

# Evidence for Elevated Coastal Vulnerability Following Large-Scale Historical Oyster Bed Harvesting

Short title: **Increased Vulnerability Following Oyster Bed Disturbance**

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Keywords: sediment deposition; oyster bed; wave modeling; environmental change;  
hurricanes

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This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/esp.3931

## **Abstract**

Living coastal barriers, such as coral reefs, tidal marshes, mangroves and shellfish beds are widely recognized for their potential role in mitigating flood risk. Limited data exists, however, for assessing the effectiveness of these natural defenses as forms of flood mitigation. In particular, very few mature shellfish beds exist today for modern study due to their destruction in the past few centuries. As an alternative method of study, we present here sedimentary reconstructions of storm overwash from coastal ponds internal to New York Harbor. We use these reconstructions to show that the initial degradation of oyster beds following European settlement of the area coincides with a significant increase in wave-derived overwash deposition at all three of our field sites. Numerical simulations of two flood events of record in the harbor (Hurricane Sandy and a severe winter storm in 1992) were run without and with oyster beds of varying heights (1 m above the seafloor-to-intertidal). Simulations show that the removal of these oyster beds increases wave energy directly off-shore of our field sites by between 30% and 200%. Sedimentary reconstructions and wave modeling experiments therefore both support oyster beds serving as a significant form of coastal protection prior to European disturbance.

## **Introduction**

Increased flood vulnerabilities due to rising sea-level, potential changes in storm activity and shoreline erosion are all well-recognized problems to coastal populations (e.g. Woodruff et al., 2013). In the past, shoreline communities have commonly turned to mitigation techniques involving “hard engineering” such as sea walls, revetments and levees for protection. However, there has been growing recognition of the drawbacks of these structures, such as high maintenance costs,

loss of coastal habitat and damage to nearby ecology (Sutton-Grier et al., 2015).

Recent studies suggest that protecting natural coastal ecosystems or restoring them through “green engineering” could provide viable alternatives (e.g. Arkema et al., 2013; Cheong et al., 2013; Temmerman et al., 2013; Sutton-Grier et al., 2015).

Reestablishing oyster reefs, once prominent along many coastlines (Kirby, 2004), has been presented as one potential option for reducing wave energy along coastlines where these shellfish once thrived (Cheong et al., 2013).

Experimental studies generally do not support the presence of oyster reefs as having a significant impact on rates of shoreline retreat (e.g. Meyer et al., 1997; Scyphers et al., 2005; Piazza et al., 2011). However, these past studies have been limited in scale and primarily restricted to monitoring shoreline impacts over just a few years following the placement of small caged or uncaged piles of disaggregated oyster shells. Thus, there is still a lack of scientific literature on the response of coastal systems to the presence versus absence of healthy and well-established oyster beds.

While presently few large-scale, modern oyster reef systems exist for study (e.g. Kirby, 2004), insight likely can be gained by assessing past coastline response to the initial destruction of these living barriers. Storm deposits preserved within coastal ponds extend back for several millennia and provide a means to perform such an assessment (e.g. Wallace et al., 2009; Brandon et al., 2013; Woodruff et al., 2015).

The goal of this study is to evaluate whether American oyster beds served as a significant form of flood protection prior to European disturbance. To perform this evaluation we present sedimentary reconstructions of severe storm activity from three coastal ponds in the outer bay of New York Harbor. Sites are located within

western Raritan Bay, a focal point of the oyster industry following European settlement. Sedimentary records span the past ~3,000 years and extend through the degradation of oyster beds following European colonization (~1600-1800 CE). This study strives to answer the question of whether the overharvesting of the oyster beds between 1600 and 1800 CE is concurrent with preserved evidence of increasing overwash deposition in sediments from coastal ponds. We complement these sedimentary observations with numerical experiments of recent storms to provide further quantitative insight on how near-shore wave activity might have been reduced in the presence of oyster reefs prior to disturbance. Our guiding question is: could the destruction of oyster beds following European colonization increase extreme wave heights in New York Harbor?

