Simulation and Observation of Wind driven Waves in a Fetch-Limited Urban Estuary: Long Island Sound

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Abstract

We have evaluated the wave module of a hydrodynamic-wave coupled numerical model inside an urban estuary. We performed four numerical experiments using different forcing scenarios in order to test the ability of the model to capture the wave field statistics inside the estuary. The geometry of the estuary renders the wave field fetch limited and leads to marked difference between western and eastern areas. We were able to capture the local wave statistics after tuning the wave growth and breaking spectral parameterizations. This allowed the model to differentiate stages of wave development and better capture wave statistics inside the estuary. Although modifications were linked to a bias high relative to the buoy observations under weak and fetch limited circumstances we deemed the modifications necessary for moderate to strong forcing. Finally, the last numerical experiment was forced with Superstorm Sandy 2012, considered an extreme weather event for the region. For this simulation we also tested different bottom boundary closure schemes for a hydrodynamic-wave coupled simulation; a classic log-layer and a wave perturbed bottom boundary (Madsen 1994). The fully coupled simulation was able to capture the maximum values of significant wave height and period recorded at the Western and Central locations of the estuary.

1. Introduction

The non-negligible interaction between waves and currents at different time, frequency and spatial scales, has driven the ocean modeling community to incorporate wave dynamics into hydrodynamic ocean models. Studies have ranged from exploring global wave effects to the ocean mixed layer (e.g. Belcher et al. 2012) down to local impacts on circulation at coastal environments (e.g. Davies and Lawrence 1995; Xie et al. 2008). Relevant wave induced effects include modification of the surface stress (e.g. Donelan et al. 1993; Drennan et al. 2003), injection of Turbulent Kinetic Energy into the ocean surface layer by wave breaking (e.g. Terray et al. 1996;Drennan et al. 1996; Scully et al. 2016) and wave driven Langmuir turbulence, which ultimately alters the mixed layer depth (e.g. Sullivan et al. 2007; Belcher et al. 2012; Kukulka and Brunner 2012) potentially having a substantial impact on air-sea interaction. Furthermore, the presence of waves adds momentum to the water column via radiation stresses (e.g. Mellor 2003 and 2005). Finally bottom interaction between currents (low frequency) and orbital velocities (high frequency) and the subsequent wave induced enhancement of bottom drag (e.g. Grant and Madsen 1984) with direct consequences to the currents structure.

To account for these effects, classic hydrodynamic models such as the Princeton Ocean Model (POM), the Regional Ocean Modeling System (ROMS), and the Advanced Circulation (ADCIRC) model have been coupled with wave models such as Wave Watch III (WWIII) and Simulating Waves Near Shore (SWAN). To date, most efforts to incorporate these effects into numerical models have been mainly purely scientific in nature; however, there is considerable relevance to coastal communities, municipalities and coastal cities in the advancement of hydrodynamic-wave coupled models. For example, understanding wave-current interaction in coastal environments aids in the prediction of storm impacts (e.g. flooding risk and structural damage), particularly with a changing climate, and can inform future mitigation and adaptation efforts. This is one of the reasons why modeling efforts are being targeted to capture and evaluate the coupled effects between storm surge and surface gravity waves under severe forcing (e.g. Xie et al. 2007; Bunya et al. 2009; Roland et al. 2009; Chen et al. 2011; Dietrich et al.2011) and the implications on flooding at coastal areas and the consequences with a rising sea level. For example, modeling results indicate that waves can increase water levels by 5-20% depending on the local bathymetry (e.g. Sheng et al. 2004; Fukanoshi et al. 2008; Dietrich et al. 2010), with enhancements of 35% in regions with a steep slope (Dietrich et al. 2010). Furthermore, wave-induced effects can account for up to 30% of the peak storm surge (e.g. Sheng et al. 2004) where hydrodynamic-wave coupled simulations by Xie et al. (2008) suggested a strong wave-induced effect on the overall flooding area, with the most dramatic effects observed in the shallow water river estuaries of the Charleston Harbor, SC.

Therefore, we have conducted an evaluation of the wave module in the Finite Volume Community Ocean Model, hereafter FVCOM (Chen et al. 2006; Huang et al. 2008; Chen et al. 2008; Chen et al. 2011). The FVCOM model is currently being implemented in a small urban estuary, Long Island Sound (LIS) (Fig. 1), to quantify the response of the system to severe weather events in a changing climate. FVCOM uses a 3-D unstructured grid, free-surface and primitive equations to calculate hydrodynamics. FVCOM was coupled with the SWAVE wave module (Qi et al. 2009), which uses an unstructured finite version of the Simulating Waves Nearshore (SWAN; the Delft University of Technology), to resolve smaller coastal scales, where shallow water processes predominate. The hydrodynamics and waves are coupled via radiation stresses, bottom boundary layer, and surface stress (e.g., Wu et al., 2011). The work presented here summarizes the evaluation of the modeled wave statistics for a range of forcing conditions (e.g., $5 < U_{10} < 26$ m s^{-1}, with and without fetch limitation) in order to check the model's capacity to recreate observed and previously documented wave dynamics inside the estuary under fully hydrodynamic-wave coupled runs. Fetch limitation, strong tidal currents, a complex bathymetry and fragmented coastline, features common among estuaries and to LIS in particular; produce a large range of deep to shallow water dynamics. To our knowledge this is the first effort to implement and validate a fully coupled high-resolution hydrodynamic-wave model in LIS. Finally, the model simulations were compared and analyzed relative to observations in an effort to shed some light on wave dynamics across the estuary.

