Modeling Wave Attenuation by Salt Marshes in Jamaica Bay, New York, Using a New Rapid Wave Model

Reza Marsooli a,1 , Philip M. Orton b , George Mellor c

a Department of Civil and Environmental Engineering, Princeton University, Princeton, NJ, USA
b Davidson Laboratory, Stevens Institute of Technology, Hoboken, NJ, USA
c Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ, USA

Abstract

Using a new rapid-computation wave model, improved and validated in the present study, we quantify the value of salt marshes in Jamaica Bay – a highly urbanized estuary located in New York City – as natural buffers against storm waves. We improve the MDO phase-averaged wave model by incorporating a vegetation-drag-induced energy dissipation term into its wave energy balance equation. We adopt an empirical formula from literature to determine the vegetation drag coefficient as a function of environmental conditions. Model evaluation using data from laboratory-scale experiments show that the improved MDO model accurately captures wave height attenuation due to submerged and emergent vegetation. We apply the validated model to Jamaica Bay to quantify the influence of coastal-scale salt marshes on storm waves. It is found that the impact of marsh islands is largest for storms with lower flood levels, due to wave breaking on the marsh island substrate. However, the role of the actual marsh plants, Spartina alterniflora, grows larger for storms with higher flood levels, when wave breaking does not occur and the vegetative drag becomes the main source of energy dissipation. For the latter case, seasonality of marsh height is important; at its maximum height in early fall, S. alterniflora causes twice the reduction as when it is at a shorter height in early summer. The model results also indicate that the vegetation drag coefficient varies one order of magnitude in the study area, suggest exercising extra caution in using a constant drag coefficient in coastal wetlands.

Keywords: wave attenuation, salt marsh, vegetation drag coefficient, Jamaica Bay.

1 Formerly at Davidson Laboratory, Stevens Institute of Technology, Hoboken, NJ, USA

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1. Introduction

Salt marshes – coastal tidal wetlands that are alternatively flooded and drained by tides – are an integral part of estuarine and coastal ecosystems and provide valuable ecological, economic, and social services. Salt marshes are known as natural measures that improve water quality, provide fish and wildlife habitats, modify mean flow and turbulence structure, trap sediment particles, and create recreation opportunities. One of the greatest benefits of salt marshes, especially for low-lying coastal urban areas, is their potential to reduce the energy of storm surges and waves, and therefore to mitigate damages from flooding and to reduce shoreline erosion. The ability of salt marshes to act as buffers against storms will become more recognized in the upcoming decades as the sea level rises and the intensity of storms increases (Horton et al. 2015).

The ability of salt marshes to mitigate surface waves has attracted attention amongst scientists, managers, and the general public. As a result, in the past few decades, a significant amount of research has been devoted to understanding wave-vegetation interactions by means of laboratory experiments (e.g. Dubi and Torum 1994, Augustin et al. 2009, Stratigaki et al. 2011, Anderson and Smith 2014, Ozeren et al. 2014), field surveys (e.g. Knutson et al. 1982, Bradley and Houwer 2009, Jadhav et al. 2013), and numerical modeling (e.g. Dalrymple et al. 1984, Mendez et al. 1999, Li and Zhang 2010, Suzuki et al. 2011, Wu and Marsooli 2012, Marsooli and Wu 2014). These studies have shown that as waves propagate through vegetation, the wave height reduces as a result of energy dissipation due to the drag force acting on plants. It has been understood that the amount of wave energy dissipation is a function of biophysical properties of vegetation, such as stem size and height, as well as hydrodynamic conditions such as wave characteristics and water depth.

To quantify wave attenuation by vegetation, several theoretical and empirical approaches have been developed in the literature. A widely-used physics-based approach, which is based on the linear wave theory, was developed by Dalrymple et al. (1984) and was later improved by Mendez and Losada (2004). This approach determines the vegetation-induced energy dissipation based on the work done by the drag force exerted on plants. The drag force is described using the Morison equation (Morison et al. 1950) and relies on a drag coefficient which is a function of the environmental conditions. Based on laboratory and field measurements, several empirical
formulas have been proposed for the vegetation drag coefficient (e.g. Kobayashi et al. 1993, Mendez and Losada 2004, Anderson and Smith 2014).

The theories of Dalrymple et al. (1984) and Mendez and Losada (2004) have been adopted in numerical models to simulate wave attenuation by vegetation. However, most of the developed models are phase-resolving wave models (e.g. Maza et al. 2013, Ma et al. 2013, Marsooli and Wu 2014) that are computationally expensive for application to a full-scale coastal wetland and, more importantly, are not able to simulate wind wave generation within a computational domain. Therefore, although these models are still useful tools to advance our knowledge on the wave-vegetation interaction processes, they are not the optimal choice for application to full-scale estuarine and coastal systems under storm conditions. Instead, modeling storm waves in such systems is carried out using a phase-averaged wave model. However, these models usually consider the vegetation-induced energy losses through an enhanced bottom friction, which is not physically correct especially for near-emergent and emergent vegetation.

In recent years, some of the existing phase-averaged wave models such as SWAN (Suzuki et al. 2011) and STWAVE (Anderson and Smith 2015) have been improved to simulate wave-vegetation interactions through a physics-based approach, i.e. the theories of Dalrymple et al. (1984) and Mendez and Losada (2004). While other models such as MDO (Mellor et al. 2008) and UMWM (Donelan et al. 2012) neglect wave-vegetation interactions, they may be applied to coastal wetlands by enhancing the bottom friction coefficient and, thus, lumping the vegetation-induced energy dissipation with the dissipation processes due to the bottom friction. Even though this approach is not physically correct, it may be acceptable for submerged vegetation with a large submergence ratio (the ratio of submergence distance to the total water depth). However, for submerged vegetation with a smaller submergence ratio, this approach is incapable of resolving wave-vegetation interactions correctly. The taller vegetation impedes the top portion of the water column where wave characteristics such as orbital velocities are significantly different from the near-bed characteristics used in the calculations of wave energy dissipation due to the bottom friction.

In the present study, we improve the MDO wave model using a physics-based approach to quantify the influence of coastal salt marshes on surface waves. MDO is a phase-averaged wave model developed by Mellor et al. (2008) to simulate the generation, propagation, and dissipation
of wind waves and swells in deep and shallow waters. Unlike STWAVE, the MDO model is an open-source code that can be freely downloaded from the Princeton Ocean Model’s website (http://www.ccpo.odu.edu/POMWEB/). This open-source wave model is also computationally fast compared to third-generation wave models (Mellor et al. 2008, Marsooli et al. 2017). For example, a comparison of computational expense of MDO and SWAN on an idealized coastal ocean grid showed MDO to be 58 times less expensive (Marsooli et al. 2017), yet accurately captures all important wave-related processes for enclosed bays and estuaries, and thus provides a valuable new option for modeling of coastal systems. Thus, it can be a new and widely-used wave model for use in operational ensemble forecasting systems (e.g. Georgas et al. 2016), as well as annual or longer simulations of biogeochemistry or water quality (e.g. Feng et al., 2015), or salt marsh erosion (e.g. Wang et al. 2017). To include a physics-based feature in MDO that captures wave-vegetation interactions, here, we formulate a vegetation-induced energy dissipation term based on the method of Mendez and Losada (2004) and implement it in the energy balance equation of MDO. To properly account for the impact of environmental conditions on the drag force exerted on vegetation, we adopt an empirical formula to determine the vegetation drag coefficient as a function of the plant Reynolds number. The performance of the model is evaluated using data from existing laboratory experiments.