### **Background on Oysters in New York Harbor**

Oyster beds were one of the most notable features of New York Harbor at the onset of European colonization, covering as much as 220,000 acres (900 km<sup>2</sup>) of the Hudson/Raritan Estuary (Kurlansky, 2006). Among the most prominent of these oyster beds were those located in Raritan Bay (part of the outer bay of New York Harbor; MacKenzie, 1992; Smith, 1970; Kochiss, 1974). Raritan Bay oysters were a staple of the early European colonists' diets (Ingersoll, 1881), as well as an important source of lime for farm fields and mortar-based construction (MacKenzie, 1992). The relatively shallow oyster beds of Raritan Bay were rapidly and efficiently harvested by hand and with rakes and tongs (Kurlansky, 2006). When oysters became scarce, the remaining oysters were obtained using dredges towed from sloops and schooners (MacKenzie, 1992; Ingersoll, 1881). Passage of a number of legislative acts regulating shell-fisheries in Raritan Bay in the late 1600's and early 1700's

provide the first evidence of overfishing (McCay, 1998; MacKenzie, 1992; Kirby, 2004). However, enforcement of these laws was weak and by the early 1800's the natural oyster beds and reefs of Raritan Bay were all but gone (Kurlansky, 2006). The oyster trade survived by importing oyster seed mainly from Chesapeake Bay (MacKenzie, 1992), but the continued decline in oyster trade and distribution indicates that these planted beds were not nearly as extensive or developed as the mature natural beds that existed prior to colonization (Kirby, 2004).

## **Methods**

### *Field Sites*

Our study focuses on three adjacent coastal ponds located on the southwestern coast of Staten Island directly facing Raritan Bay (Figure 1). Drowned fluvial valleys carved into Staten Island's glacial moraine and later separated from the ocean by small barrier beaches likely form these finger-shaped basins (Brandon et al., 2014). Our primary field site, Seguine Pond, is the most northeasterly of the three ponds, followed 0.6 km and 1.9 km to the southwest by Arbutus Lake and Wolfe's Pond, respectively. Historical records support a stable barrier at Seguine Pond over the past few centuries (Brandon et al., 2014). Barrier beaches at Arbutus Lake and Wolfe's Pond have undergone some anthropogenic modifications beginning with a small groin at Arbutus present in maps following 1890 CE (Bien and Vermeule, 1890), and a dam/sea wall constructed at Wolfe's Pond in 1933 CE (Day, 2007). All modification to our two secondary study sites appears to have occurred significantly later than initial European settlement and primary oyster bed disturbance between the early 1600s and late 1700s.

## *Field Work and Laboratory Analyses*

Core locations are shown in Figure 1 and were collected using a combination of piston push- and vibra-coring following methods similar to Brandon et al. (2014). Cores were driven to the point of refusal in basal units of glacial material. Total core lengths were 5.5 m, 6.5 m and 5.0 m for the Seguine, Arbutus and Wolfe's sites, respectively.

All cores were initially split and scanned on both a Geotek and ITRAX core scanner to obtain optical (0.1 mm resolution) and x-radiograph (0.5 mm resolution) images, as well as down-core profiles of magnetic susceptibility (MS, 5 mm resolution). X-ray fluorescence (XRF) from the ITRAX core scanner also provided down-core profiles for the relative abundance for Zn, a heavy metal whose increases in sediments have been linked to the onset of industrial activities in the region (e.g. Brandon et al., 2014). Once identified, storm layers from our primary field site (Seguine Pond) were subsampled at 1 cm intervals, combusted to remove organic material and sieved at 63  $\mu\text{m}$  to obtain the percentage of coarse material by mass (hereafter defined as %coarse).

All cores were collected following significant regional flooding by Hurricane Sandy in 2012. A red surficial layer of denser, coarse-grained sediment associated with overwash from the Sandy event was evident at all three sites, and an age of 2012 CE was assigned at the base of this uppermost storm deposit. Additional chronological constraints employed at each site include: the 1954 CE onset and 1963 CE peak in cesium-137 ( $^{137}\text{Cs}$ ; Pennington et al., 1973), the 1850-1900 CE onset of industrial-associated heavy metals (e.g. Woodruff et al., 2013) and discrete radiocarbon ( $^{14}\text{C}$ ) activities (Reimer et al., 2013). Depth-to-age models and

associated uncertainties were obtained for each core using the Bayesian approach described by Brandon et al. (2014) and Woodruff et al. (2015), bounded by  $^{137}\text{Cs}$ , heavy metal and radiocarbon age constraints.

