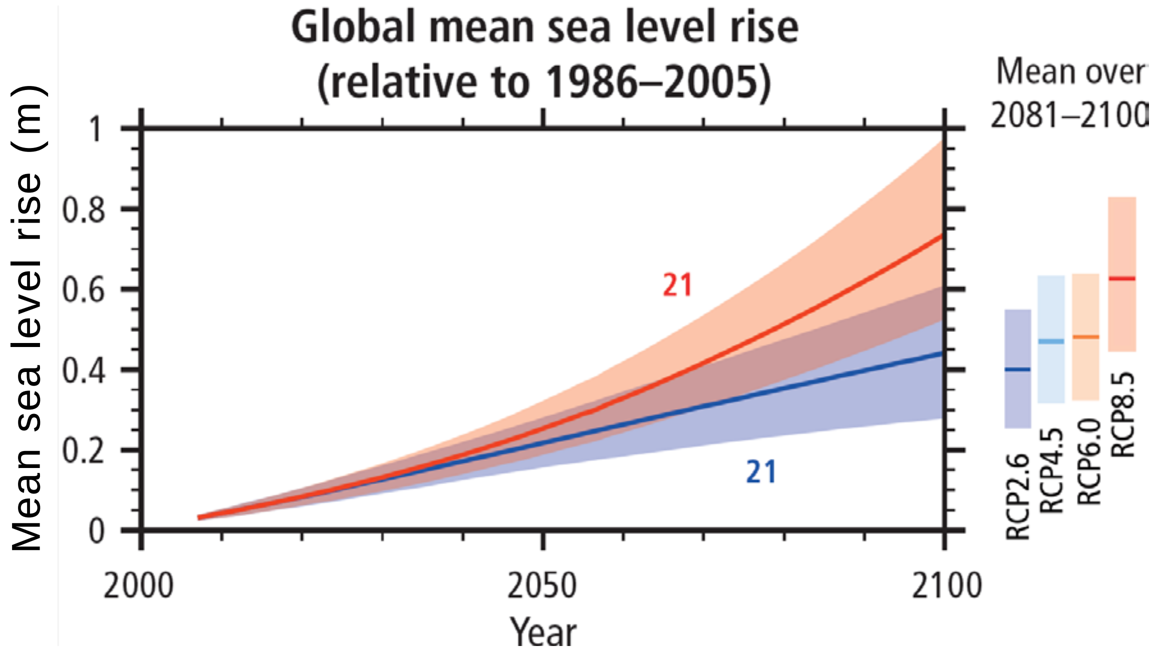


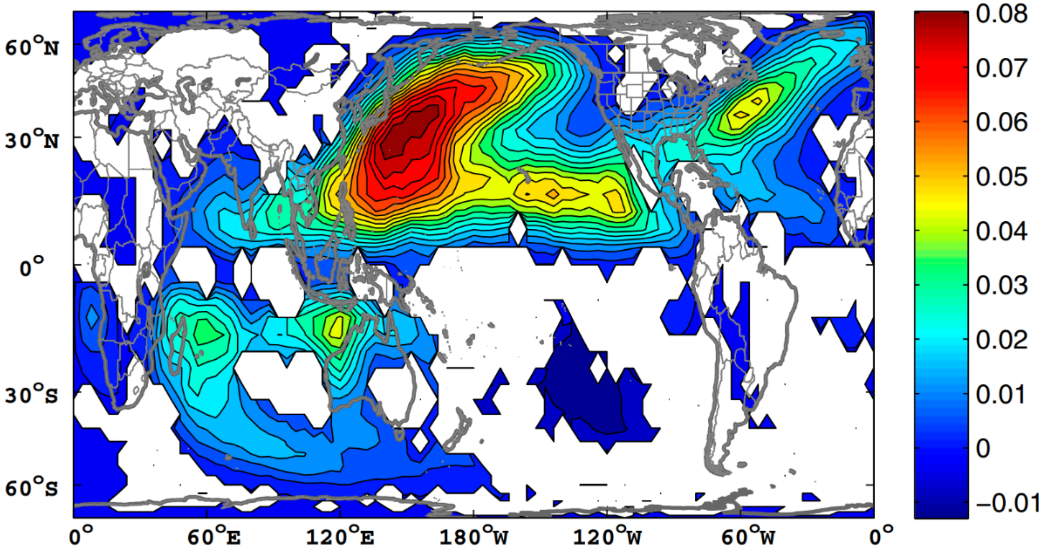
Figure 2.1(d) of IPCC AR5

- *IPCC AR5 predicted that the global mean sea level will rise on the order of 0.3-1.0 m by 2100 under the presumed low to high greenhouse gas emission scenarios*

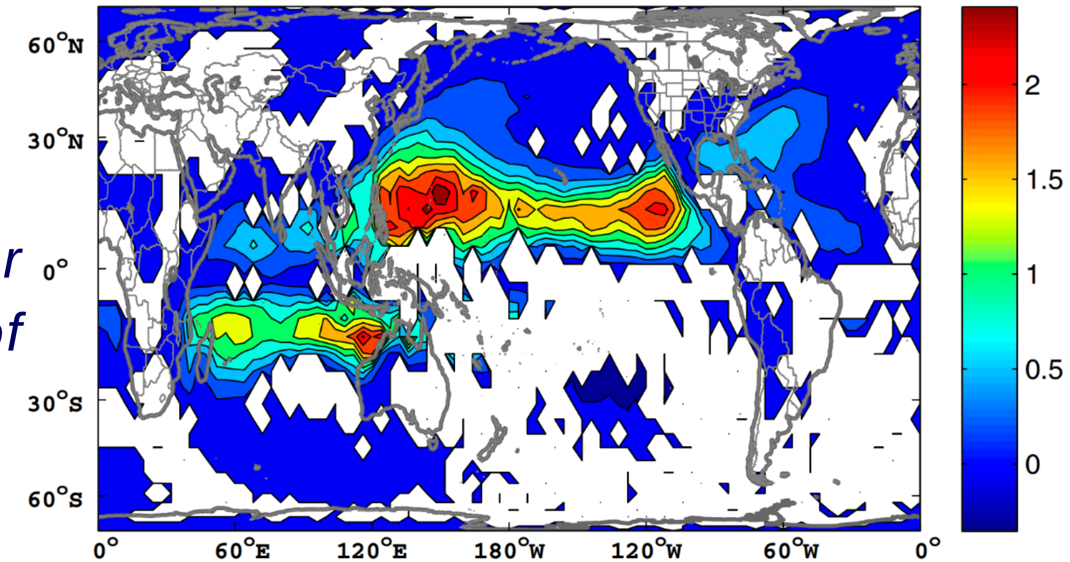
- *Nicholls (2002, 2006) identified enhanced storm flooding and lowland inundation as one of the four major impacts of sea level rise*

- *Kirshen et al. (2008) and Roberts et al. (2017) both predicted decreased return intervals for major coastal floods along the northeastern coast of U.S. in the second half of 21st century*

Intensification of storminess



- Change in track density of tropical cyclones



- Change in power dissipation index of tropical cyclones

Both figures are from Emanuel (2013)