1.1 General circulation and winds in LIS

The LIS is a tidally driven estuary, where the sea surface displacement on the adjacent continental shelf is responsible for the observed barotropic driving force impacting the general circulation. The strong tides inside LIS are resonant with the M_2 tidal constituent, with the strongest tidal currents located in the eastern section of the estuary (i.e. at the mouth of LIS). In this area, tidal axes are oriented across sound at the surface with an along isobath direction near bottom (Bennett et al. 2010; O'Donnell et al. 2014). As an estuary, the LIS does receive fresh water input, although a large fraction of fresh water discharge happens close to the mouth of the estuary via the Connecticut River. This renders the LIS unusual relative to other estuaries. The main source of fresh water is the Connecticut River (Fig. 1), with a contribution of 75% of the total gauged flux (e.g. Gay et al., 2004). The wind forcing over the estuary exhibits a marked periodicity with consistent seasonal variability, both in wind magnitude and direction (e.g. Isemer and Hasse 1985, O'Donnell et al. 2014). Studies have focused on wind measurements collected at the Western, Central and Eastern areas (WLIS, CLIS and ELIS metocean buoy stations) to explore wind and stress distributions in the LIS. Data shows wind stresses pointing to the northeast during summer and southeast during winter, with an overall stronger forcing during the winter months (e.g. Klink 1999; Lentz 2008). Annual means of stresses are dominated by the winter months and the CLIS and WLIS are significantly different with annual means of 0.026 N m^{-2} and 0.012 N m^{-2} respectively (O'Donnell et al. 2014). The seasonality and strength of the wind forcing has direct implications on surface currents and wave generation, where the directionality of the forcing plays into the fetch limitation of the system (Fig.2).

1.2 Oceanographic observations for the validation exercises

We relied on the metocean buoy stations at the Western and Central LIS (lisicos.uconn.edu) for wave statistics inside the LIS, which are maintained and operated by the University of Connecticut. Both of these buoys are equipped with met packages from R.M. Young and include wind speed and direction, air temperature, barometric pressure, and relative humidity. The Central Sound buoy is equipped with a directional wave sensor manufactured by Axys Technologies sampling every 30 minutes for 22 minutes at 4 Hz. A non-directional wave module by Neptune Sciences is installed on the Western Sound buoy, sampling every 30 minutes for 17 minutes at 2 Hz.

We also relied on a wave observations at the Block Island Sound (BLIS) region which were collected with an upward looking 600 KHz RDI Teledyne Acoustic Doppler Current Profiler. The sampling frequency was set at 1 Hz with a burst duration of 20 minutes occurring every 30 minutes. The instrument provided measurements of the frequency and direction for surface gravity spectra based on the surface pressure measurements. This signal was partially processed with the proprietary RDI software WavesMon.

2. The FVCOM-SWAVE Numerical Model

The model was forced at the open boundary with eight harmonic tidal components for the region (e.g. Foreman 1978), which were tuned based on observations inside the estuary (i.e. New London, Bridgeport and New Haven tide gauges) Riverine discharge was limited to the Connecticut River. The atmospheric forcing was based on the North American Mesoscale (NAM) and the Weather Research and Forecasting (WRF) model simulations, where at this point only the wind field was included (i.e. no heat fluxes and no precipitation). The spin up for the model ranged between 1 – 2 days. The horizontal grid resolution (Δx, Δy) was set at 250 m with 11 sigma layers in the vertical (z). The turbulent closure model corresponds to the q-ql Mellor and Yamada (1982) level 2.5 (i.e. MY-2.5), where q is the turbulent kinetic energy and l is the turbulent scale. The bottom boundary layer follows a *law-of-the-wall* classic behavior, where the bottom drag coefficient follows by matching a logarithmic profile at height z_{ab} (depending on model resolution) and the aerodynamic roughness length (z_o). The SWAVE module is a direct adaptation from SWAN and the reader is referred to the SWAN user manual and also to Qi et al., (2009) and the FVCOM User Manual for further details on the numerical approach to the solution of the wave action equation. The SWAVE spectral frequency range was set in the range 0.05 – 1 Hz with 32 logarithmically spaced frequencies and an angular distribution resolution of 10° (Δdeg) with 36 equally spaced angles with a $f^{-4.0}$ Hz spectral tail roll off. It is relevant to note that the spectral tail roll off needs to be modified depending on which wave growth parameterization is used. Spectral sources and sinks of wave energy were slightly modified to better capture the wave dynamics inside the estuary.