### *Modeling*

We use the coupled Advanced Circulation/Simulating Waves Nearshore (ADCIRC/SWAN) model (Luettich et al., 1992; Ris et al., 1994; Booij et al., 1996), to quantify storm tides and significant wave heights in the presence and absence of oyster beds. Significant wave height is a common oceanographic measure, defined as the mean trough-to-crest height of all waves in the 67<sup>th</sup>- to 100<sup>th</sup>-percentile height range. The model was run using the U.S. Federal Emergency Management Agency's (FEMA) Region II operational unstructured numerical grid with enhanced resolution (up to 70 m) in the New York/New Jersey area (FEMA, 2014a,b). A detailed description of the model and validation against wave and water level observations can be found in FEMA (2014b), and an application of mapping sea level rise effects on flood zones is given in Orton et al. (2014, 2015). Important modifications from FEMA's modeling are (1) we used model version 51 instead of 49, and (2) we include the effects of spatially variable bottom friction on waves (e.g. due to oyster beds), one of the standard options coded within ADCIRC (Madsen et al. 1988).

The effects of oyster beds on wave heights produced by two historic storms are considered here. We drive the model with wind and atmospheric pressure observations from a severe extratropical cyclone that occurred on December 12, 1992 CE (Cardone et al., 1996) and from Hurricane Sandy in 2012. The 1992 "Nor'easter" (a specific form of extra-tropical cyclone) produced the region's third

highest storm tide since 1844 CE, whereas Hurricane Sandy produced the highest (Talke et al. 2014). The 1992 Nor'easter represents flooding and waves that may occur a few times per century, whereas Sandy represents a more rare case, estimated by recent studies to have a return period between 140 and 420 years (Orton et al. submitted). Wind and pressure data for both storms are from Oceanweather, Inc, who creates reanalysis datasets that merge available observations, modeling and kinematic analysis (Cox et al., 1995; FEMA 2014c).

The simulations for each storm include a control case without oyster beds, which is compared to a simulation with 3 m high reefs, with a maximum elevation set at mean sea level. For the simulations with oyster reefs, beds were added to the model's bathymetry at all locations in western and southern Raritan Bay with water depths between 1 and 6 m, roughly corresponding to areas of historic oyster beds documented in the bay (Mount and Page, 1784-1794; Lodge, 1781; MacKenzie, 1992). Bathymetry for the control model grid (present-day) is shown in Figure 2, including a dashed line showing the regions where oyster reefs were added for the experiments. To account for the frictional effects of rough oyster beds on water flow and waves, a Mannings-n roughness coefficient of 0.035 was assigned at the locations of these raised beds, roughly corresponding to "oyster-sized" roughness elements (2.5-5 inch or 6.4-12.7 cm; Bray, 1979). A sensitivity analysis was also conducted where the reef elevation and Mannings-n roughness were perturbed, with additional model runs for reef elevations of 1 m and "intertidal" (at sea level), and for Mannings-n values of 0.025 and 0.045.



## Results

### *Sediment Cores*

Results from our primary core site at Seguine Pond are presented in Figure 3. Surficial sediments deposited by Hurricane Sandy in 2012 are evident as a red, anomalously dense, coarse-grained deposit at the top of the core. An accompanying peak in MS highlights the deposit's enrichment in ferromagnetic hematite. Prior analyses indicate that all other post-1840 CE hurricanes that produced storm tides in excess of 2 m at the south end of Manhattan are also present as coarse-grained layers at Seguine Pond (Brandon et al., 2014; Talke et al., 2014). New magnetic susceptibility data presented here indicate these storm layers are accompanied by peaks in MS (Figure 3B). A prominent deposit located just below the 1850-1900 CE onset of heavy metals is also consistent with an extremely damaging hurricane in 1821 CE. This storm is the only storm since 1800 CE that likely produced a larger storm surge than Hurricane Sandy, though it likely had a slightly smaller storm tide because the surge peaked at low tide (Redfield, 1831; Brandon et al., 2014; Orton et al., submitted).

A distinct drop in the number and coarseness of event layers is observed below the 1821 CE deposit (Figure 3C). This decrease in overwash occurrence continues down to roughly 200 cm. Below 200 cm there is a near absence of distinguishable event deposits with the exception of coarser basal material at the very bottom of the core. We also observe an abundance of oyster shells below 200 cm, compared to a lack of shell material above (Figure 3A). Sediments below 200 cm are also notably grayer, compared to the redder, more hematite-enriched sediments above (Figure 3A).

A radiocarbon sample collected at 204 cm in the Seguine Pond core yields an age range of 1463 to 1616 CE (Figure 3D, Table S1). The transition to increasing storm-induced overwash just above 200 cm therefore occurred sometime shortly following. The first substantial deposit above this age constraint occurs at a depth of 160 cm, with an estimated median age of ~1690 CE (Figure 3D). The first significant historical hurricane known to have impacted the New York City region was in 1693 CE (Ludlum, 1963), and is consistent with the age of this initial deposit.