Lack of study of wave overtopping

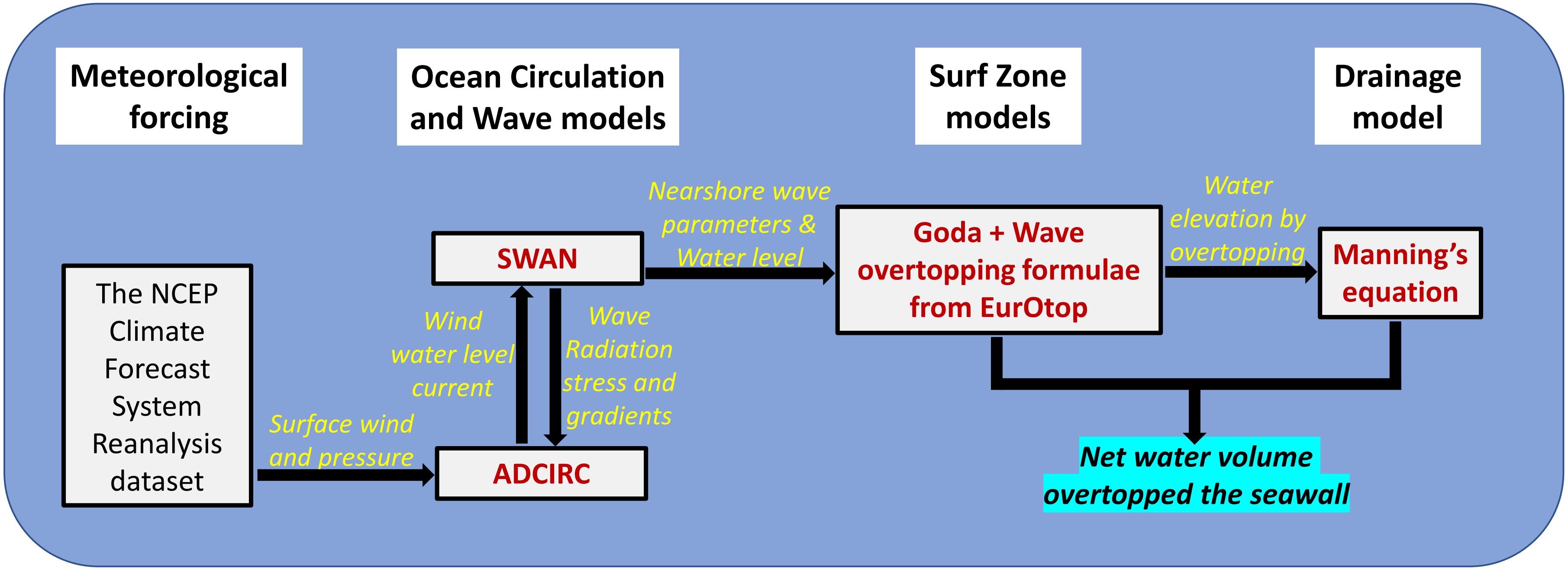
- In Massachusetts, approximately 360 km, or 20% of the coastline, is protected by seawalls.
- Wave overtopping of seawalls occurs frequently during the storm season
- seawall breaches resulting in major flooding of coastal communities has been reported during severe storms
- Lack of field observation and model study of wave overtopping along the northeastern coast of United States

Objectives

- To develop an integrated atmosphere-ocean-coast model for coastal flooding prediction
- To investigate the contribution of wave, tide, surge and their interaction to coastal flooding
- To predict coastal flooding due to wave overtopping at coastal defense
- To examine the impact of sea level rise on wave overtopping and inundation

"Clouds-to-coast" modelling framework

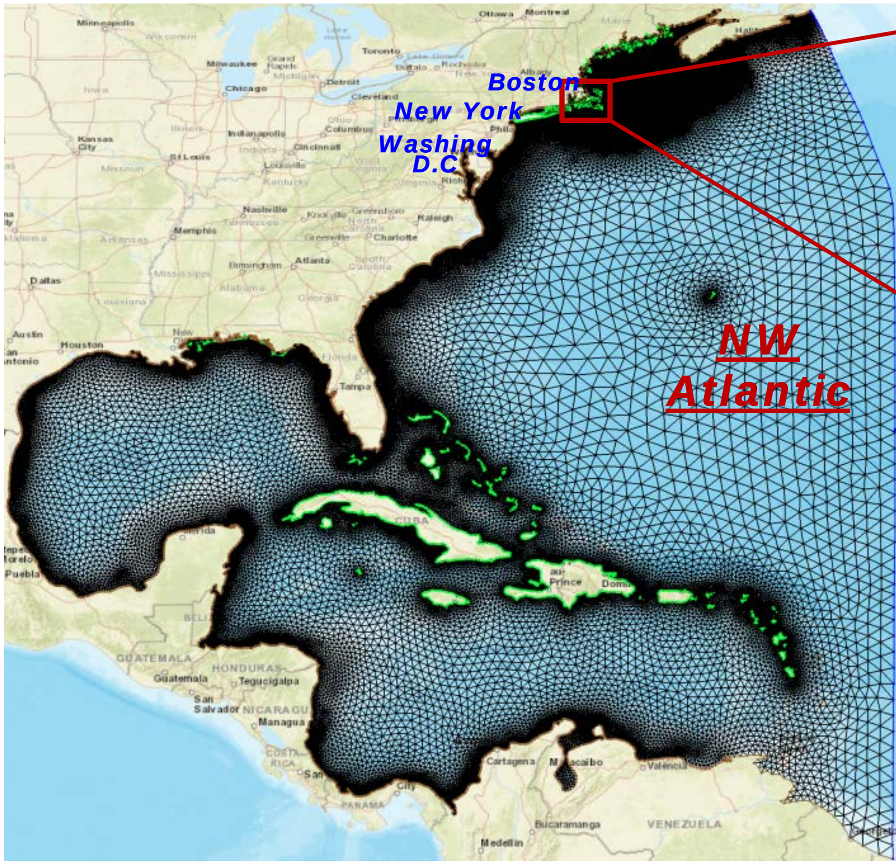
- An integrated atmosphere-ocean-coast ("Clouds-to-coast") modeling study of flooding due to overtopping at coastal defense