To quantify the influence of coastal-scale salt marshes in mitigating storm waves, we apply the improved MDO wave model to Jamaica Bay, a back-barrier bay located in New York City (NYC). The marsh islands of Jamaica Bay are one of the largest extents of tidal wetlands in NYC and provide valuable benefits to the ecology of the region. However, since the late-1800s, widespread water quality problems and extensive physical alteration of the bay’s shorelines and bathymetry have negatively impacted the wetland communities. For example, the bay has lost over 4856 hectares of its former 6475 hectares of wetlands since the mid-1800s (New York City Department of Environmental Protection, 2007a). Moreover, Jamaica Bay’s salt marshes may be more vulnerable to the impacts of future sea level rise because of the sediment supply deficiency and other potential natural and anthropogenic stressors (Hartig et al. 2002). If the marsh islands disappear in the coming decades, some coastal communities, e.g. Broad Channel with a population of about 3000, would become more vulnerable to storm waves. The results of the present study reveal the value of salt marshes in Jamaica Bay to protect the coastal communities.
against storm waves which, in turn, may encourage conducting new wetland restoration projects within the bay.

2. Wave Model

2.1. Directionally Dependent Wave Energy Equation

MDO (Mellor et al. 2008) is a spectral wave model for wind-generated waves and swells in deep and shallow waters. The model solves the wave energy balance equation in geographical and directional spaces, and parameterizes the energy distribution in frequency space based on the spectrum of Donelan et al. (1985) (henceforth, the DHHS spectrum). The DHHS spectrum is based on extensive wind-wave data obtained on Lake Ontario and contains elements of the Joint North Sea Wave Project (JONSWAP) spectrum (Hasselmann et al. 1973). The model determines the directional frequency using a transport equation derived from wavenumber irrotationality and conservation of wave crests. The transport equation for frequency contains an empirical source term which drives the frequency towards wind-driven peak frequency in regions of wave direction $\theta$ which are wind-driven and are also determined from the DHHS spectrum given the wind direction (more details can be found in Mellor et al. 2008). Regions which are not wind-driven are considered to be swell.

After integrating the full spectral equation with respect to frequency, the directionally dependent, depth-integrated wave energy equation in a sigma coordinate system is

$$
\frac{\partial E_\theta}{\partial t} + \frac{\partial}{\partial x_i} \left[ \left( c_{gi} + u_{Ai} \right) E_\theta \right] + \frac{\partial}{\partial \theta} \left( c_\theta E_\theta \right) + \int_{-1}^{0} S_{r,ij} \frac{\partial U_i}{\partial x_j} D d \zeta = S_{\theta, in} - S_{\theta, Sdis} - S_{\theta, Bdis} - S_{\theta, Ydis}
$$

(1)

where $E_\theta$ is the frequency integrated energy divided by water density (i.e. kinematic energy), which is a function of spatial coordinates and time and, importantly, a function of wave direction $\theta$ ($\pi < \theta < \pi$); $t$ is the time; $x_i$ is the horizontal coordinate ($i=x, y$ and $j=x, y$); $c_{gi}$ is the group speed; $u_{Ai}$ is the Doppler (advective) velocity formulated in Mellor (2003) and Mellor (2008); $c_\theta$ is the refraction speed which is calculated based on Komen et al. (1994) and Golding (1978); $D=h+\eta$ is the total water depth with $h$ is the bathymetry referenced to a vertical datum and $\eta$ the mean (phase-averaged) surface elevation referenced to the same vertical datum; $S_{r,ij}$ is the wave
radiation stress; $U_i$ is the horizontal velocity representing current plus the Stokes drift; $\zeta$ is the sigma variable (-1 $< \zeta < 0$) defined as $\zeta = (z - \eta)/D$ with $z$ is the vertical coordinate; $S_{0,\text{in}}$ is the wind growth source term; and $S_{\theta,\text{dis}}$ and $S_{\theta,B\text{dis}}$ are, respectively, the dissipation terms due to wave processes at the surface and bottom. Implemented into the model in the present study, the last term on the right hand side of equation (1), i.e. $S_{\theta,V\text{dis}}$ is the energy dissipation term due to the drag force exerted by waves on plants. The group speed, refraction speed, and Doppler velocity in equation (1) are energy weighted quantities averaged over frequency.

The first term on the left hand side of equation (1) represents the local rate of change of wave energy in time, the second term represents propagation of energy in horizontal space, the third term stands for depth- and current-induced refraction (changes in the direction of wave energy propagation), and the fourth term represents energy exchange with the mean velocity. Source and sink terms on the right hand side of equation (1) represent the wave energy generation and dissipation terms. A detailed description of wind growth source term $S_{0,\text{in}}$ and the dissipation terms $S_{\theta,\text{dis}}$ and $S_{\theta,B\text{dis}}$ can be found in Mellor et al. (2008) and is not repeated here. The dissipation term due to vegetation, $S_{\theta,V\text{dis}}$, is described in the next section. In the present study, terms related to the mean velocity (currents) can be neglected since we only focus on wave-vegetation interactions and the complex wave-current-vegetation interactions are not considered.

**2.2. Energy Dissipation Due to Vegetation, $S_{\theta,V\text{dis}}$**

Surface waves propagating through vegetation lose energy by performing work on plants which directly results in smaller wave heights (Dalrymple et al. 1984). By neglecting the skin friction of plants, the phase-averaged total rate of energy dissipation per unit area over the plant height is

$$S_{V\text{dis}} = \int_{-D}^{-D+D} Fudz$$

where $u$ is the wave orbital velocity, $\alpha$ is the relative plant height (i.e. ratio between plant height and water depth), and $F$ is the vegetation-induced drag force due to the viscous effects. The drag force can be calculated using the method of Morrison et al. (1950) as
where $\rho$ is the water density, $C_{D,v}$ is the vegetation drag coefficient, $b_v$ is the area per unit height of each vegetation element standing normal to $u$, and $N_v$ is the number of plants per unit horizontal area. We assume that plants can be represented by cylindrical elements standing vertically, and therefore $b_v$ can be set to the plant/stem diameter.