Sediments from Arbutus Lake and Wolfe's Pond exhibit similar depositional patterns to that observed at Seguine (Figure 4). Resultant deposition from Hurricane Sandy was evident in surface sediments at each of these sites as a red, coarse-grained event layer accompanied by a peak in MS (Figure 4). Storm-induced MS peaks at the Arbutus and Wolfe's sites increase in both frequency and magnitude beginning at sediment depths of 96 cm and 80 cm, respectively. This increase continues up to respective depths of 53 cm and 44 cm for the Arbutus and Wolfe's Pond sites. Age constraints date this period of increasing storm-induced overwash to roughly 1600 and 1800 CE at both sites (Figure 4), and are concurrent with the timing for increasing overwash at Seguine Pond (Figure 3).

## *Numerical Simulations*

Numerical modeling results for the 1992 Nor'easter's peak significant wave heights in Raritan Bay are presented in Figure 5. Peak significant wave heights at the model grid node just off-shore of Seguine Pond for the control simulation (i.e. without oyster beds) are 1.59 m, compared to a height of 1.03 m for the 3 m high reefs. The removal of these reefs therefore leads to a 54% increase in simulated wave heights. This wave height increase of 54% translates to an increase in wave energy of 138%, when assuming a standard proportionality between wave energy and wave height squared (Sorensen, 2006).

The sensitivity to reef height is strong, with significant wave heights of 1.35 m and 0.92 m, for the 1 m high reefs and the intertidal reefs, respectively. Thus, for the control case of no oysters relative to the suite of reef simulations significant wave height increases by 18-73% and the energy associated with these waves increases by 39-199%. The sensitivity to reef roughness is extremely small, with wave heights only varying by a few millimeters, for the 0.025 and 0.045 Mannings-n values.

Results for Hurricane Sandy show significant wave attenuation by the reefs, though not as pronounced as for the 1992 Nor'easter. This is a result of deeper water depths over the reefs in this record-setting flood, which reduce wave breaking as the waves pass over the reefs. Peak significant wave heights just off-shore of our field sites for the control simulation are 2.17 m, compared to a height of 1.64 m for the 3 m high reefs, indicating that removal of these reefs would lead to a 32% increase in wave heights and 75% increase in wave energy. The 1 m high reefs and intertidal reefs resulted in wave heights of 1.89 and 1.53 m. Increases of between 15 and 42% in significant wave height and 32 to 101% in wave energy are therefore

observed for the Sandy control case of no oyster reefs relative to the 1-m high and inter-tidal reef cases, respectively.

Peak averaged flood level above mean sea level (i.e. storm tide) is far less affected by the removal of oyster reefs, and with subtle and opposing results for the two storms. For the 1992 Nor'easter, reef removal causes a negligible increase of 0.01 m in storm tide just offshore of the study site, and an increase of 0.10-0.15 m at the western end of Raritan Bay (4-6%), while not decreasing mean flood levels elsewhere. Conversely, for Hurricane Sandy removal of reefs causes a small flood level decrease of 0.06 m (1%) offshore of the study site, and 0.10-0.15 m (3-4%) at the western end of the bay. Similar to reef heights, the sensitivity of storm tides to roughness was small.

## Discussion

Sea-level rise (Fitzgerald et al., 2008; Woodruff et al., 2013), variability in storm activity (Wallace et al., 2014; Donnelly et al., 2015), storm hysteresis (Otvos et al., 2008), barrier transgression and changes in sediment supply (Syvitski et al., 2005) all potentially provide alternative explanations for the 1600-1800 transition to more overwash. However, when reviewed in detail, none of these alternative explanations appears consistent with observations from the region.

With respect to sea-level impacts, coastal pond sediments at all three sites date back over 3000 years (e.g. Figure 3; Table S1). The observed 1600-1800 CE onset of increased overwash deposition therefore post-dates initial marine inundation and barrier-beach formation of our sites by several millennia. Further, detailed sea-level reconstructions for the region suggest relatively moderate and steady rates of sea level rise over most of the last few millennia, with a recent onset of accelerated

sea-level rise beginning around 1850 CE (Horton et al., 2013; Kemp et al., 2013).

The observed 1600-1800 CE onset of increased overwash deposition therefore pre-dates recent rates of accelerated sea-level rise by 150-200 years.