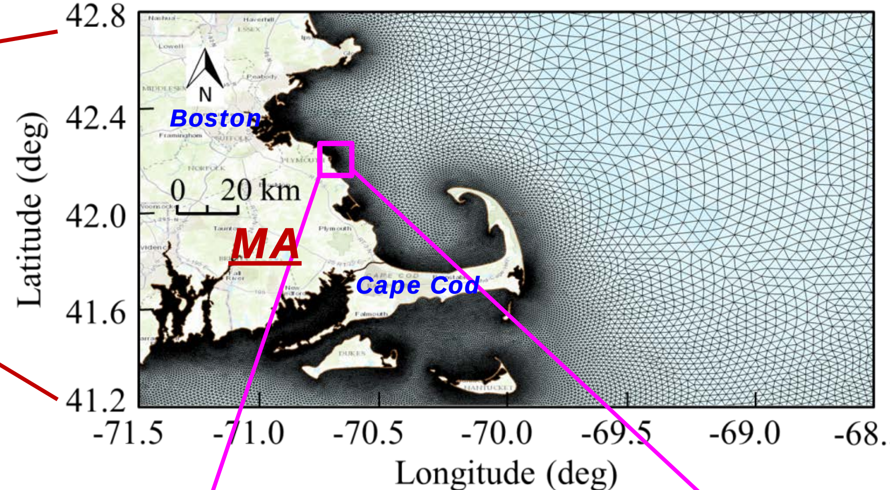


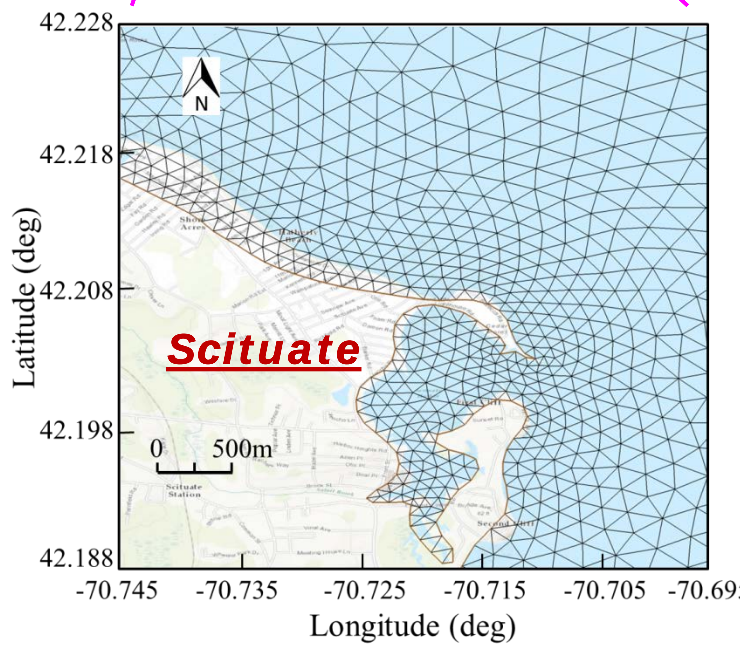
ADCIRC: The ADvanced CIRCulation model

SWAN: Simulating WAves Nearshore

Unstructured grid for SWAN-ADCIRC





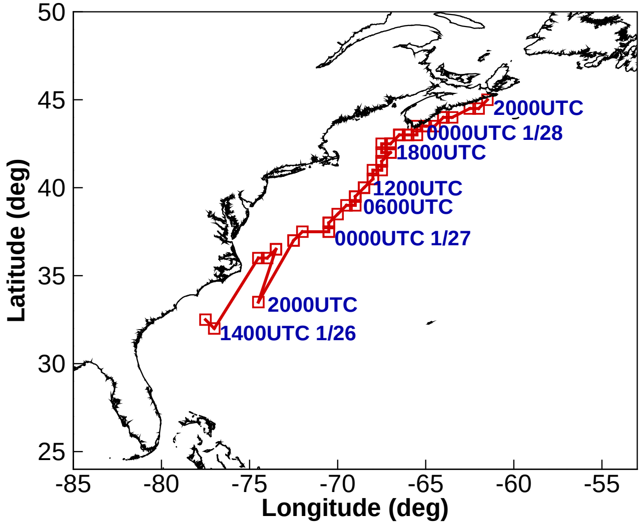


Grid size: ranging from 100 km in deep basin to 60 m at the Scituate coast

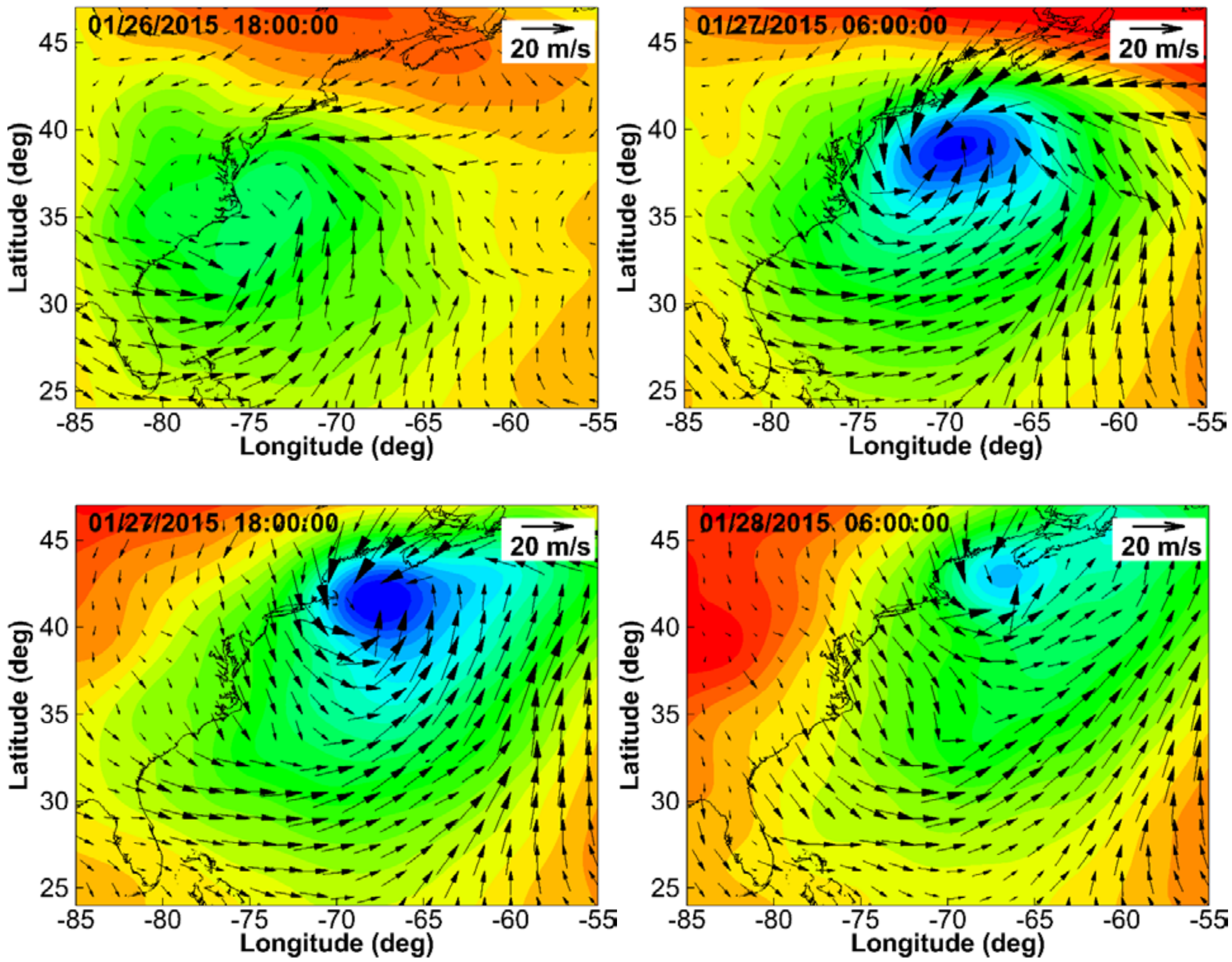
The January 2015 North American Blizzard

- Storm track: northeastward off the Mid-Atlantic coast to the east coast of Canada
- Lowest recorded pressure: 970 hPa
- Highest wind gust: 42.5 m/s

Storm track



Surface wind and pressure

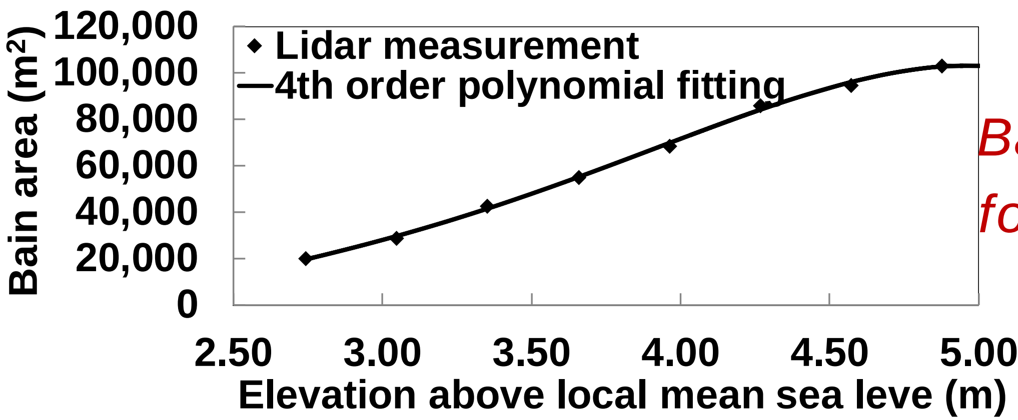


Field site - Scituate, Massachusetts, USA

- Located approximately 40 km to the southeast of Boston
- Frequently subjected to large ocean waves generated by northeasterly winds
- The Avenues Basin in Scituate is periodically flooded due to storm waves overtopping the seawall and overwhelming the drainage system

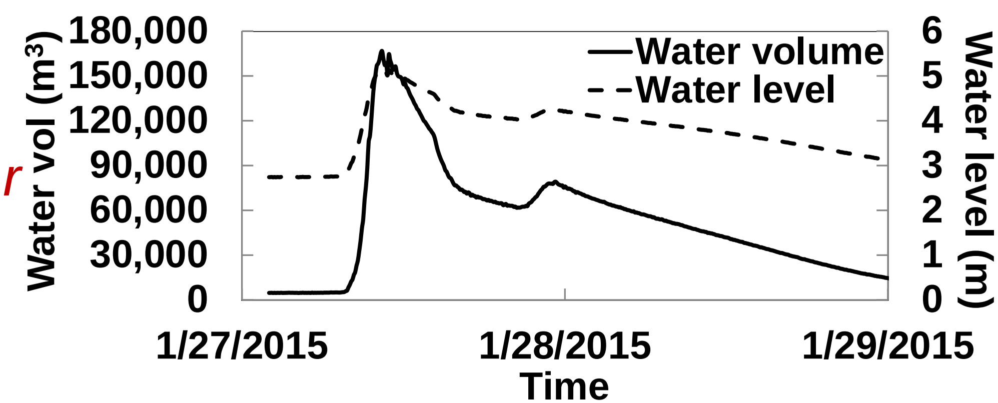
Field measurements

- Staff gauge + Hobo data logger to measure the still water level
- Basin area: USGS Lidar data
- Water volume in the basin: integrating the basin area over the whole range of water level