2.1 Atmospheric Forcing: Wind Energy Input

The SWAVE wave module was run as a third generation wave model (GEN3), where both, the Snyder et al. (1981) (e.g. Komen et al. 1984) and the Janssen (1991) wave growth parameterization were initially evaluated. The total wind input from wind forcing was prescribed to have a linear and exponential growth component, where the total wind input (S_{in}) follows from the addition of the two growth parameterizations:

$$S_{in}(f,\theta) = A + B\,F(f,\theta) \qquad (1)$$

where $F(f,\theta)$ is the frequency-direction sea surface spectrum. The *B* parameterization corresponds to the Snyder et al., (1981) or to the Janssen (1991) and *A* represents the linear growth by Cavaleri and Malanotte-Rizzoli (1981) The linear wave growth by Cavaleri and Malanotte-Rizzoli (1981) was active during all simulations.

2.2 Energy Dissipation: Wave Breaking

This energy sink term is not well understood and available parameterizations are highly empirical. The model was run using the generalized Komen et al. (1984) wave breaking parameterization to complement the Snyder et al. (1981) wave growth parameterization and the Janssen (1991) breaking parameterization when the same wave growth parameter was used. The spectral source term can be stated as (Ris 1997; Booij et al., 1999):

$$S_{diss}(f,\theta) = \Gamma\, f_m \left(\frac{k}{k_m}\right) F(f,\theta) \qquad (2)$$

where Γ is a steepness (s) dependent coefficient (e.g., Janssen 1992) :

$$\Gamma = C_{ds}\left[(1-\delta) + \delta\left(\frac{k}{k_m}\right)\right]\left(\frac{s}{s_m}\right)^n \qquad (3)$$

where C_{ds} is an empirical coefficient of proportionality, s corresponds to the overall steepness parameter, *n* is a numerical constant and the subscript *m* denotes an average where k_m follows from:

$$k_m = (\langle 1/\sqrt{k} \rangle)^{-2} \qquad (4)$$

and the steepness parameter s follows from:

$$s = E(k_m)^2 g^{-2} \qquad (5)$$

where E is the zero order moment of the spectrum ($F(f, \theta)$).

2.3 Energy Dissipation: Bottom Friction

The spectral dissipation function due to bottom friction effects (S_{bf}) can be written in the general form (Weber 1991a,b):

$$S_{bf}(k) = -C_f \frac{k}{\sinh(2kH)} G(k) \qquad (6)$$

where k is the magnitude of the wavenumber, H is the water depth and C_f is a friction coefficient with units of velocity i.e. m s $^{-1}$, $G(k)$ is the wavenumber spectrum where $G(k) = F(f)\, df/dk$. The Madsen wave friction coefficient (f_w) follows from equation (6):

$$f_w = \begin{cases} 0.15 \;;\; \frac{a_b}{k_N} < 1.57 \\ \frac{1}{4\sqrt{f_w}} + log_{10} \frac{1}{4\sqrt{f_w}} = m_f + log_{10} \frac{a_b}{k_N} \quad ; \quad \frac{a_b}{k_N} > 1.57 \end{cases} \qquad (7)$$

where the roughness element length (k_N) corresponds to the actual physical roughness length (i.e. associated to the sediment size and distribution), a_b is the bottom excursion amplitude ($a_b = u_b\, \omega_b^{-1}$), where u_b is the bottom orbital velocity, ω_b the bottom wave frequency and m_f is a constant of value -0.08. Then the friction coefficient follows from:

$$C_f = \sqrt{2}\, f_w\, \langle u_b^2 \rangle^{1/2} \qquad (8)$$

2.4 Quadruplet non-linear interaction

Quadruplet non-linear interactions were activated using the default settings for DIA (Hasselmann et al. 1985). Triad non-linear interactions were not active during these simulations.

3. Results

We performed a few numerical tests to compare the two wave growth parameterizations (i.e. Snyder et al. 1981 and Janssen 1991) and concluded that the Janssen (1991) wave growth parameterization, with default coefficients produced lower significant wave heights relative to the Snyder et al. (1981) parameterization (all other spectral parameterizations held constant). This was the case particularly at low wind speeds and was consistently biased low when compared to observations. The Snyder et al. (1981) performed better, but when compared to observations of significant wave height and dominant period at the WLIS (fetch limited location) it was also biased low. The Snyder et.al (1981) wave growth did perform well at the CLIS and BLIS and we therefore attempted to slightly modify it to better represent the underdeveloped wave field conditions at the Western end of LIS. Modifications to the wave growth parameter coefficients are displayed in Table 3.1 where we enhanced the coefficients C and D. Further fine-tuning was needed for the severe weather simulation were we introduced one more modification to the Snyder et al. (1981) wave growth parameter aside the enhancement of the C and D coefficients. Writing the full expression for B from equation (1) we have:

$$B = max\{0, C\frac{\rho_a}{\rho_w}\left[D\ \frac{u_*}{c}\cos(\theta_{wave} - \theta_{wind}) - X\right] * f\Big\} \qquad (9)$$

where $(\theta_{wave} - \theta_{wind})$ is the difference between wave and wind direction, u_* is the atmospheric friction velocity and c is the phase speed of the waves. The term *X* in equation (9) has a default value of 1. This induces a negative energy flux at frequencies that are lower than the spectral peak. This accounts for the assumption of a minimized or even negative wind-wave coupling when waves are travelling faster than the wind. In the underdeveloped WLIS we reduced X to 0.85. This value minimizes the energy reversal at lower frequencies and enhances the wind energy input at the peak. The reduction of X from 1 to 0.85 enhances the wave growth at WLIS with a minimum impact on CLIS and the Eastern locations. For example, by solely enhancing C and D (and leaving X = 1) the model overestimates the wave growth at CLIS during the high forcing ($U_{10} > 25$ m s^{-1}) with a bias high of 29% whereas this modification in combination with the tuning to the wave breaking coefficients leads to a bias low of 6% at CLIS and better captures the maximum significant wave height at the CLIS and WLIS.

Modifications to the breaking coefficients were also explored and applied. Default coefficients appear to overestimate the dissipation due to breaking inside the estuary. We found that to better capture significant wave height and dominant wave period observations, the coefficient $C_{ds,}$ had to be modified from its default value (Table 3.2) with best results in the range: 1.10 x 10^{-5} –1.18 x 10^{-5} (Table 3.2) The exponent *n* was kept constant at 1.0. In the underdeveloped seas inside LIS, breaking should be theoretically distributed across all frequencies (e.g. Gemmrich et al. 2008), whereas equation (2) heavily weights dissipation at the peak based on default values. We hypothesized that this was leading to an overestimation of the actual breaking and attempted to reduce the weight of the spectral dissipation at the dominant frequencies. At this point this is somewhat speculative, as we do not have wave breaking observations aside from anecdotal observations from several field campaigns.

The modifications presented in Table 3.2 reduced the spectral dissipation at the peak, but maintained an active dissipation at higher frequencies. This was achieved by increasing the delta (δ) parameter and by reducing the C_{ds} coefficient. The overall reduction in dissipation by breaking once the coefficients were fine-tuned was estimated at approximately 52% across the frequency domain, where approximately 75% of the reduction happens at frequencies in the 0.05 – 0.3 Hz. The other relevant dissipative term is the bottom friction parameterizations, where at this time we did not perform a full evaluation of it. The Western end has shallow waters (~20 m deep), which can certainly interact with the wave field in a severe event such as Sandy. Here, we have chosen a roughness element length (k_N) of 0.02 m to estimate the Madsen et al. (1988) spectral parameterization, which was used during our last simulation. During all simulations triad non-linear interactions were turned off and the quadruplet non-linear interactions were solved using default DIA coefficients.

The model was compared against observations and the performance was evaluated based on the root-mean-squared-error (Eq. 10) the model bias (Eq. 11), which states the under-over prediction (%) and the index of agreement, which is a parameter of the skill of the model (Eq. 12).

$$rms = [\langle (X - x)^2 \rangle]^{1/2} \qquad (10)$$

$$bias = 100\,\frac{\sum_{i=1}^{N}(X_i - x_i)}{\sum_{i=1}^{N}|X_i|} \qquad (11)$$

$$IA = 1 - \left[\sum_{i=1}^{N}(X_i - x_i)^2 \Big/ \sum_{i=1}^{N}(|X_i - \langle x \rangle| + |x_i - \langle x \rangle|)^2\right] \qquad (12)$$

where brackets denote temporal averages and X and x correspond to model and observations respectively.

3.1 Case 1: Response to fetch limited weak wind forcing

The first simulation corresponds to a period of weak atmospheric forcing conditions, which are commonly observed in the LIS during the summer months. The strength of the forcing was defined in terms of the wind speed where a low mean wind speed (U_{10}< 5.0 m s^{-1}) was satisfied in combination with a relative constant wind direction assuring a limited fetch during the model run (i.e. Westerly and South-Westerly winds). The period selected was June 19-24, 2013. Observations from the CLIS (lisicos.uconn.edu/clis) buoy showed an average wind speed of 4.97 m s^{-1} with a dominant wind direction of 212° making the forcing predominately from the southwest. Wind conditions at the WLIS (lisicos.uconn.edu/wlis) buoy were similar with the same mean wind speed of 4.95 m s^{-1} and wind direction of 212° (SW).