By substituting equation (3) into (2) and assuming that $u$ in both vegetated and non-vegetated waters can be calculated based on the linear wave theory, Dalrymple et al. (1984) formulated the vegetation-induced energy dissipation for regular waves as

$$S_{dis} = \frac{2}{3\pi} \rho C_{D,v} b_v N_v \left( \frac{k g}{2\sigma} \right)^3 \sinh^3 \left( \frac{ka h}{3k} \cosh k h \right) H^3$$

where $k$ is the wave number, $\sigma$ is the wave angular frequency, and $H$ is the wave height. Based on the assumption of an invariant Rayleigh-like wave height distribution, Mendez and Losada (2004) modified equation (4) for irregular (random) waves as follows

$$S_{dis} = \frac{1}{2\sqrt{\pi}} \rho C_{D,v} b_v N_v \left( \frac{k g}{2\sigma} \right)^3 \sinh^3 \left( \frac{ka h}{3k} \cosh k h \right) H_{rms}^3$$

where $C_{D,v}$ is a vegetation drag coefficient that can be different from the drag coefficient in equation (4), and $H_{rms}$ is the root-mean-square wave height. We adopt equation (5) and reformulate it in the form of wave energy for use in the MDO wave model. To be consistent with MDO, the wave energy $E$ in the remainder of this paper represents the kinematic energy, in other words, energy divided by water density.

From Rayleigh distribution, the significant wave height can be related to the wave energy in the form of $E = g H_s^2 / 16$, and by knowing that $H_s = 1.41 H_{rms}$, we relate the root-mean-square wave height to the wave energy as follows

$$H_{rms} = \sqrt{\frac{8E}{g}}$$

Substituting equation (6) into (5) yields
Finally, the directional energy dissipation due to vegetation is calculated as

\[
S_{\text{v dis}} = \frac{2}{\sqrt{\pi g}} g^2 C_{D,v} b_v N_v \left( \frac{k}{\sigma} \right)^3 \sinh^3 k\alpha h + 3 \sinh k\alpha h \frac{3 k \cosh^3 k h}{3 k \cosh^3 k h} E \sqrt{E}
\]  

We incorporate equation (8) into the wave energy balance equation of MDO to compute the directional wave energy dissipation due to vegetation.

### 2.3. Vegetation Bulk Drag Coefficient, \( C_{D,v} \)

To correctly simulate wave attenuation due to vegetation, the drag coefficient \( C_{D,v} \) in equation (8) must be appropriately given in the model. Basically, \( C_{D,v} \) can be either set to a predefined constant coefficient or determined using an empirical formula. However, setting \( C_{D,v} \) to a predefined value can be a challenging task, especially in coastal-scale domains where environmental conditions (e.g. wave orbital velocity and vegetation submergence ratio) spatially and temporally change. Under both oscillatory and non-oscillatory flows, laboratory experiments have shown that the drag coefficient varies with hydrodynamic conditions and vegetation properties (e.g. Kobayashi et al. 1993, Tanino and Nepf 2008, Ozeren et al. 2014, Anderson and Smith 2014). Thus, an empirical formula attempts to estimate \( C_{D,v} \) by relating it to non-dimensional parameters such as the plant Reynolds number, \( \text{Re} \), and Keulegan-Carpenter number, \( \text{KC} \).

Most existing empirical formulas of vegetation drag coefficient estimate a bulk drag coefficient that is independent of the wave frequency and does not change in the wave spectra. However, Jadhav et al. (2013) derived a frequency-dependent formula and showed that the drag coefficient can vary with the wave frequency and reach to its maximum near the spectral peak. Therefore, spectral models based on a frequency-dependent vegetation drag coefficient should be used to study the spectral distribution of energy dissipation due to vegetation. On the other hand, based on a series of field data collected along a transect at a salt marsh site in Louisiana coast of the Gulf of Mexico, Jadhav et al. (2013) showed that the mean error in the modeled wave height attenuation based on a frequency-dependent drag coefficient differs less than 3% from that based...
on a frequency-independent drag coefficient. Thus, wave models based on frequency-independent formulas still can properly reproduce wave height attenuation due to vegetation.

We implement several well-established frequency-independent formulas in MDO to determine the vegetation drag coefficient as a function of environmental conditions. A detailed model validation using a series of laboratory experiments, not shown here, indicate that the formula of Kobayashi et al. (1993), described below, is able to accurately determine the vegetation drag coefficient. Other formulas adopted in the model, including those developed by Mendez and Losada (2004), Anderson and Smith (2014), and Wu et al. (2016), resulted to over/underestimated drag coefficients in some of the test cases. Therefore, in the remainder of this study, the vegetation drag coefficient is determined using the formula of Kobayashi et al. (1993).

Kobayashi et al. (1993) derived an empirical formula (henceforth, KRA) based on data collected by Asano et al. (1988) from 60 laboratory experiments of regular (monochromatic) waves over submerged artificial kelp. The kelp was made of polypropylene strips with a height $h_v$, width $b_v$, and thickness of $0.25$ m, $5.2$ cm, and $0.03$ mm, respectively. The experiments were conducted for vegetation densities of $1100$ and $1490$ plants.m$^{-2}$ and relative plant heights of $0.48$ and $0.55$.

The KRA formula relates the vegetation drag coefficient $C_{D,v}$ to the plant Reynold number $Re$ as

$$C_{D,v} = 0.08 + \left( \frac{2200}{Re} \right)^{2.4}$$

(9)

where $Re = \frac{u_c b_v}{\nu}$, $\nu$ is the kinematic viscosity of water ($10^{-6}$ m$^2$.s$^{-1}$), and $u_c$ is a characteristic wave orbital velocity. The KRA formula was developed for $2200<Re<18000$.

Kobayashi et al. (1993) defined the characteristic velocity $u_c$ as a spatially constant velocity that represents the maximum horizontal orbital velocity on top of vegetation at the leading-edge of vegetation zone. However, defining $u_c$ as a spatially constant characteristic velocity in MDO can negatively impact the model performance and limit the applicability of the model. This is because estuarine and coastal salt marshes usually have complex geometry and irregular edge shape, and are patchy distributed in space, that make spotting the leading-edge of vegetation zones impractical. Moreover, water depth and wave characteristics in a coastal-scale domain can
significantly change in time and space, which can impact the wave orbital velocity and consequently the Reynolds number. Thus, we define $u_c$ in the model as the local maximum horizontal velocity on top of vegetation in each computational cell within the vegetation zone. The characteristic velocity $u_c$ is computed based on the linear wave theory and using the significant wave height and average wave angular frequency.