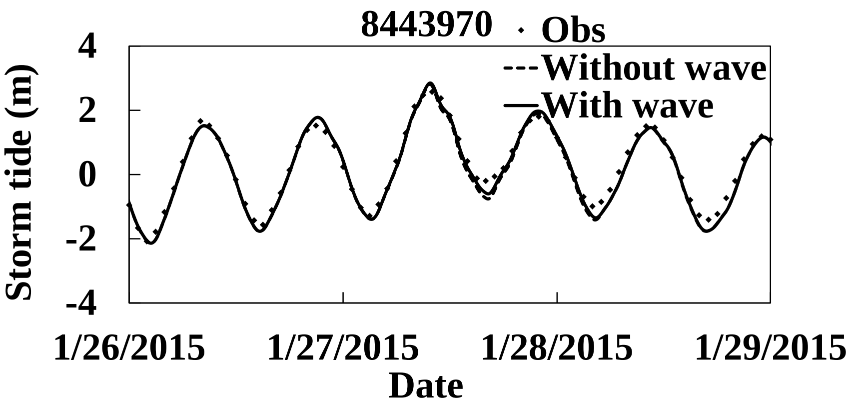
Basin area vs. elevation for the Avenues Basin

Water level vs. water volume in the basin

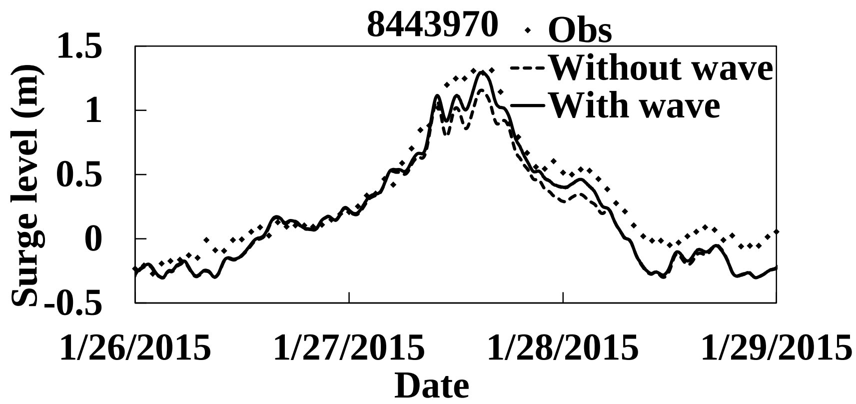


Water level and waves validation

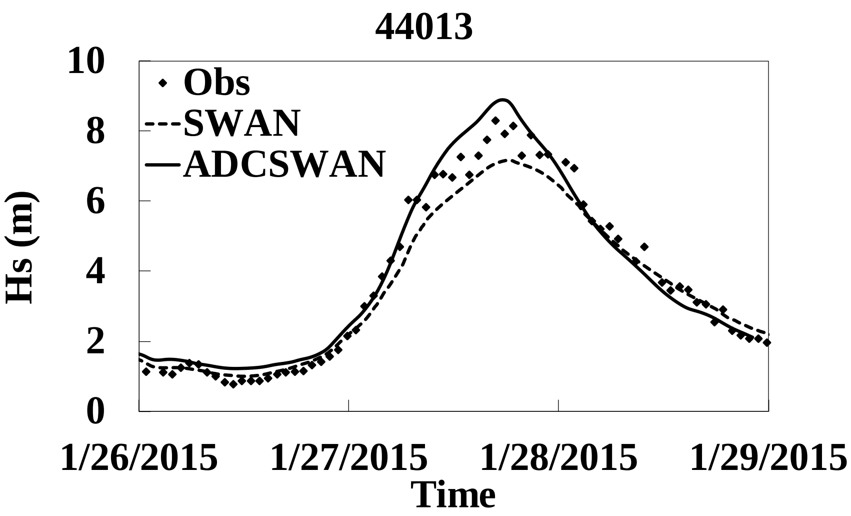
Total water level



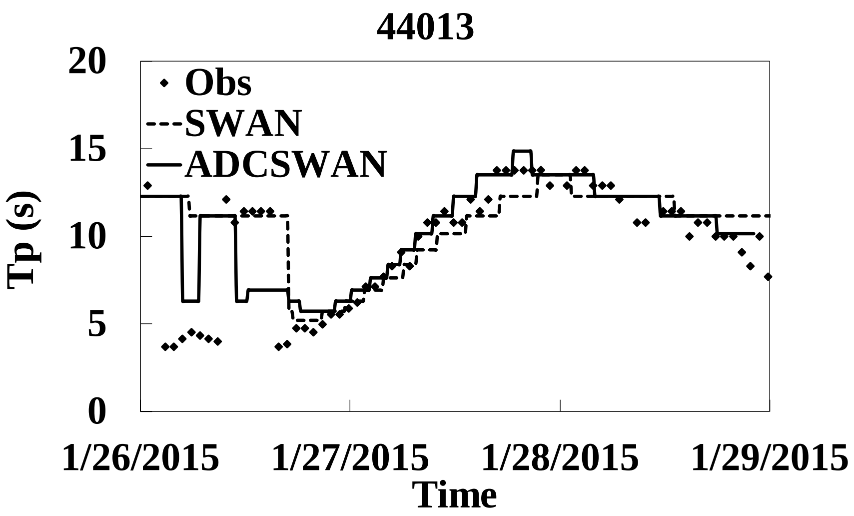
Surge level



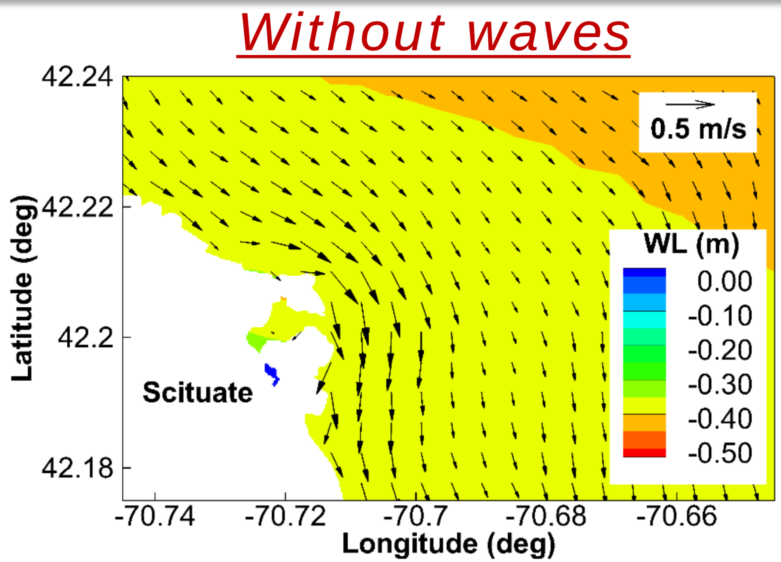
Significant wave height

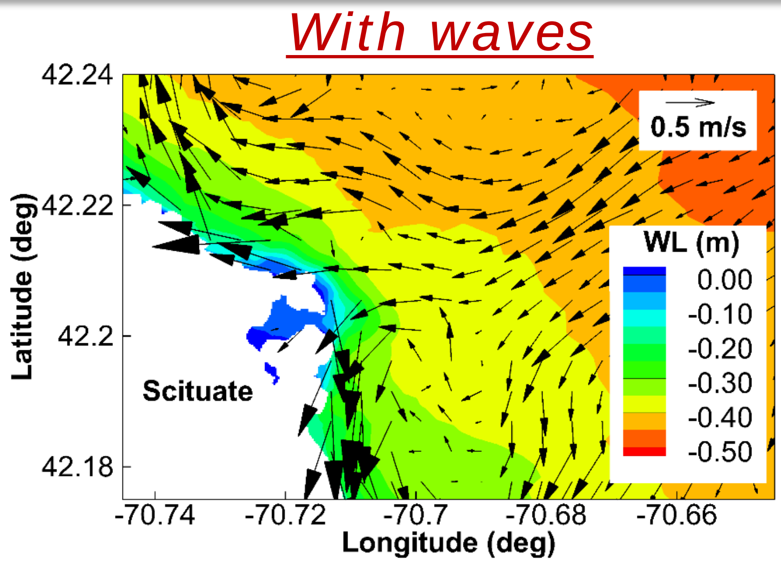


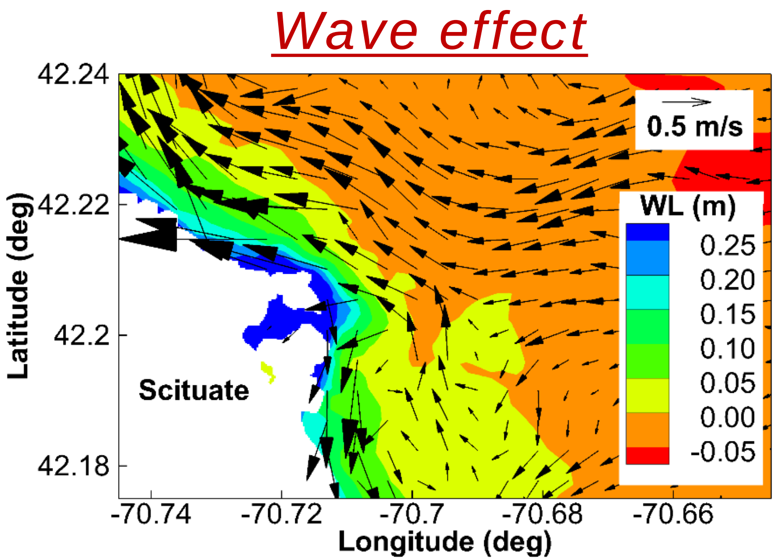
Peak wave period



Wave effect on water level and current at storm peak



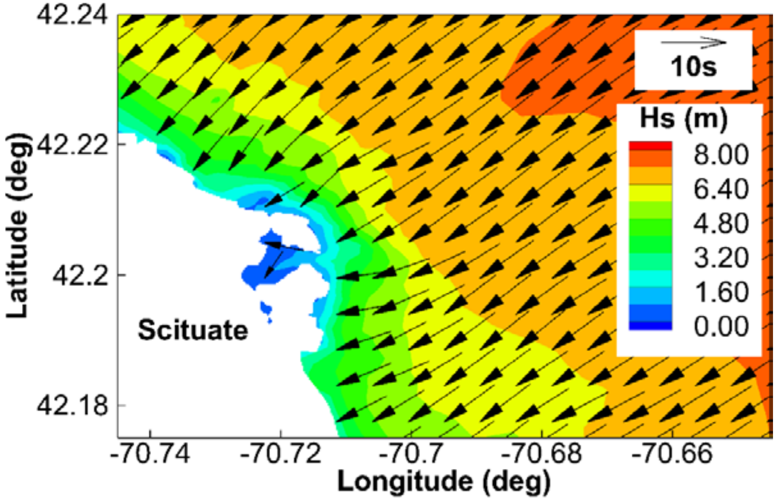




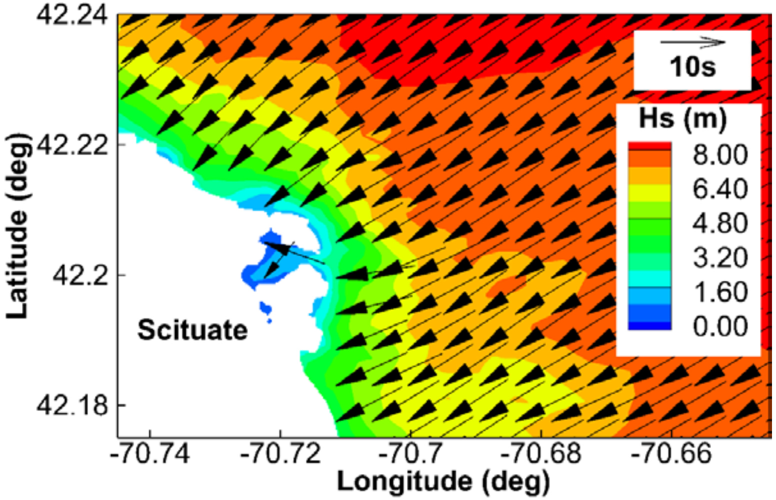