During this simulation the model was biased high at the Western and Central sound locations (Fig 1). The significant wave height at WLIS showed a 48% bias high and an index of agreement (Eq. 10) of 0.59. The significant wave heights at the CLIS location were biased high by 43% with an index of agreement of 0.61. Modeled significant wave heights were biased low relative to observations at BLIS with and index of agreement of 0.36 (Fig. 3-a). At the CLIS the dominant period comparisons (Fig 3-b) had a 0.96 correlation coefficient with a bias high of 4%. Nonetheless the index of agreement was only 0.40 as the model had a delayed response to changes in local wind conditions only capturing the mean behavior, but not fully capturing the dynamic range of the dominant period. Dominant periods at the WLIS exhibited a high correlation coefficient 0.92 and were bias low by 15% with an index of agreement of 0.50. At BLIS wave scales were not well captured, where the model overestimated the dominant period by 37% with an index of agreement of 0.30.

By complementing the wind forcing (i.e. wind speed) distribution over the LIS with the dominant phase speed, we explored the difference in the wave field evolution at CLIS relative to the WLIS. In order to do so we rely on the inverse wave age parameter; defined as the ratio of wind speed at the reference height of 10 meters (U_{10}) to dominant phase speed (c_p), which follows from the dispersion relation once the peak period is identified. The inverse wave age can be stated as: U_{10}/c_p. The inverse wave age is relevant to the wave growth parameterization and was used to estimate the dominant wave scales and the potential differences in developing stages across the LIS wave field. For $U_{10}/c_p < 1.2$ the wave field is defined as a mature or developed state, whereas for $U_{10}/c_p \geq 1.2$ the sea state is said to correspond to a young or developing sea. For example, during this simulation the CLIS had an observed inverse mean wave age (i.e. U_{10}/c_p) of 1.26 and an inverse mean wave age of 1.22 at WLIS. Modeled inverse mean wave ages were 1.21 and 1.22 at CLIS and WLIS respectively.

The wind forcing at both sites was correlated and of comparable magnitudes, leaving the developing differences to the capacity of the waves to react to the forcing. On average the model was able to capture the overall wave field structure across the LIS for a fetch limited scenario. Modeled waves were shorter and smaller at WLIS than at CLIS based on significant wave heights (sigH) and dominant periods (T_p) (Table 3.4). Average significant wave height distribution and dominant period are shown in Figures 4-a and 4-b. Observations at BLIS show a mean ratio $\langle U_{10}/c_p \rangle = 0.87$, suggesting a more mature state with waves coming from the shelf (non-locally generated swell). Modeled inverse wave age at BLIS was close to one (i.e. $\langle {U_{10}}/{c_p} \rangle = 1$). Modeled waves at BLIS were not able to capture the dominant peak period. This could be improved by modifying the open boundary conditions (OBC) to include swell propagating into the estuary.

4.1.2 Case 2: Response to fetch limited moderate forcing

The second case considered rapid changes in wind magnitude, but with a relatively constant and dominant westerly wind direction (average wind direction 268°) making the system fetch limited again. The maximum wind speed was observed to be 14 m s^{-1} at CLIS and 13 m s^{-1} at WLIS, both during the beginning of the simulation, followed by a period of calm (U_{10} < 5.0 m s^{-1}) and a final ramp up in wind speed (U_{10} > 10.0 m s^{-1}) The average wind speed during the simulation was 5.1 ± 0.15 m s^{-1}. The model run covered four days from February 16-20, 2015. Once again, the wind forcing was highly correlated at both sites and we associated the observed and modeled differences between sites to behavior of the wave field.

The physical conditions during this run kept the model at an average underdeveloped stage at CLIS and WLIS with a mean inverse wave age of 1.01 and 1.26 respectively (i.e. $\langle {U_{10}}/{c_p} \rangle$. The modeled scenario was consistent with observations resulting in the CLIS and WLIS exhibiting a developed state with an average inverse wave age of 0.97 and 1.14 respectively

This difference in development can also be seen in Fig. 5 and Table 4.5 where significant wave heights and dominant periods at CLIS and WLIS were found to be on average different with larger waves observed at CLIS. Figure 5 shows the 1:1 comparison for significant wave height and dominant period in CLIS and WLIS. The model shows high correlation coefficients between hindcast and observations of significant wave height and dominant period with low *rms* errors (Table 3.5). Mean dominant periods were well captured at both central and western locations (Table 3.6). The dominant wave period at CLIS had a correlation coefficient of 0.93 and an *rms* of 0.9 s and was biased low by 8.5% with an index of agreement of 0.85. At WLIS the model estimates of dominant wave period where also biased low (by 13%) with an index of agreement of 0.60. Significant wave heights were also well captured during this simulation, with an index of agreement of 0.86 and bias high of 5% at the CLIS and an index of agreement of 0.87 with a bias high of 17% at the WLIS.

The average structure of the wave field is shown in Figure 6, where there is a marked difference between the CLIS and WLIS environments. This model simulation showed a more severe contrast between CLIS and WLIS relative to the previous case. We attribute this to the strong wind dependence of the system. The strong forcing registered on February16 and17 and at the end of February19th (U_{10} > 10.0 m s^{-1}) rapidly develops the wave field at the CLIS, but the fetch limitation at WLIS keeps this region underdeveloped with overall shorter waves. The significant wave height difference under strong forcing (U_{10} > 10.0 m s^{-1}) between the CLIS and WLIS was on average twofold. The overall average (Table 3.6) and significant wave height and wave scale distribution was well captured by the model hindcast.