3. Model Evaluation

We evaluate the performance of the improved MDO wave model using two laboratory experiments documented in the literature. In subsection 3.1, the model is first evaluated using the data from Lovas (2000) to evaluate the ability of MDO to reproduce wave propagation over submerged vegetation in the surf zone. By comparing the model results with the laboratory data of Wu et al. (2011) in subsection 3.2, we assess the model ability to simulate wave attenuation due to near-emergent and emergent live $S. alterniflora$.

In the test cases examined in this section, the domain is independent of the lateral direction. Thus, the computational grid of MDO has only five rows in $y$ direction. We implement a cyclic boundary condition on the lateral boundaries of the grid. The measured wave characteristics are used as the upstream boundary condition, and a closed boundary that entirely dissipates the outgoing waves is used as the downstream boundary condition. The computational mesh consists of a uniform horizontal grid spacing of 0.1 m. The time step is set to 0.01 s and the simulation period is sufficiently long to reach the steady-state solution. Because the vegetation drag coefficient calculated by KRA becomes very large when the Reynolds number approaches zero, we cap the calculated drag coefficient at a highest value of 10 to assure that the model remains numerically stable. Other parameters in MDO are set to a default value, including a wave breaking parameter, $\gamma$, of 0.7, and a bottom drag coefficient of 0.003.

3.1. Wave Attenuation due to Submerged Vegetation in Surf Zone

Lovas (2000) carried out a series of experiments in a 40 m long and 5 m wide wave flume to study the influence of vegetation on waves in the surf zone. A 7.26-m-long artificial vegetation
model was placed on a sloping bed with a bottom gradient of 1:30. The vegetation elements had a diameter of 0.025 m, height of 0.2 m, and density of 1200 plants.m$^{-2}$. Two experiments are selected here to evaluate the accuracy of the MDO wave model. In the first experiment, the significant wave height, $H_s$, is 0.22 m and the peak wave period, $T_p$, is 2.5 s. In the second experiment, $H_s$ and $T_p$ are 0.125 m and 3.5 s, respectively. In both experiments, the water depth (in the flat section of the domain) is 0.77 m.

The measured and modeled longitudinal profiles of significant wave height are compared in Figure 1. The MDO wave model based on the KRA drag formula accurately reproduces the wave height profiles. To better evaluate the performance of KRA, the results from MDO based on two constant drag coefficients are also shown in Figure 1. While MDO based on a constant drag coefficient of 0.1, which is calibrated using measurements, accurately reproduces the wave height profiles, MDO based on a drag coefficient of 0.35 significantly overestimates the wave attenuation. The comparisons reveal the high sensitivity of the model to a constant drag coefficient, i.e. a drag coefficient that is slightly larger/smaller than the calibrated value can lead to significant errors in the model results. Therefore, setting the vegetation drag coefficient to a constant value requires a precise calibration process. However, calibrating the drag coefficient for a coastal-scale wetland is not trivial due to lack of adequate measurements under different environmental (storm) conditions. Moreover, the environmental conditions such as wave characteristics and vegetation submergence ratio change over time and space, making the use of a constant drag coefficient a challenging task.

To separately quantify the influence of vegetation drag and depth-induced breaking on wave heights, Lovas (2000) carried out another series of experiments in the absence of vegetation. Similarly, we run the MDO wave model for the same experiments 1 and 2 but in the absence of vegetation. Figure 2 compares the measured wave heights with the results from MDO in the presence and absence of vegetation. In experiment 1, the wave height continuously reduces on the sloping section of the domain, mainly due to depth-induced breaking in the absence of vegetation and both depth-induced breaking and vegetation drag in the presence of vegetation. The contribution of vegetation drag on wave attenuation is as significant as the contribution of depth-induced breaking. In experiment 2, in the absence of vegetation, waves continuously shoal on the sloping bed and start breaking only at the very shallow region of the domain, i.e. at a
water depth of about 0.18 m. In the presence of vegetation, on the other hand, shoaling does not take place in the vegetation zone because of wave energy dissipation caused by vegetation drag. As a result, waves continuously attenuate over the vegetation zone.

Figure 2 also compares the results from MDO with the results reported by Suzuki et al. (2011) who utilized SWAN to simulate the same experiments of Losada (2000). In the presence of vegetation, the wave heights calculated by MDO and SWAN agree well whereas in the absence of vegetation there are some discrepancies between the calculated wave heights, especially in experiment 1. In the shallow non-vegetated regions of the wave flume, the main source of wave attenuation is depth-induced breaking (energy dissipation due to wave breaking dominates energy dissipation due to bottom friction). Thus, the discrepancies between MDO and SWAN can be due to the different wave-breaking dissipation parameterization methods implemented in these models. While, Suzuki et al. (2011) adopted the breaking model of Thornton and Guza (1983) with $\gamma=0.6$ in SWAN, MDO adopts the method of Battjes and Janssen (1978) with $\gamma=0.7$. Mellor et al. (2008) and Marsooli et al. (2017) have successfully evaluated the MDO wave model with $\gamma=0.7$ using laboratory and field data. Therefore, no attempt is made in the present study to change the breaker parameter $\gamma$. This article is protected by copyright. All rights reserved.
Figure 1. Spatial variation of measured and calculated (MDO based on KRA and two constant drag coefficients) significant wave height for experiments of Lovas (2000) (experiment 1: $H_s=0.22$ m, $T_p=2.5$ s, and experiment 2: $H_s=0.125$ m, $T_p=1.35$ s). Vertical dashed lines show the upper and lower boundaries of the vegetation zone. The green patch in the lower panel represents the vegetation zone.
Figure 2: Comparisons between measured significant wave height and results from SWAN and MDO for experiments of Lovas (2000) (experiment 1: $H_s=0.22$ m, $T_p=2.5$ s, and experiment 2: $H_s=0.125$ m, $T_p=1.35$ s). Squares: measurements in the presence of vegetation, plus: measurements in the absence of vegetation, open red circles: results from SWAN in the presence of vegetation, solid red circles: results from SWAN in the absence of vegetation, solid lines: results from MDO in the presence of vegetation, dashed lines: results from MDO in the absence of vegetation. Results from SWAN are from Suzuki et al. (2011). Vertical dashed lines show the upper and lower boundaries of the vegetation zone. The green patch in the lower panel represents the vegetation zone.

3.2. Wave Attenuation due to Near-Emergent and Emergent Spartina alterniflora

Next, we evaluate the ability of the MDO wave model to simulate wave attenuation due to live $S.\ alterniflora$, a dominant species in the intertidal wetlands along the Atlantic coast of North and South America. Wu et al. (2011 and 2012) collected green $S.\ alterniflora$ plants from the coast of Louisiana, USA, and placed them in a laboratory wave flume 20.6 m long, 0.69 m wide, and 1.22 m deep to measure wave attenuation by salt marshes. The stem density, height, and diameter
were 405 plants m$^{-2}$, 0.59 m, and 0.65 cm, respectively. The wave conditions included regular and irregular waves. We choose four experiments conducted under irregular waves, shown in Table 1, to evaluate the ability of MDO to reproduce the wave height reduction due to S. alterniflora.