- *Wave setup is in the order of 0.3 m*
- *Strong wave-induced current*
- *The wind-driven current ranges from 0.2 m/s to 0.5 m/s. The wave-induced current reached 1.0 m/s and is dominant in the system.*

Water level and current effect on peak wave field

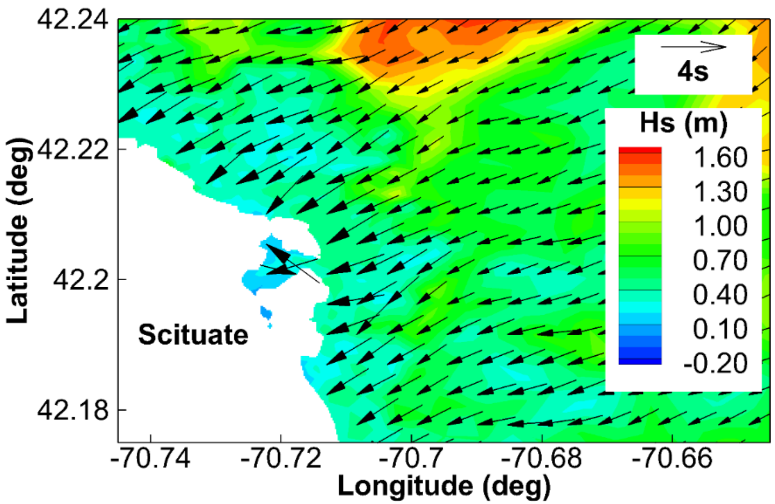
Without water level and current



With water level and current



Water level and current effect

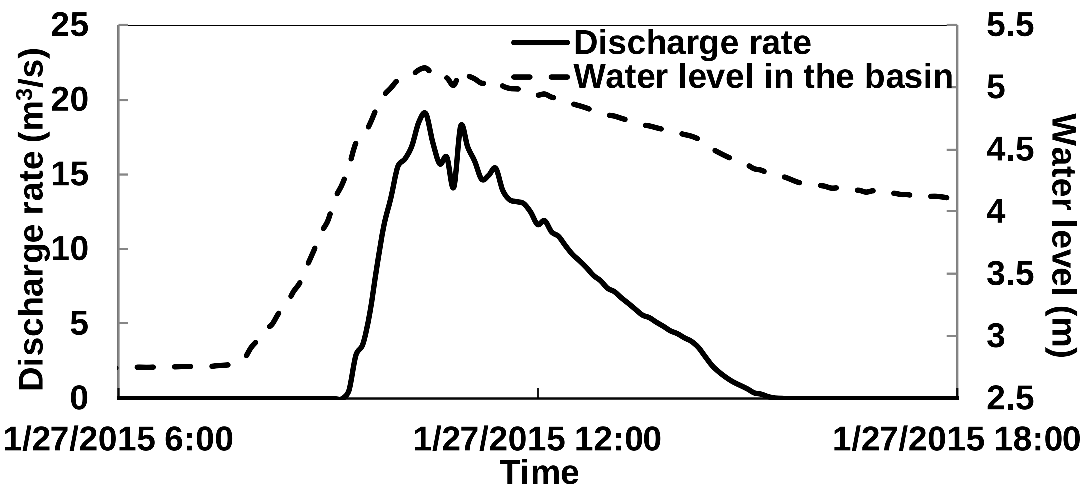


- *In relatively deeper water, the significant wave height increased by 0.5m to 1.5m*
- *At the coast, the impact of tide-surge is negligible since the wave height reached its peak near rising mid-tide*