Steady landward migration of a barrier could also result in a particular location exceeding some threshold for overwash deposition, such that the distance from a core site to the barrier becomes close enough that sediment can be carried landward to it during a storm event. However, the distance of our separate core sites to their respective barriers varies significantly (Figure 1). The transition in overwash is also observed throughout the transect of cores presented by Brandon et al. (2014). Thus, the spatial coherency of increasing overwash between 1600-1800 CE at varying distances from the barrier appears inconsistent with a set threshold barrier distance being exceeded during barrier transgression. Further, the seaward location of the study's small barrier beach systems are set by the landscape on either end of these beaches (e.g. Woodruff et al., 2015; Woodruff et al., 2008). As such, the cohesive, more erosion-resistant headland moraines that these barrier beaches are attached to have likely served to stabilize them and reduce rates of transgression under pre-1850 rates of relatively modest sea-level rise.

A recent synthesis of storm reconstructions from the U.S. East Coast also provides no evidence for an increase in regional storminess following 1600 CE (Donnelly et al., 2015). Instead, one of the most active intervals in this regional storm reconstruction occurs between 1400 and 1675 CE, when storm layers are absent at our Raritan Bay sites (Figures 3 and 4). Further, for thousands of years our sites appear to have remained resistant to storm induced overwash, while flood reconstructions clearly document extreme storms routinely impacting the region (e.g. Scileppi and Donnelly, 2007; Donnelly et al., 2004). Factors additional to changes in

storminess and/or barrier degradation due to the chance passing of a single hurricane therefore seem to be required to explain the onset of increased overwash deposition following 1600 CE at our three separate sites.

A human-induced decrease in sediment supply to the coast could also potentially cause the degradation of barrier beaches at our sites, and in turn the observed increase in storm-induced flooding. However, widespread deforestation in the region shortly following colonization is largely thought to have increased sediment loads to the coast rather than decreasing them (e.g. Kirwan et al., 2011). Further, recent studies find little direct evidence in northeastern watersheds for a deforestation-induced increase in sediment load for regional rivers (Cook et al., 2015; Yellen et al., in press, this issue). It is possible that background increases in MS at our three sites is due to land clearance. However, earlier work by Brandon et al. (2014) clearly shows that peaks in MS above this background rise coincide with marine-derived event layers that date to coastal flood events of record for New York Harbor, rather than fluvial deposits enhanced by land clearance.

Dredged channels in the harbor provide an additional man-made alteration that could impact flooding at our field sites. For example, the discontinuity in wave height across the center of the bay for model results presented in Figure 5 is a result of the modern-day shipping channel (Figure 2). However, MacKenzie (1992) notes that these channels were primarily dug from 1890 to 1905 CE. Channel dredging therefore post-dates the early 1600 onset for increasing overwash at our field sites by several centuries and in turn rules these anthropogenic features out as a potential causes for the observed transition between 1600 and 1800 CE.

Oyster reefs generally extend vertically to mean low water (Hargis and Haven, 1999), such that the 3 m high and intertidal oyster bed cases in our numerical

simulations likely bracket oyster reef conditions present in Raritan Bay prior to European disturbance. A 138% reduction in wave energy for the 1992 Nor'easter with 3 m high beds therefore supports reefs providing significant coastal protection from waves prior to their disturbance between 1600 and 1800 CE. The destruction of these reefs therefore provide a reasonable explanation for the increase in storm-induced overwash observed over the same interval at all our three study sites. Further, a 75% reduction in wave energy for the Hurricane Sandy case shows that 3-m high oyster beds would even provide protection for the highest of flood events in at least 250 years.

Unlike wave heights oyster reefs had very little impact on storm tides. However, the rise in water level associated with these storm tides occurs over 6-8 hours. This relatively gradual increase in water elevation, while capable of inundating coastlines, is unable on its own to produce the flow velocities necessary for significant coarse-grained sediment transport to our backbarrier coring locations (Brandon et al., 2014). Thus when oyster beds were in place prior to 1600 CE, model results support field sites still being inundated during severe storms, but with smaller waves riding on top that had less competence for transporting coarse-grained material.

In summary, the 1600-1800 CE European destruction of wide shallow shoals of oyster beds and reefs in New York's outer harbor is well documented (Ingersoll, 1881; Smith 1970; Kochiss, 1974; MacKenzie, 1992; McCay, 1998; Kirby, 2004). Overwash reconstructions from our three separate sites all show an increase in the frequency and magnitude of overwash sedimentation concurrent to this disturbance. The importance of off-shore coral reefs in reducing wave activity is also well established (e.g. Ferrario et al., 2014; Hardy and Young, 1996; Hardy et al., 1990;

Lugo-Fernandes et al., 1998). Our modeling work extends this result to oyster reefs by showing a significant drop in wave height and in turn wave energy and transport competence at the coast when oyster beds are included. As with any sedimentary record, there will always be a certain level of uncertainty related to its interpretation. However, based on the above-presented assessment, oyster bed destruction between 1600-1800 CE appears to provide the most viable explanation for increasing overwash deposition observed over this same interval. In doing so our study provides the first evidence to date for natural oyster beds serving as a significant form of flood protection prior to European disturbance.