Figure 3 compares the measured wave heights with the results from MDO based on KRA and two constant drag coefficients. MDO based on KRA favorably captures the influence of S. alterniflora on wave heights, except for experiment 4 where it slightly overestimates the wave attenuation. The good agreements between the measurements and model results indicate the capabilities of the MDO wave model based on KRA to simulate wave attenuation due to S. alterniflora. On the other hand, while MDO based on a constant drag coefficient of 8 reproduces accurate results for experiment 3 and slightly underestimated wave heights for other experiments, MDO based on a constant drag coefficient of 1 miscalculates the influence of vegetation on the wave heights.

![Figure 3](image_url)

Figure 3. Spatial variation of measured and calculated (MDO based on KRA and two constant drag coefficients) root-mean-square wave height for experiments of Wu et al. (2011). Vertical dashed lines show the upper and lower boundaries of the vegetation zone.

Study Area

Jamaica Bay is a large coastal embayment surrounded by the Rockaway Peninsula to the South, Queens to the East and North, and Brooklyn to the West (Figure 4). It is one of the largest coastal wetland ecosystems in New York State and the largest natural open space left in NYC. The bay comprises a productive coastal ecosystem including the largest tidal wetland community in the New York metropolitan area (National Park Service 2007, Swanson et al. 2016). Jamaica Bay’s salt marshes provide ecological services, such as habitat and food sources for wildlife, water filtration, and shoreline erosion control. In addition to the benefits to the ecosystem, it is also believed that the salt marshes serve as a buffer against storm tides and waves (National Park Service 2007, New York City Department of Environmental Protection 2007a and 2007b). However, 3-D hydrodynamic modeling shows that Jamaica Bay’s salt marshes had little impact on the maximum water elevation induced by Hurricane Irene (Marsooli et al. 2016), and more simplified 2-D modeling has even suggested that massive marsh expansion in the center of the bay cannot significantly mitigate hurricane storm tides, due to deep shipping channels that rim the edges of the bay (Orton et al. 2015).

Jamaica Bay has lost over 4856 hectares of its former 6475 hectares of wetlands since the mid-1800s (New York City Department of Environmental Protection, 2007a), and there is a much larger open-water area for waves to grow in the bay. As a result, there are few case studies where marshes may provide protection from waves. One such case was recently studied in Smith et al. (2016), where marsh impacts on waves were studied for southerly winds during a hypothetical hurricane, and were found to reduce wave impacts on uninhabited shoreline near Broad Channel, Queens. Here, we study a case where waves during west wind events are known to impact a community of waterfront homes. Figure 4 shows the satellite image of the study area. The study area, enclosed by a red rectangle, addresses wave vulnerability for the populated area of Broad Channel, Queens, which has homes exposed to west winds and has experienced increased wave impacts in recent years due to marsh island erosion. Broad Channel is the only inhabited island in the bay, and has a population of about 3000. This low-lying neighborhood is prone to flooding and waves during moderate to severe weather conditions. It is believed that the
marsh islands that are located to the west of the neighborhood, and include Stony Creek, Yellow Bar, Black Wall, and Rulers Bar, act as natural buffer zones to storm waves (http://narrative.ly/defending-the-marsh/).

The dominant plant species in Jamaica Bay’s salt marshes is *S. alterniflora* with a stem diameter of 0.6 cm, a typical value for salt marshes in the region. Based on data collected from Jamaica Bay’s marsh islands in February and March 1996, a biological productivity study (EEA, Inc. 1997) reported that the density of *S. alterniflora* varies between 20 to 390 plants.m⁻². This study showed that the average density in Yellow Bar Marsh Island is 192 plants.m⁻². Recent measurements collected by New York City Department of Parks & Recreation (data was obtained by contacting the Department of Parks & Recreation and Natural Area Conservancy) using stem height showed a range of average stem heights for *S. alterniflora* from 0.26 m to 0.58 m.

**Computational Domain**

A rectilinear computational grid with a constant grid spacing of 5 m is generated for the study area. To align the lateral axis of the computational grid with waterfront homes in Broad Channel, which are located in the eastern boundary of the grid, the computational domain is rotated 12° clockwise with respect to the east-west axis. Cyclic boundary conditions are imposed to the southern and northern boundaries of the grid. The eastern boundary is closed boundary with no wave reflection and a Neumann boundary condition with zero gradient is used in the western boundary.

The bathymetry of the model is based primarily on United States Geological Survey (USGS) bathymetric/topographic data collected by LIDAR in 2013-4, and secondarily on slightly older data collected in 2007-8 by Flood (2011). The LIDAR data cover dry land, marsh islands, and shallow waters (shallower than approximately 2 m) and the Flood data cover deeper waters such as the navigating channels in the perimeter and middle of the bay. The bathymetry of the computational domain is shown in the upper frame of Figure 5.

The spatial distribution of salt marshes in the model is based on the New York City urban ecological land-cover map obtained from the Natural Area Conservancy (O'Neil-Dunne et al. 2014). This land-cover map provides the distribution of salt marshes in 2010 but does not include
the marshes that have been restored in the past few years. For instance, it does not include approximately 10 hectare of Black Wall and Rulers Bar, the easternmost marsh islands in the study area, which have been restored since 2012. Based on the satellite images from Google Maps, the USGS’ DEM, and the information from engineers who are involved in the Jamaica Bay’s restoration projects, the restored marshes within the study area are included in the model. The lower panel of Figure 5 shows the distribution of salt marshes.

**Numerical experiments**

To quantify the impact of vegetation height on waves in the study area, we run the model for two different stem heights of 0.3 m and 0.6 m, which can represent the average stem height of *S. alterniflora* during early summer (June) and the months they are at peak height (September and October), respectively. In both models, the stem diameter and density are set to 0.6 cm and 200 plants.m\(^{-2}\), respectively. The model is also run for cases with no vegetation, in which case the depth-induced breaking and bottom friction, \(S_{\theta,\text{dis}}\) and \(S_{\theta,B\text{dis}}\), over shallow areas and marsh islands are the only sources of energy dissipation (Table 2).

In addition to the variation in the stem height of *S. alterniflora*, we study two idealized storm scenarios with westerly winds, blowing from 282 degrees clockwise from north along the domain’s axis. If the marsh islands eventually disappear, as is predicted at the study area (Clough et al. 2014), then the westerly wind directions will have a greatly increased fetch, amplifying the wave impacts at Broad Channel. In the first scenario, the water elevation is 0.5 m above the mean sea level (with respect to the North American Vertical Datum of 1988, NAVD88) and the study area is exposed to a constant wind speed of 20 m.s\(^{-1}\). This is a common moderate storm event typically seen after a cold front passes at high tide, before negative storm surge (“blow-out”) reduces water levels. In the second scenario, the water elevation and the wind speed are, respectively, 2 m and 30 m.s\(^{-1}\). This is a rare severe hurricane scenario, similar to cases such as 1788, 1821 and 1893, when hurricanes passed from south to north over the area, leading a high storm surge, and then west winds after their passage (Orton et al. 2016).