Drainage rate simulation

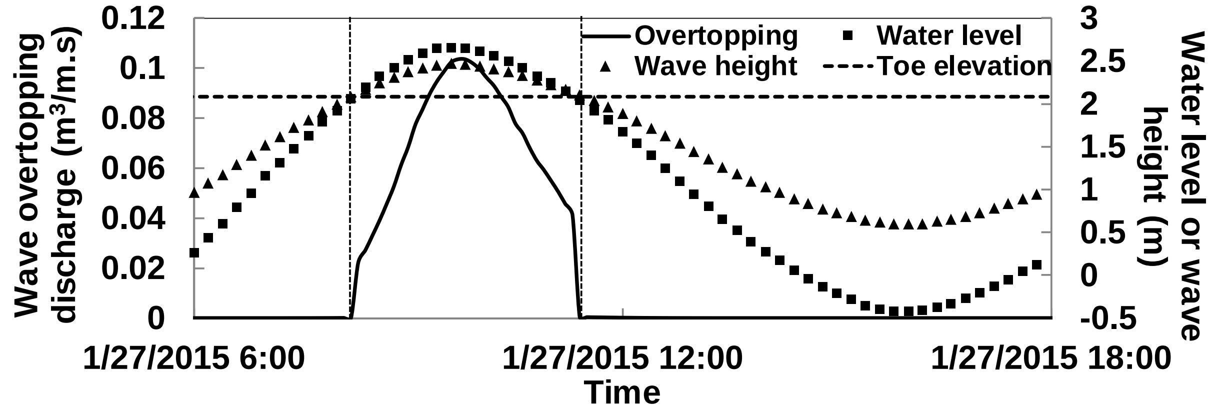
- The flow corridor was simplified as an isosceles trapezoid.
- The drainage rate was calculated at the 6-minute interval based on the measured water level
- The peak discharge rate through the corridor was 19.0 m^3/s.
- The flow discharge rate through the outlet pipe was 0.7 m^3/s

Discharge rate vs. water level

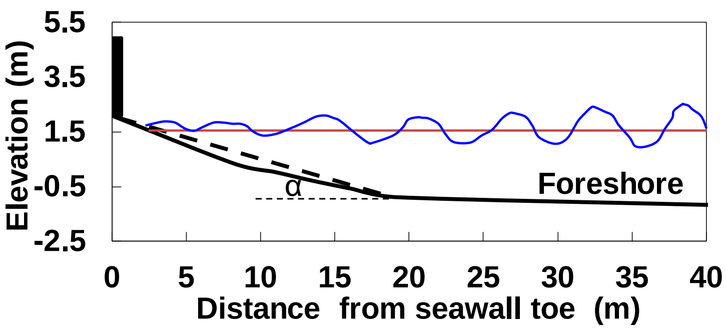


Wave overtopping and water level

<u>*Wave overtopping vs. water level and significant wave height*</u>



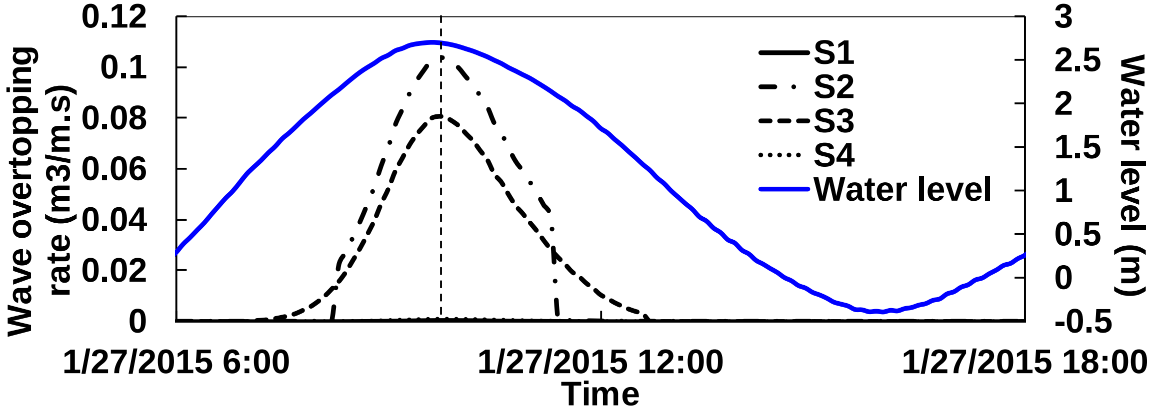
<u>*The sketch of the cross-shore profile at S2*</u>



- Between 8:12UTC and 11:24UTC on 1/27/2015, the seawall toe at S2 became submerged. With increased water level during this period, the significant wave height at the toe of the integral structure increased accordingly. Large waves rushed up the structure, resulting in significant wave overtopping at this site.

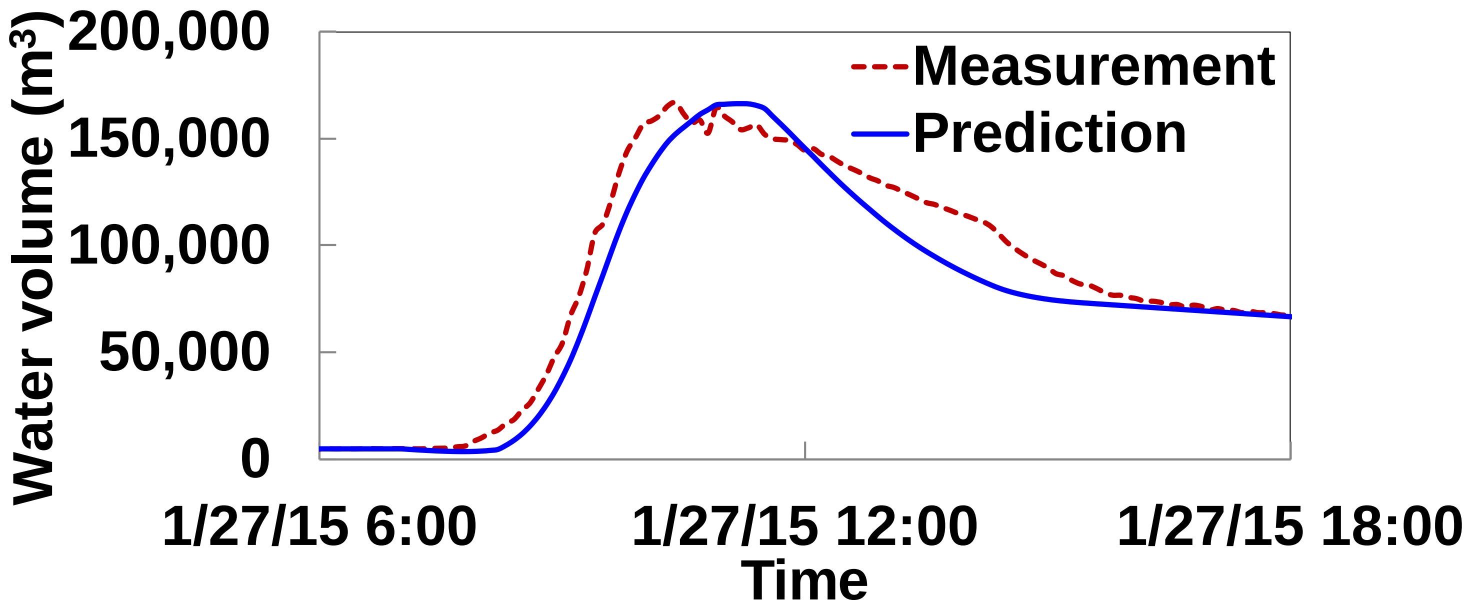
Alongshore variation of wave overtopping

Mean wave overtopping discharge at S1-S4



- At S2 and S3, the mean wave overtopping discharge reached 0.10 $m^3/m.s$ and 0.08 $m^3/m.s$
- Wave overtopping at S1 and S4 is negligible
- Wave overtopping discharge is in general in phase with water level at the toe of the seawall. At storm peak, seawall toe at S2 and S3 was submerged, while the seawall toe at S1 and S4 was still emergent
- Wave overtopping discharge at S2 increased more rapidly than that at S3, which was mainly due to more vigorous wave breaking resulted from the larger slope at S2 than that at S3