## **Conclusion**

We employ event deposits preserved in the sediments from a series of coastal ponds and lakes to assess how the disturbance and decline of oyster beds in Raritan Bay (New York and New Jersey, USA) following European settlement impacted the magnitude of overwash to these backbarrier settings. Prior to ~1800 CE, a dramatic decline is observed in the number and coarseness of storm-induced overwash deposits dating back to ~1600 CE. This is preceded by a near absence of overwash deposition between 1600 and the development of barrier-beach systems around 3000 yrs BP. Model results and historical records support the depletion of oyster beds as the most likely cause of increasing overwash sedimentation between 1600 and 1800 CE. These results suggest that coastal areas in Staten Island are experiencing between roughly 30% and 200% higher wave energy from extreme storms than they were prior to reef destruction. This translates into increased vulnerability of these areas to storm waves: a result most likely shared by other coastal areas that have lost their natural oyster beds.



## Acknowledgments

Funding for this work was provided by the Hudson River Foundation Expedited Grant #004/12E, the Hudson River Foundation Graduate Fellowship 02–13, the National Science Foundation (RAPID grant #1313859 and instrument and facility support via grant IF-0949313), the Dalio Explore Fund, and the John D. and Catherine T. MacArthur Foundation. We thank H. Baranes, O. Beaulieu, B. Douglas, H. Kinney, M. Koerth, L. Kumpf, S. Madsen, C. Maio and R. Sullivan for their laboratory and field assistance. We also thank C. Dellatte at the Staten Island Museum for her assistance with the historical research. Modeling was supported, in part, by a NOAA-RISA funded project (Consortium for Climate Risk in the Urban Northeast) and a grant of computer time from the City University of New York High Performance Computing Center under NSF Grants CNS-0855217, CNS-0958379 and ACI-1126113

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Figure 1: (Left Panel) Field site locations on the southern coast of Staten Island (red box). (Right Panel) Aerial image of the three field sites on November 3, 2012 or five days after Hurricane Sandy's landfall. The colored circles indicate the position of the cores from Seguine, Arbutus and Wolfe's Ponds with positions of N 40.52438°, W 74.16921°; N 40.52230°, W 74.17820°; and N 40.51459°, W 74.19209°, respectively.

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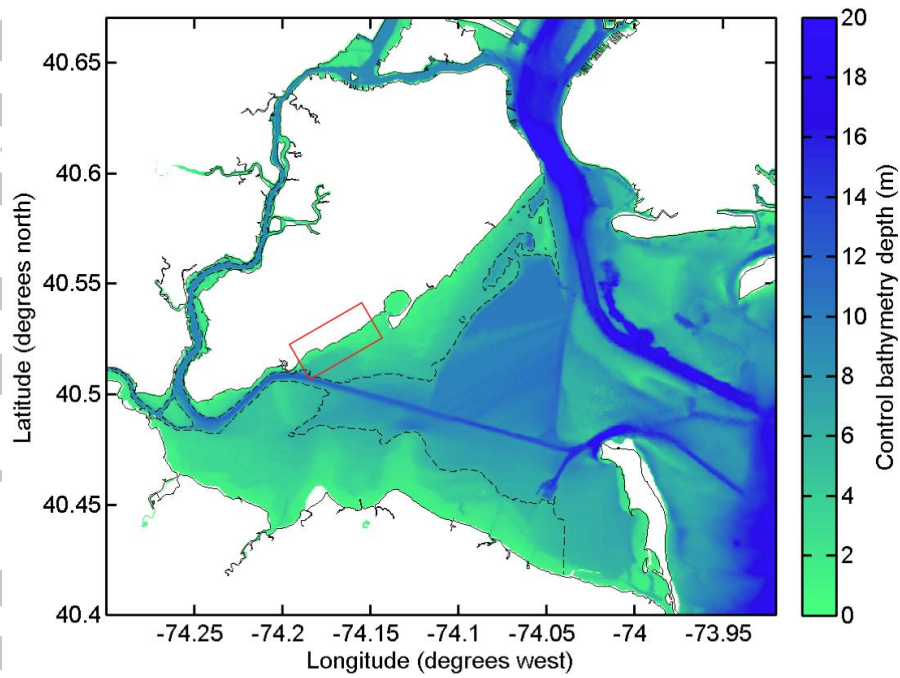


Figure 2: Bathymetry for the control model grid (present-day), including a dashed line showing the shallow regions where oyster reefs were added for the experiments. Red box indicates location of aerial photo shown in Figure 1.