Table 2 summarizes all 6 numerical experiments that we study in this section. For each storm scenario the model is run for three different vegetation scenarios, i.e. no vegetation, tall vegetation, and short vegetation.
Figure 4. The study area (enclosed by the red rectangle) located in Jamaica Bay, New York. The satellite image is acquired from Google Earth.

Figure 5. Upper panel: bathymetry of the study area (relative to NAVD88). Lower panel: distribution of salt marshes (shown as red patches).
Results

The spatial distribution of significant wave height in the study area is shown in Figure 6. In moderate storm scenarios (runs 1 to 3), the calculated wave heights adjacent to the eastern boundary of the domain, where the waterfront homes are located, are nearly equal in the presence and absence of salt marshes. In contrast, in severe storm scenarios, waves calculated in the absence of vegetation (run 4) are larger than those calculated in the presence of vegetation (runs 5 and 6). In the moderate storm studied here, the water elevation is 0.5 m above the mean sea level, resulting to a small water depth in shallow regions of the study area. In shallow waters, waves lose a significant portion of their energy due to interactions with the seabed, in other words, due to depth-induced breaking and bottom friction. Therefore, waves that reach the salt marshes are very small, and therefore any additional reduction due to *S. alterniflora* is small. On the other hand, the water elevation in the severe storm studied here is 2 m above the mean sea level, resulting in deeper water depth above the marsh substrate and, in turn, a smaller contribution of depth-induced breaking and bottom friction to wave attenuation. Therefore, bigger waves can reach the salt marshes and, thus, vegetation-induced drag becomes a primary source of wave attenuation.

Figure 7 shows the amount of vegetation-induced wave height reduction, which is computed by subtracting the calculated wave heights in the absence of vegetation from the calculated wave heights in the presence of vegetation. The results indicate that tall *S. alterniflora* is more effective in mitigating wave heights than short *S. alterniflora*. The taller vegetation impedes the top portion of the water column where wave orbital velocities are bigger and therefore larger drag forces are exerted on plants. In all scenarios, the maximum vegetation-induced wave height attenuation is obtained on the marsh islands, as a result of direct wave-vegetation interactions. Waves behind the marsh islands are also attenuated because a significant portion of the incident wave energy is dissipated over the marsh islands and smaller waves propagate downstream.

Longitudinal profiles of wave heights, for example the profile at y=0.5 km shown in Figure 8, indicate that while waves are mitigated in shallow regions, they grow over the deep channels. The calculated wave heights adjacent to the eastern boundary of the study area are nearly equal (about 0.35 m) in runs 1 to 3 whereas they significantly differ in runs 4 to 6. In runs 1 to 3, the
incident waves are almost completely dampened over the marsh islands, due to the combined effects of depth-induced breaking, bottom friction, and vegetation drag, and almost no wave energy is transported to the deep channel behind Rulers Bar. Waves at this channel are local wind-generated waves. On the other hand, when the incident waves are partially dampened over the marsh islands (e.g. runs 4 and 5), bigger waves can propagate toward the deep channel behind Rulers Bar. Therefore, waves near the eastern boundary are a function of local wind energy as well as wave energy transported from upstream. The bigger the incident waves (i.e. the less the energy dissipation over the marsh islands) the bigger the waves at Broad Channel.

Figure 9 shows the percentage of wave attenuation due to vegetation along a lateral transect in front of Broad Channel (adjacent to the eastern boundary of the study area). In scenarios associated with a moderate storm (i.e. runs 2 and 3), tall and short S. alterniflora cause, respectively, up to 5 and 3 percent reduction in wave heights. The results elucidate that wave heights at Broad Channel are smaller than 0.45 m, as a result of intense energy dissipation that occurs in shallow waters and over the marsh islands. In scenarios associated with a severe storm (i.e. runs 4 and 5), the wave height reductions are, respectively, up to 23 and 11 percent for tall and short S. alterniflora. The model results, not shown here, indicate higher amounts of vegetation-induced wave height reduction at the immediate back-side of marsh islands. For example, in the severe storm case, the wave height reductions due to tall and short plants are, respectively, up to 38 and 18 percent behind Rulers Bar (at x=3.25 km).
Figure 6. Significant wave height calculated by the MDO wave model in the study area located in Jamaica Bay, NY. Run 1: moderate storm with no vegetation; Run 2: moderate storm with short vegetation; Run 3: moderate storm with tall vegetation; Run 4: severe storm with no vegetation; Run 5: severe storm with short vegetation; Run 6: severe storm with tall vegetation.

Figure 7. Vegetation-induced wave height reduction, $\Delta H_s$, calculated by the MDO wave model in the study area located in Jamaica Bay, NY.
Figure 8. Longitudinal profiles of calculated wave height at y=0.5 km. The lower panels show the seabed elevation relative to the water surface for each experiment. Green patches in the lower panels represent salt marshes (plant height is not scaled).

Figure 9. Lateral profiles of vegetation-induced wave height reduction (in percent) at x=3.415 km (adjacent to the eastern boundary). The lower panels show the seabed elevation relative to the water surface.

5. Discussion

The MDO wave model is an open-source phase-averaged wave model developed by Mellor et al. (2008) with the intention of rapid modeling of surface waves in shallow and deep waters. The
parameterization of wave energy distribution in frequency space makes this model computationally cost-effective compared to third-generation wave models, yet it accurately captures wave characteristics and processes such as radiation stress (Mellor et al. 2008, Marsooli et al. 2017). The original MDO model lacks a physics-based approach to calculate vegetation-induced energy dissipation. Therefore, it is not an optimal model for application to coastal estuaries that include wetlands, such as Jamaica Bay. In the present study, we improved MDO to simulate vegetation-induced wave energy dissipation using a physics-based approach. The low computational cost and the new vegetation module of MDO provide a valuable new option for important but computationally expensive areas of coastal research such as ensemble forecasting and simulations of processes that require annual or longer simulations (e.g., salt marsh erosion).