This simulation exhibited a wide dynamic range of conditions (Table 3.6) leading to a sharp contrast in wave energy between the Central, Western and coastal areas (Fig. 6a).

4.1.3 Case 3: Response to unlimited fetch under moderate forcing

The third case corresponds to an unlimited fetch scenario with moderate to strong forcing. The simulation was run for seven days between January 1-8 2014 with a mean wind speed of 7.47 ± 3.4 m s^{-1} and an average wind direction of 100º (easterly wind). In Figure 7 we show the comparison across the sound from BLIS, CLIS to WLIS of significant wave heights (Fig 7-a) and dominant period (Fig. 7-b).

At the WLIS location the modeled dominant period was bias high by 11% with an *rms* of 1.2 s (Table 3.7) with an index of agreement of 0.54. The dominant periods at CLIS showed good agreement and were biased high (2.8%) and had an index of agreement of 0.61. The modeled significant wave height at WLIS had an index of agreement of 0.79 and was biased high by 20% with an *rms* of 0.29 m. At the CLIS location the modeled significant wave height had an index of agreement of 0.74 with a bias high of 11%, but missed the maximum observed significant wave height. Correlation coefficients were high (Fig 7) at both locations inside the estuary, particularly for the dominant period comparison. At BLIS the index of agreement dropped to 0.38 with a bias low of 14% for the dominant period. Significant wave heights had an index of agreement of 0.61 and were bias low by 17%.

During the simulation, the WLIS observations exhibited on average underdeveloped seas, with an inverse wave age of: $\langle {}^{U_{10}}/_{c_p} \rangle$= 1.76. The average inverse wave age at CLIS was observed to be: $\langle {}^{U_{10}}/_{c_p} \rangle$= 1.47. The Block Island Sound site showed an average inverse wave age of 1.20. Modeled inverse wave age at CLIS, WLIS and BLIS were 1.43, 1.64 and 1.30 respectively. The spatial distribution of significant wave heights and dominant periods is shown in Figure 8, where the model shows a more homogeneous distribution of wave energy inside the LIS.

The overall wave field structure appears to be rather homogeneous throughout the LIS with differences constrained at the coast (Fig. 7).

4.1.4 Case 4: Response to a severe weather event: Unlimited fetch under extreme forcing

The severe weather event was chosen to be the Superstorm Sandy 2012. The model simulation covered ten days between the 21 and 31 of October 2012. The maximum wind intensity inside the estuary was recorded at 22:00:00 on Oct -29 with wind speeds in excess of 24 m s^{-1} at the CLIS. Although the wind magnitude was not particularly high e.g. Hurricane Gloria reached 33 m s^{-1} at the same location, the long duration of the storm in addition to the direction of the forcing made it an exceptional event. For example, wave heights in the continental shelf reached over 9 m with dominant periods in excess of 12 seconds at Long Beach, NY. Inside the estuary reported observations of significant wave heights were 4 m at the central buoy location and reached an excess of 3 m at the western end.

4.1.4-a Hydrodynamic- Wave Coupled simulation with a Logarithmic Bottom Boundary Layer

First we run a simulation with a classic log-layer as the bottom boundary. The modeled dominant periods and significant wave height comparisons showed high correlation coefficients at both locations and acceptable *rms* errors (Table 3.9). For this longer simulation we present a time series of the significant wave heights (Fig. 9) and dominant period (Fig. 10) in order to give an idea of the build up of the storm and how the model captured the evolution inside the estuary.

The index of agreement at CLIS was 0.91 for the dominant period with a bias low of 10%. The index of agreement at CLIS was 0.94 for the significant wave height comparison with a bias low of 8%. At the WLIS location the significant wave height hindcast had an index of agreement 0.84 and had a bias low of 41%, as the model failed to capture the full evolution of the wave energy in the WLIS area with the spectral parameterizations despite the previous calibration. The dominant period at the WLIS was better captured by the model, with an index of agreement of 0.84 and a bias low of 18% (Table 3.10)

The modeled wave field at the CLIS location was on average underdeveloped ($\langle U_{10}/c_p \rangle =$ 1.63) and reached a peak inverse wave age value of 3.4 at the storm maximum consistent with observations. In the WLIS region, the wave field was also on average underdeveloped ($\langle U_{10}/c_p \rangle$=1.84) with a maximum inverse wave age value of 4.57. Observations at CLIS and WLIS showed an average inverse wave age of 1.79 and 1.73 respectively. During the storm maxima, observations reported $\langle U_{10}/c_p \rangle = 3.23$ and $\langle U_{10}/c_p \rangle = 4.33$ at CLIS and WLIS respectively. Maximum significant wave heights and periods are presented in Table 3.11. These results show how the wave field inside LIS evolved under a severe (long duration, high wind) event (Fig).