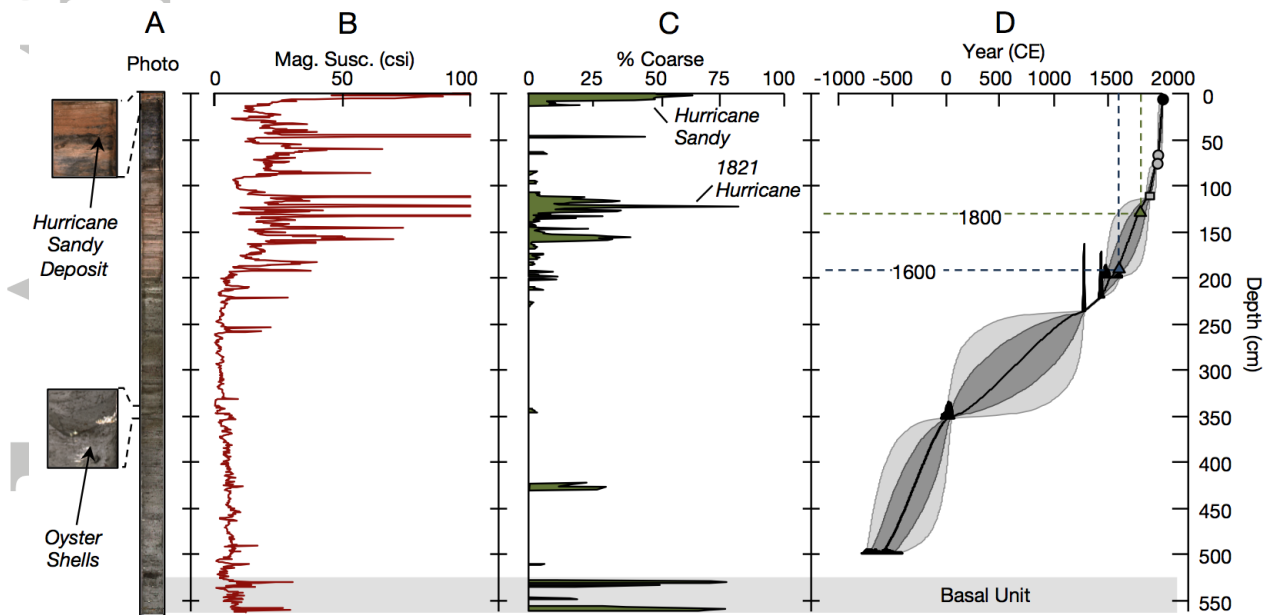


Figure 3: Sediment results from Seguíne Pond. Note the transition from gray sediments to red sediments in the core photo (A) at just above 200 cm. B) Spikes in magnetic susceptibility correspond to coarse-grained overwash deposits (C) as identified with depth profile of %coarse (> 63 μm). D) Bayesian age-depth model for core, with depth of  $^{137}\text{Cs}$  (grey circles), heavy metal (grey rectangle) and  $^{14}\text{C}$  (black age probability distributions) age controls. Black line denotes median ages, and dark and light shading represents 1 and 2 sigma uncertainties, respectively. Green and blue triangles identify depth for median ages of 1600 and 1800 CE. Images of representative overwash and oyster shell deposits are provided to the left of the core photo and are both 5 cm in height.