Application of the improved MDO wave model to Jamaica Bay revealed the capabilities of salt marshes in the center of the bay to protect the coastal communities in Broad Channel against storm waves. We quantified the influence of salt marshes on storm waves generated by westerly winds because the waterfront homes in Broad Channel are most vulnerable to waves propagating eastward. The results presented in this study complement the findings from a recent study conducted by Smith et al. (2016) who quantified the influence of Jamaica Bay’s salt marshes on waves generated by southerly winds. Both studies demonstrate the efficacy of present-day salt marshes in Jamaica Bay for wave mitigation. While our results suggest that the salt marshes are able to effectively protect waterfront homes in Broad Channel against eastward waves, the results from Smith et al. (2016) provide evidence that the salt marshes can also mitigate northward waves and therefore protect the northernmost shorelines of the bay against erosion caused by waves. In the present study we used a stem density of 200 stems.m$^{-2}$, which is based on measurements in Jamaica Bay, whereas Smith et al. (2016) used a stem density of 400 stems.m$^{-2}$, a typical value observed in the Louisiana Coast of Gulf of Mexico (Jadhav et al. 2013). This stem density is larger than the average density of $S. alterniflora$ in Jamaica Bay and, consequently, may overestimate the ability of present-day salt marshes to reduce wave energy. However, it can be reasonable to consider the density of 400 stems.m$^{-2}$ as the density of future restored salt marshes which may be healthier than the compromised present-day marshes and thus have a higher density of stems.

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Smith et al. (2016) showed that an extensive bay-wide wetland restoration can significantly improve the efficacy of salt marshes for wave mitigation along the northern shorelines. Here, we argue that wetland restoration and/or constructing new wetlands in the center of the bay can also provide a higher level of protection for coastal communities in Broad Channels, especially against eastward/southeastward waves. For example, extending Black Wall and Rulers Bar to the same width as Yellow Bar can effectively improve their performance as natural buffers against storm waves. To better support this claim, we compare the vegetation-induced wave height reductions achieved along lateral transects behind Yellow Bar and Rulers Bar. Figure 10 shows that, behind Yellow Bar, the wave height reductions due to tall and short S. alterniflora are, respectively, up to 30 and 24 percent during the moderate storm, and 51 and 33 percent during the severe storm studied here. These reductions in wave heights are much higher than reductions achieved behind Rulers Bar and near Broad Channel (Figure 9). This is mainly due to the differences in the morphology of the marsh islands and their surrounding channels. Yellow Bar is a wide marsh island, extending the full width of the study area, with relatively shallow neighboring channels. In contrast, the easternmost marsh islands (Black Wall and Rulers Bar) only partially cover the width of the study area and, therefore, waves can develop around these islands and propagate toward Broad Channel. As part of a habitat restoration or nature-based flood protection project, extending the Black Wall and Rulers Bar marshes north/southward can provide a higher level of protection for the population that lives in Broad Channel.

In addition to the horizontal extent of the marsh islands, the elevation of marsh substrate and the plant height also control the performance of salt marshes as natural protective measures against storm waves. In the present study, we showed that the height of S. alterniflora and, as a result, seasonality can greatly impact the effectiveness of salt marshes to mitigate storm waves in Jamaica Bay. The model results indicated that the tall S. alterniflora (which is usually seen during late summer and early fall) can more effectively reduce wave heights than the short S. alterniflora (seen during late spring and early summer). During the cold season, on the other hand, S. alterniflora dies off and the main contribution of marsh islands to wave attenuation is only through depth-induced wave breaking (no vegetation drag). Though not quantified here, broken and decomposing plants on the marsh surface winter and spring season may affect wave heights through an enhanced bottom friction. The present study also showed that the water depth over the marsh substrate significantly impacts the efficacy of marsh islands for wave mitigation.
In storm events with smaller water depth over the marsh islands, significant wave attenuation can be achieved through depth-induced wave breaking over the marsh substrate. Therefore, in addition to the horizontal extension of the marsh islands, raising the elevation of marsh surface (to keep up with sea level rise) would provide the coastal communities in Broad Channel a stronger defense line against storm waves.

The model results elucidate the dependence of vegetation drag coefficient, $C_{D,v}$, on the environmental conditions. For example, Figure 11 shows the spatial variations in the calculated vegetation drag coefficient and Reynolds number within the study area in Jamaica Bay. The vegetation drag coefficient varies one order of magnitude, and remains smaller than 2 in most regions within the marsh islands. The KRA drag formula determines the drag coefficient as a function of Reynolds number, a non-dimensional number that describes the hydrodynamic regime. The larger the Reynolds number the smaller the vegetation drag coefficient. The calculated Reynolds number changes between 319 and 7105 within the salt marshes. In most regions, $Re$ remains within the range of $2200 < Re < 18000$ considered in developing KRA. Despite the strong correlation between the drag coefficient and the environmental conditions, the numerical models applied to estuaries and coastal waters usually adopt a spatially and temporally constant drag coefficient. For example, in their regional-scale STWAVE model of Jamaica Bay, Smith et al. (2016) used a constant drag coefficient to simulate the impact of wetlands in reducing wave heights. They set $C_{D,v}$ to 0.35 based on the peak wave conditions of the no vegetation simulation ($H_{mo}$=1.2 m, $T_p$=4 s, $D$=8 m). However, our results in the present study suggest that $C_{D,v}$ can vary one order of magnitude.

To better evaluate the influence of a varying vegetation drag coefficient on the model results, here we compare the results presented in the previous section (Run 5) with the results from MDO based on a constant drag coefficient. We run the model for $C_{D,v}$=0.35, i.e. the value used by Smith et al. (2016), and $C_{D,v}$=8, i.e. the value that we used for S. alterniflora in section 3.2. Figure 12 shows that MDO with a constant drag coefficient of 0.35 underestimates (compared to results from MDO based on KRA) the influence of vegetation on the wave heights whereas MDO with a constant drag coefficient of 8 significantly overestimates the wave attenuation.
The method of Mendez and Losada (2004), which is based on linear wave theory and the Morison equation (Morison et al. 1950), has been a practical physics-based method to describe wave energy dissipation due to the drag force exerted on vegetation elements. For example, the phase-averaged wave models such as SWAN (Suzuki et al. 2011), STWAVE (Anderson and Smith 2015), and MDO presented here, adopt this method to simulate wave attenuation due to vegetation. This method was developed for waves only and the effect of currents is usually taken into account through the vegetation bulk drag coefficient $C_{D,v}$. Recently, Losada et al. (2016) have proposed a new method to describe the wave energy loss due to vegetation when waves and currents coexist. This new method is also based on the Morison equation but the horizontal velocity takes into consideration both the current velocity and the wave orbital velocity. Losada et al. (2016) conducted a series of laboratory experiments to develop a new empirical formula that determines $C_{D,v}$ under waves traveling in the same or the opposite direction of currents. This new formula, even though it introduces more complexity, would help to improve our understanding of three-way wave-current-vegetation interactions.