Model-data comparisons of overtopping water volume



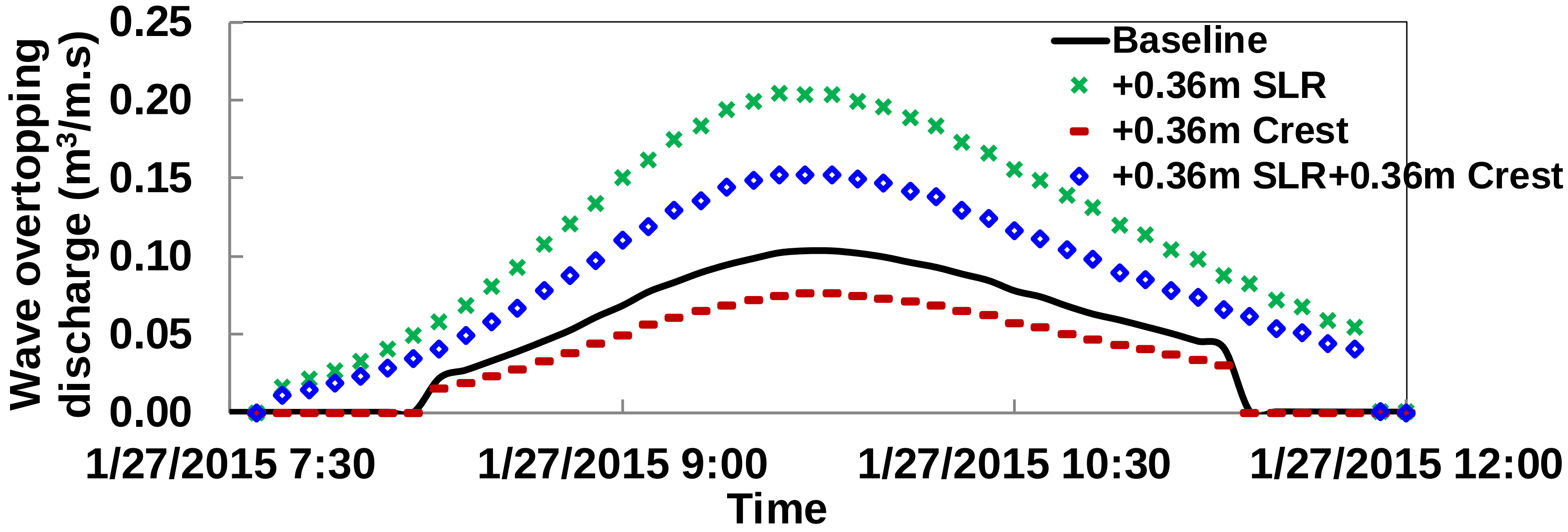
- ❑ The prediction agrees reasonably well with the measurement.
- ❑ The slight lag of predicted peak volume mainly results from slight phase difference between the predicted water level and observed data.
- ❑ The model predicted rapid decrease of water volume in the basin after the peak, which may be partially attributed to the parameterization of flow rate through the corridor.

Impact of sea level rise and crest elevation

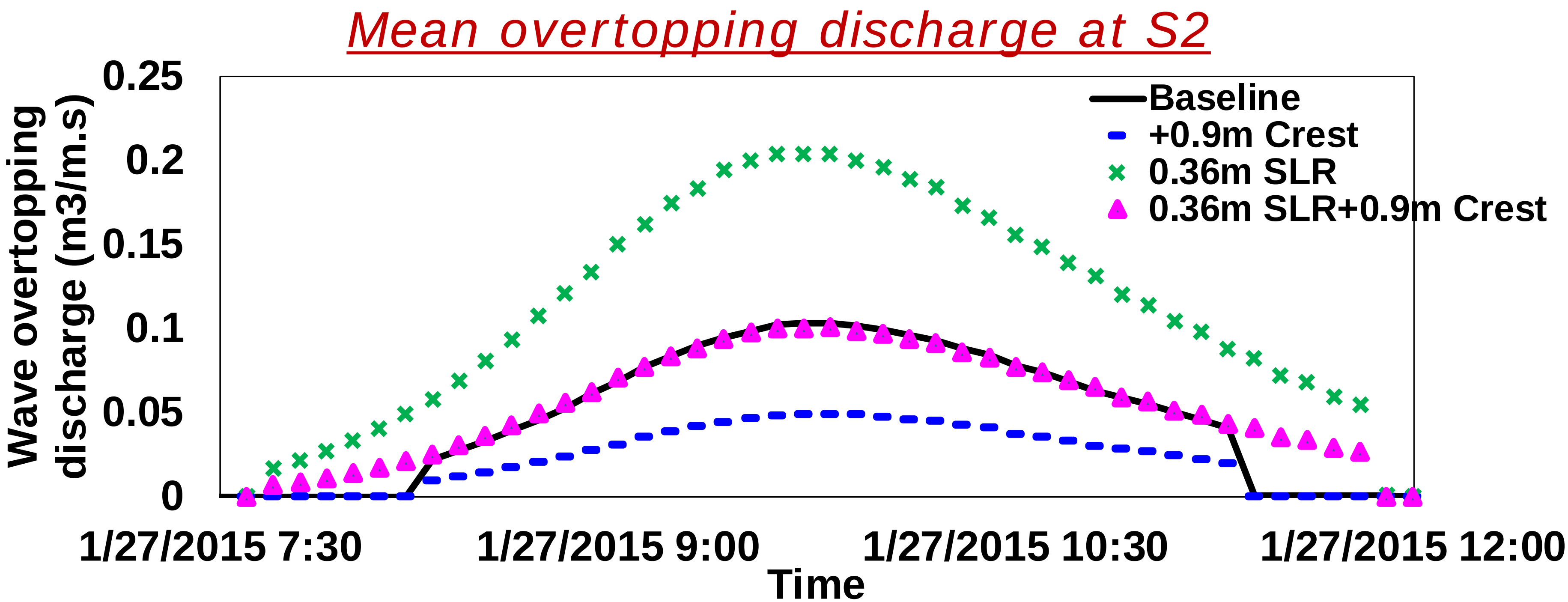
- The relative sea level rise estimates for Boston, MA

Scenario	2050 (m)	2100 (m)
Highest	0.55	2.08
Intermediate High	0.36	1.28
Lowest (Historic Trend)	0.12	0.25

Mean wave overtopping discharge at S2



Adaptation of the seawall



- *Without considering any sea level rise, the mean wave overtopping discharge will be reduced to 0.05 $m^3/m.s$ by raising the seawall crest by 0.9 m*

- *With 0.36 m sea level rise, the mean wave overtopping discharge will be the same as the current case by raising the seawall crest by 0.9 m*

Conclusion and discussion

- *An integrated "clouds-to-coast" nearshore circulation and wave model and surf zone model was constructed and validated*
- *At the storm peak, the significant height is increased by 0.7 m at the Scituate coast with tide-surge effect. The wave setup along the coast varies from 0.1 m to 0.25 m depending on the coastline geometry.*
- *The wave overtopping prediction agrees reasonably well with the measurement. The slight lag of predicted peak volume mainly results from slight phase shift of predicted water level*
- *The mean wave overtopping discharge would increase by twice in an intermediate high sea level rise scenario of 0.36 m by 2050.*
- *The wave overtopping discharge would increase by 1.5 times by raising the seawall crest elevation with the same amount of sea level rise of 0.36 m, which mainly results from larger waves approaching the coast with increased water depth.*
- *With 0.36 m sea level rise, the wave overtopping discharge would be the same as the current wave overtopping by raising the seawall crest by 0.9 m*

Thanks!

Questions and comments?

The rest of the slides are for detailed model description

Coupled ADCIRC and SWAN

ADCIRC—Governing equation

- *Governing Equation: Solve the shallow water equations (SWE) for water levels and vertically-integrated momentum equations for currents*

Deducing from taking time derivative of vertically-integrated continuity equation

$$\frac{\partial^2 \zeta}{\partial t^2} + \tau_0 \frac{\partial \zeta}{\partial t} + S_p \frac{\partial \tilde{J}_\lambda}{\partial \lambda} + \frac{\partial \tilde{J}_\phi}{\partial \varphi} - S_p U H \frac{\partial \tau_0}{\partial \lambda} - V H \frac{\partial \tau_0}{\partial \varphi} = 0$$

$$\frac{\partial U}{\partial t} + S_p U \frac{\partial U}{\partial \lambda} + V \frac{\partial U}{\partial \varphi} - f V$$

$$= -g S_p \frac{\partial}{\partial \lambda}\left[\zeta + \frac{P_s}{g\rho_0} - \alpha\eta\right] + \frac{\tau_{s\lambda,winds} + \tau_{s\lambda,waves} - \tau_{b\lambda}}{\rho_0 H} + \frac{M_\lambda - D_\lambda}{H}$$

$$\frac{\partial V}{\partial t} + S_p U \frac{\partial V}{\partial \lambda} + V \frac{\partial V}{\partial \varphi} + f U$$

$$= -g \frac{\partial}{\partial \varphi}\left[\zeta + \frac{P_s}{g\rho_0} - \alpha\eta\right] + \frac{\tau_{s\varphi,winds} + \tau_{s\varphi,waves} - \tau_{b\varphi}}{\rho_0 H} + \frac{M_\varphi - D_\varphi}{H}$$