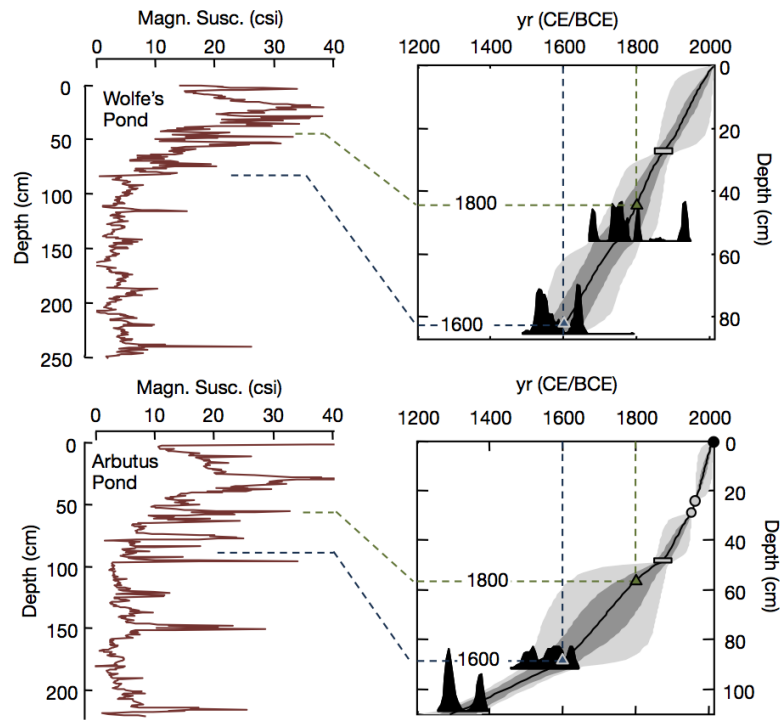


Figure 4: Magnetic susceptibility (MS) depth profiles for Wolfe's Pond (Top Left) and Arbutus Lake (Bottom Left). Age constraints in each core for the rise in MS between 1600 and 1800 CE (dashed green and blue lines) are provided in right panels. Chronologies are presented using a format identical to the age model in Fig. 3.



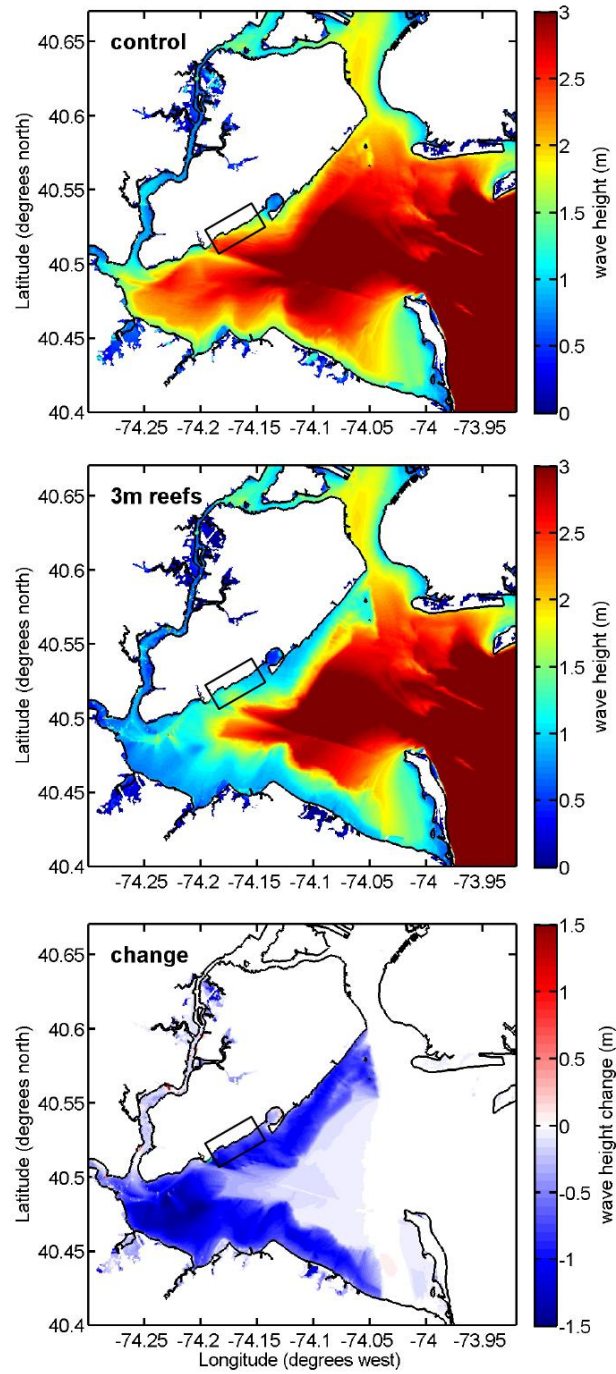


Figure 5: A comparison of the significant wave heights produced by the 1992 Nor'easter for (top) the control case using present-day bathymetry and (middle) a hypothetical modified bathymetry with oyster beds of 3 m elevation. The bottom panel shows the wave height change for the oyster bed case relative the control.