There are uncertainties in simulating wave attenuation by vegetation using the MDO model, as with other numerical models developed in the literature. The estimation of the vegetation drag coefficient is one of the main uncertainties. Other uncertainties in the model include the plant swaying motion (of flexible vegetation such as seagrass) and the destruction of plant communities and the collapse of mudflats during storm events. Lastly, the common use of linear wave theory for orbital velocity in theories of vegetation-induced energy dissipation (e.g. Dalrymple et al. 1984, Mendez and Losada 2004, Losada et al. 2016) can introduce additional uncertainty.
Figure 10. Lateral profiles of vegetation-induced wave height reduction (in percent) immediately behind the Yellow Bar Marsh Island (x=2.30 km). The lower panels show the seabed elevation relative to the water surface.

Figure 11. Spatial distribution of calculated vegetation drag coefficient, $C_{D,v}$, and Reynolds number, $Re$, for run 5.
Figure 12. Longitudinal profiles of wave height at y=0.5 km (top left panel) and lateral profiles of vegetation-induced wave height reduction (in percent) at x=3.415 km (top right panel) calculated by MDO based on KRA drag formula and constant drag coefficients of 0.35 and 8. The results are shown for Run 5. The lower panels show the seabed elevation relative to the water surface.

6. Summary and Conclusions

In this study, we improved the MDO phase-averaged wave model, based on the Morison equation (Morison et al. 1950), to account for wave energy dissipation due to vegetation-induced drag force and, thus, to quantify the influence of salt marshes on storm waves. The empirical formula of Kobayashi et al. (1993) was adopted in the model to determine the vegetation drag coefficient as a function of the plant Reynolds number. We evaluated the performance of the improved model using existing laboratory data. Comparisons between the measurements and model results showed that the improved MDO wave model accurately simulates wave attenuation due to submerged and emergent vegetation.

We applied the MDO wave model to Jamaica Bay, New York, to quantify the role of its salt marshes to protect the coastal communities in Broad Channel against storm waves. The effectiveness of S. alterniflora, the dominant species in Jamaica Bay’s salt marshes, in reducing wave heights was investigated using a series of numerical experiments. The model results showed that S. alterniflora with an average stem height of 0.6 m is more effective at reducing
wave heights than *S. alterniflora* with an average stem height of 0.3 m. For example, for the severe storm case tested in the present study, tall plants caused up to 23 percent reduction in the wave heights along a lateral transect in front of Broad Channel whereas the wave height reduction due to short plants was only up to 11 percent. This is because the taller *S. alterniflora* impedes the top portion of the water column where wave orbital velocities are larger and, thus, larger drag forces are exerted on plants. The model results also showed that the influence of vegetation drag on wave heights is more pronounced during a severe storm than a moderate storm. In the moderate storm studied for this location, the water depth is small and, thus, waves lose a significant portion of their energy in shallow waters around the marsh islands, mainly due to depth-induced breaking and bottom friction. Therefore, waves that reach the salt marshes are small and wave-vegetation interactions become negligible. On the other hand, during a severe storm with high water elevation, the contribution of depth-induced breaking and bottom friction to wave attenuation is small, which allows bigger waves to reach the salt marshes. Thus, vegetation-induced drag becomes a primary source of wave attenuation. If the marshes disappear, as is expected to occur in the coming decades, the communities in Broad Channel, Jamaica Bay, will be exposed to more energetic waves, especially during storm events with extreme water elevations.

This study also showed that the vegetation drag coefficient in a coastal-scale salt marsh can significantly vary as a function of vegetation properties and storm conditions. The model results showed that the drag coefficient in our study area spatially varies one order of magnitude during a single storm event. Therefore, a constant drag coefficient may over/underestimate the value of salt marshes as natural protective measures against storm waves. The empirical formula of Kobayashi et al. (1993), as was successfully used in the present study, may be adopted in other studies to determine a variable drag coefficient as a function of Reynolds number.

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their insightful comments and suggestions. We also would like to thank Dean Tayler from the U.S. Geological Survey and Kim Fisher from Wildlife Conservation Society for providing us the bathymetry/topography DEM of Jamaica Bay, NY. Finally, we acknowledge the use of the grid generator software developed by Larry Yin from Stevens Institute of Technology for generating the computational grid of Jamaica Bay. The New York City urban ecological land-cover map and biophysical properties of salt marshes in Jamaica Bay can be obtained by contacting the New York City Department of Parks & Recreation, Natural Area Conservancy, and/or the Science and Resilience Institute at Jamaica Bay. The bathymetric/topographic data of Jamaica Bay can be obtained by contacting the U.S. Geological Survey. Data in Figures 1 and 2 are digitized from Figure 4 in Suzuki et al. (2011). Data in Figure 3 are digitized from Appendix A in Wu et al. (2011). The source code of the MDO wave model is available at http://shoni2.princeton.edu/ftp/glm/.

References


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Table 1. Experiments of Wu et al. (2011) used in the present study to evaluate the accuracy of the MDO wave model to simulate wave attenuation by *S. alterniflora*.

<table>
<thead>
<tr>
<th>experiment</th>
<th>$H_{rms}$ (m)</th>
<th>$T_p$ (s)</th>
<th>$h$ (m)</th>
<th>$\alpha$ (-)</th>
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<td>0.5</td>
<td>1.18</td>
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<td>0.7</td>
<td>0.84</td>
</tr>
<tr>
<td>4</td>
<td>0.038</td>
<td>1.6</td>
<td>0.7</td>
<td>0.84</td>
</tr>
</tbody>
</table>

Table 2. Numerical experiments examined in this study to quantify the influence of Jamaica Bay’s salt marshes on storm waves. Wind direction is 282 degree (meteorological convention) in all experiments.

<table>
<thead>
<tr>
<th>Run</th>
<th>Strom condition</th>
<th>Vegetation characteristics</th>
<th>Wind speed (m.s$^{-1}$)</th>
<th>$\eta$ (m)</th>
<th>$h_v$ (m)</th>
<th>$N_v$ (plants.m$^{-2}$)</th>
</tr>
</thead>
<tbody>
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<td>moderate</td>
<td>no vegetation</td>
<td>20.0</td>
<td>0.50</td>
<td>-</td>
<td>0.0</td>
</tr>
<tr>
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<td>moderate</td>
<td>short vegetation</td>
<td>20.0</td>
<td>0.50</td>
<td>0.30</td>
<td>200.0</td>
</tr>
<tr>
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<td>moderate</td>
<td>tall vegetation</td>
<td>20.0</td>
<td>0.50</td>
<td>0.60</td>
<td>200.0</td>
</tr>
<tr>
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<td>severe</td>
<td>no vegetation</td>
<td>30.0</td>
<td>2.0</td>
<td>-</td>
<td>0.0</td>
</tr>
<tr>
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<td>short vegetation</td>
<td>30.0</td>
<td>2.0</td>
<td>0.30</td>
<td>200.0</td>
</tr>
<tr>
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