The WLIS region remained underdeveloped, where wave growth was mainly limited by the local bathymetry and surface dissipation by wave breaking and bottom friction. This is also true within CLIS, but to a lesser degree. The deeper bathymetry at CLIS allowed longer and faster waves to develop (Table 3.11) yielding a more mature sea.

4.1.4-a Hydrodynamic- Wave Coupled simulation with Wave-Current interaction at the Bottom Boundary Layer.

Finally, this simulation was run using the sediment module available in FVCOM, where the Madsen (1994) bottom boundary layer (BBL) scheme was implemented. This allowed the waves to be fully coupled with the hydrodynamics at both boundary layers and through the radiation stresses in the water column.

The index of agreement at CLIS was 0.90 for the dominant period with a bias high of 5.4% (Fig. 10) and 0.88 for the significant wave height comparison with a bias high of 38.8% (Fig. 9). At the WLIS location the significant wave height hindcast had an index of agreement 0.91 and was biased low by 16%. The dominant period at the WLIS was better captured by the model, with an index of agreement of 0.88 and a bias low of 5.3% (Fig. 10). Although the maximum peak period recorded at the WLIS was missed by the model (~40% bias low) This simulation yields lower *rms* at WLIS compared to a log-layer BBL (Table 3.12)

Maximum significant wave heights and periods were better captured during this simulation (Table 3.13). Despite the improvement from the previous simulation, the WLIS was biased low relative to the maximum observations recorded during Sandy 2012.

5.0 Discussion

We have performed a series of numerical experiments to test the model's sensitivity in capturing the structure of the wave field inside a fetch limited urban estuary under different forcing scenarios. First we evaluated the performance of the Janssen (1991) and the Snyder et al. (1981) wave growth parameterizations. We found that at low to moderate wind speeds ($2 \leq U_{10} \leq 8$ m s^{-1}) the Janssen (1991) parameterization had the tendency to produce significant wave heights that were biased low relative to observations. The default Snyder et al. (1981) parameterization behaved better exhibiting lower *rms* relative to observations. Nonetheless, both parameterizations were biased low. Under stronger forcing ($U_{10} > 10$ m s^{-1}) the Janssen (1991) improved its performance and both parameterizations exhibited little difference relative to observations. Under very strong forcing ($U_{10} > 20$ m s^{-1}) the Janssen (1991) exhibited better agreement with the data, although further evaluation is deemed necessary at this stage. Under strong forcing ($U_{10} > 15$ m s^{-1}) both default parameterizations were biased low. Furthermore, the iterative nature of the Janssen (1991) makes it computationally more expensive than the Snyder et al. (1981). Based on these considerations, we opted to run our numerical simulations based on a modified version of the Snyder et al. (1981) parameterization. We did this by fine-tuning the parameterization coefficients (Table 3.1) to improve modeled significant wave heights (sig_H) and dominant periods (T_p) inside the estuary. Finally under the severe forcing event we also explored a modification of the X term in equation (10), which allowed for an enhancement of energy in (i.e. wind input) at lower frequencies. The enhancement in energy input grows as the forcing becomes larger. For example this leads a 2% increase in the integrated spectral energy for a 15 m s^{-1} and 9% enhancement at wind speeds larger than 24 m s^{-1} with less than a 1% enhancement for wind speeds lower than 10 m s^{-1}. This was useful during the last simulation of Superstorm Sandy (2012), where we improved the modeled maximum significant wave height and peak wave period. Further enhancement can be achieved by enhancing the coefficients C and D, but the effects on the CLIS and ELIS suggested this is not a good alternative.

Regarding the wave dissipation inside LIS, observations suggest that the wave field inside the estuary remains underdeveloped and therefore we opted to tune the wave breaking down from default value of C_{ds} of 2.36 x 10^{-5}. We find that the default breaking coefficients overestimate dissipation, with a heavy weight on the dominant frequencies. In doing so we enhanced the energy input (wind driven) into the system. We found that the best results were in the 1.10 x 10^{-5} - 1.18 x 10^{-5} range, with even lower values yielding good results at WLIS. Further work and observations on the subject are required to further improve breaking parameterizations inside the LIS estuary,

The bottom friction parameterization selected was the Madsen (1994) formulation with a roughness length (k_N) of 0.25 m. The FVCOM-SWAVE model was not run with bottom wave-current interaction and during these simulations a bottom log-layer was in place. Therefore the bottom friction parameterization became relevant only at coastal areas where the wave field was able to directly interact with the bottom.