Newtonian equilibrium tide potential

Numerical scheme: Jacobi Conjugate Gradient (JCG) method

Coupled ADCIRC and SWAN

SWAN—Governing equation and numerical scheme

- Governing Equation: Conservation of wave action density in geographic and spectral space

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial \lambda}[(c_\lambda + U)N] + \cos^{-1}\varphi \frac{\partial}{\partial \varphi}[(c_\varphi + V)N\cos\varphi] + \frac{\partial}{\partial \theta}[c_\theta N] + \frac{\partial}{\partial \sigma}[c_\sigma N] = \frac{S_{tot}}{\sigma}$$

$$S_{\text{tot}} = S_{\text{wind}} + S_{\text{nl3}} + S_{\text{nl4}} + S_{\text{wc}} + S_{\text{bot}} + S_{\text{db}}$$

- Numerical Scheme
  - First order implicit Euler scheme for time integration
  - Four-direction Gauss-Seidel relaxation for sweeping algorithm

Surf Zone model

Goda's random wave breaking model (1975)

- *The breaker index based on compilation of various laboratory data on different beach slopes:*

$$\frac{H_b}{h_b} = \frac{A}{h_b/L_0}\left\{1-\exp\left[-1.5\frac{\pi h_b}{L_0}\left(1+15\tan^{4/3}\theta\right)\right]\right\}$$

$$H_{1/3} = \begin{cases} K_s H_0' & : h/L_0 \geq 0.2 \\ \min\{(\beta_0 H_0' + \beta_1 h), \beta_{max} H_0', K_s H_0'\} & : h/L_0 < 0.2 \end{cases}$$

$$\left.\begin{aligned} \beta_0 &= 0.028(H_0'/L_0)^{-0.38}\exp\left[20\tan^{1.5}\theta\right] \\ \beta_1 &= 0.52\exp[4.2\tan\theta] \\ \beta_{max} &= \max\left\{0.92, 0.32(H_0'/L_0)^{-0.29}\exp[2.4\tan\theta]\right\} \end{aligned}\right\}$$

$$K_s = \sqrt{\frac{(c_g)_0}{c_g}} = \left[\left(1+\frac{2kh}{\sinh 2kh}\right)\tanh kh\right]^{-1/2}$$

$$= \left[\tanh kh + kh\left(1-\tanh^2 kh\right)\right]^{-1/2}$$

Where H_b and h_b denote the wave height and water depth at breaking

Wave overtopping model

EurOtop II (2016) for sloping structure with wave wall

- With submerged wave wall toe

$$\frac{q}{\sqrt{g * H_{m0}^3}} = \frac{0.023}{\sqrt{tan\alpha}}\gamma_b * \xi_{m-1,0} * \exp\left[-\left(2.7 * \frac{R_c}{\xi_{m-1,0} * H_{m0} * \gamma_b * \gamma_f * \gamma_\beta * \gamma_v}\right)^{1.3}\right]$$

with a maximum of $$\frac{q}{\sqrt{g * H_{m0}^3}} = 0.09 * \exp\left[-\left(1.5 * \frac{R_c}{H_{m0} * \gamma_f * \gamma_\beta * \gamma^*}\right)^{1.3}\right]$$

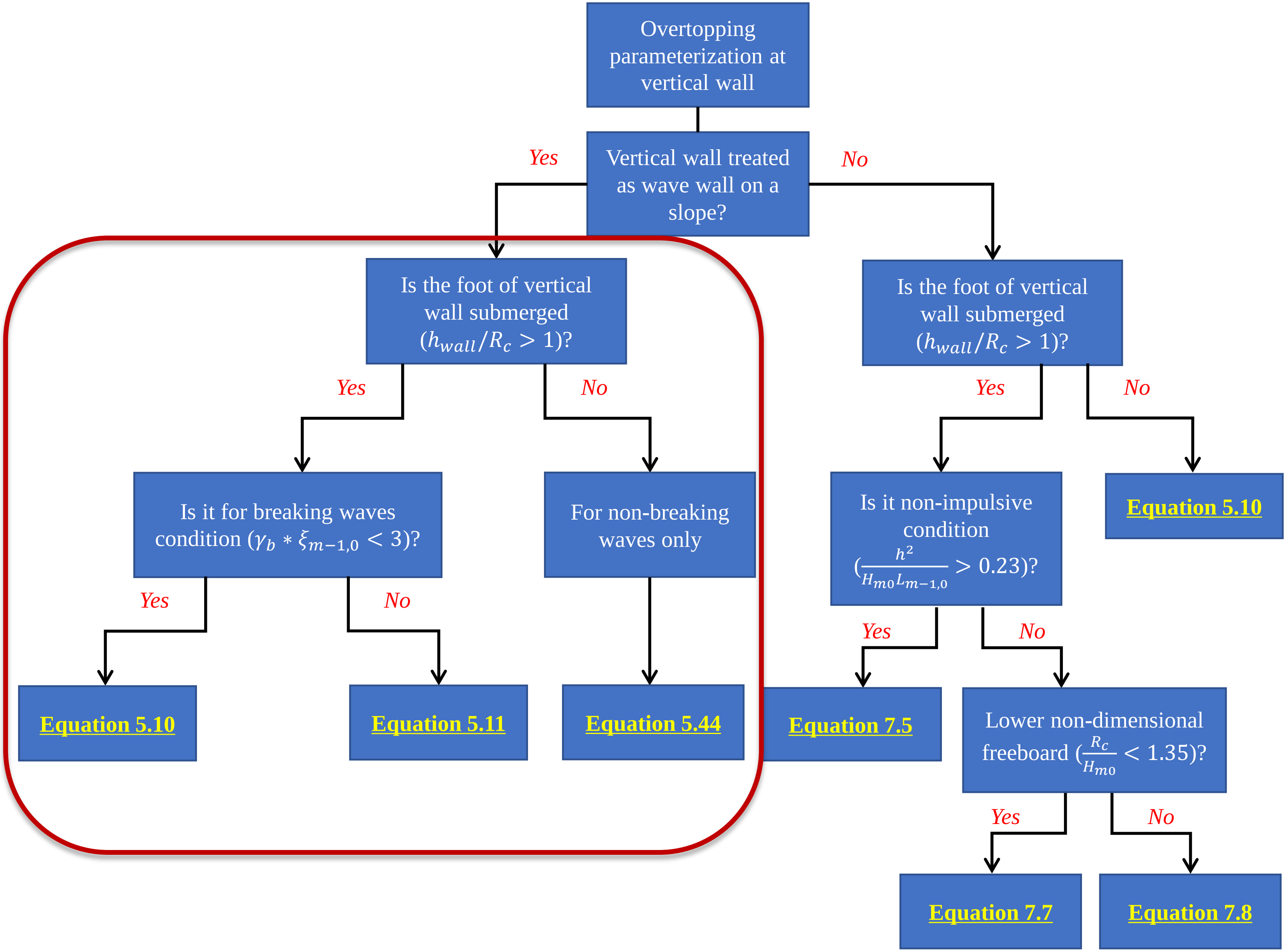
- With emerged wave wall toe

$$\frac{q}{\sqrt{g * H_{m0}^3}} = 0.09 * \exp\left[-\left(1.5 * \frac{R_c}{H_{m0} * \gamma^*}\right)^{1.3}\right]$$

$$\gamma^* = \gamma_v = \exp\left(-0.56 * \frac{h_{wall}}{R_c}\right)$$

Where q is the mean overtopping discharge, H_{m0} is the incident wave height at the toe of the structure, $tan\alpha$ is the characteristic slope of the structure, $\xi_{m-1,0}$ is breaker parameter, R_c is the crest freeboard, γ_b is the influence factor for a berm, γ_f is the influence factor for roughness elements on a slope, γ_β is the influence factor for oblique wave attack, γ_v is the influence factor for a wave wall, h_{wall} is the height of the wave wall

Flow chart wave overtopping prediction



The drainage model

Manning's equation (1996) for open channel flow

$$V = \frac{1}{n} R^{2/3} S_f^{1/2}$$

Where V is flow velocity, n is Manning roughness coefficient, R is hydraulic radius of open channels, S_f is friction slope. For uniform flow, the friction slope S_f can be replaced by the bed slope of open channels S_0.