The first sets of numerical simulations were fetch limited under varying forcing conditions. For both of these cases (i.e. Case 1 and Case 2), the modeled significant wave heights inside the LIS showed a significant bias high for Case 1 with improved agreement in Case 2 (Tables 3.4, 3.6 and 3.8). Modeled peak periods (T_p) and therefore peak wave scales were better captured giving good estimates of wave field development stages. The bias high could be due to a lack of dissipation, although during these simulations waves behave like deep water waves making bottom friction less relevant of a dissipation mechanism. Enhancing dissipation through wave breaking could solve the issue, although during weak forcing and young seas, the expectation of breaking was low. The overall bias high exhibited by the model inside the LIS for fetch limited cases was associated with too strong of a dependency on wind forcing, potentially due to the modified wave growth parameter. For example, during the weak and fetch limited forcing (i.e. Case 1) the modeled significant wave heights within CLIS exhibited a 0.66 zero-lag correlation with the x-component of the wind (along LIS wind) and a 0.63 zero-lag correlation with the y-component of the wind (across LIS wind). Observations on the other hand show a 0.64 and 0.47 zero-lag correlation respectively. During this low forcing scenario, observations suggest a max correlation between wind and waves (along the sound) to be 0.67 and lagged approximately 2 days (with the waves trailing the weak wind forcing), where the magnitude of the lag was not fully captured by the model (0.6). At the WLIS the model hindcasted a 0.57 zero-lag correlation between significant wave heights and the x-component of the wind and a 0.50 zero-lag correlation with the y-component of the wind. Observations at WLIS suggest a 0.38 and 0.20 zero-lag coefficient for the x and y wind components. At both locations the model appears to significantly overestimate the resulting correlation between waves and the wind forcing.

Model results during the moderate and limited fetch scenario (i.e. Case 2) the x-component of the wind forcing shows a 0.93 zero-lag correlation, whereas the observations at CLIS suggest a 0.70 correlation (at zero-lag). The y-component of the wind (across sound component) showed a modeled 0.74 zero-lag compared to a 0.49 zero-lag correlation in the observations. The behavior at WLIS was similar, where the model captures the overall behavior of the correlation coefficient in time, but overestimates its magnitude. Nonetheless, the modified parameterization was needed to improve model performance inside the LIS under moderate to stronger forcing. This was the case for the latter two simulations. For example, during the unlimited fetch scenario under moderate forcing (i.e. Case 3), the model showed that the zero-lag correlation coefficient of x and y-component of the wind forcing with significant wave heights were respectively 0.7 and a 0.10 at CLIS with observations suggesting a 0.50 and a 0.21 zero-lag correlation coefficient for the x-component and y-component of the wind with significant wave heights. At the WLIS the overall structure of the correlation was well captured, with differences within 10% in the correlation coefficient magnitudes at zero-lag up until the zero correlation was reached by observations and model at approximately 4 days. We associate the improvement in the correlation between wind and significant wave height as a key component of the improvement of the model in the Western end of the estuary. This was further confirmed during the Superstorm Sandy simulation. For example, the y-component of the wind forcing and the significant wave height had a modeled correlation coefficient of 0.31with a 15-hour lag at the CLIS. Buoy observations showed a 0.28 correlation coefficient at the 15-hour lag at the same location. At the WLIS the max correlation was observed and modeled at 21 hr lag with a correlation coefficient of 0.38. Overall the modeled runs were able to differentiate the local wave climatology existing in LIS (Fig. 2), with short and long waves during summer and winter respectively under moderate to strong forcing. Nonetheless, in the presence of weak forcing ($U_{10} < 5.0$ m s^{-1}) the model was not able to capture adequate wave growth rates and at this point we recommend further evaluation of the spectral terms in the wave action equation. Nonetheless, under moderate to strong forcing under limited or unlimited fetch the model has the capacity to differentiate different stages of wave development (i.e. inverse wave age) and growth accounting for the different Easter and Western regions inside the LIS.

6.0 Conclusions

We have performed several simple numerical experiments to evaluate the FVCOM-SWAVE model inside the Long Island Sound urban estuary. For moderate to strong forcing an enhancement of the Snyder et al. (1981) wave growth was necessary in combination with a reduction of the breaking intensity. Our modifications succeeded in better capturing the short wave scales in a commonly underdeveloped state at the WLIS. We found the wave field within the WLIS region to remain consistently underdeveloped and unable to fully develop given the geometry of the estuary and the nature of the wind forcing tested so far. Waves within WLIS remain short (relative to the forcing) and in comparison to those within CLIS under severe events (i.e. Super Storm Sandy of 2012). Under more moderate cases the CLIS and WLIS regions can reach the same level of development and ultimately similar wave statistics if the wind forcing exhibits a North-East/ East direction.

The modeled bias high was attributed to the modified wave growth coefficients. For weak forcing hindcast or forecasting ($U_{10} < 6$ m s^{-1}) we recommend default wave growth coefficients with modified wave breaking coefficients (reduced). Finally, we concluded that the FVCOM-SWAVE coupled model works well in such an environment. Although significant wave heights were biased high for weak forcing scenarios, the wave scales were on average well captured by the modified growth coefficients. These results can be used in combination with observations to further explore the differences between the CLIS, BLIS and WLIS regions of the Sound from a wave field development stand point (wave age). The model proves to be a valuable tool in providing wave field evolution and information within the LIS with acceptable uncertainty.

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