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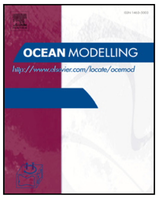

Dynamics of wave–current–surge interactions in Lake Michigan: A model comparison

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ABSTRACT

Wave, storm surge dynamics, and wave–current–surge interactions (WCSI) were investigated by applying a pair of unstructured-grid-based models to Lake Michigan under two strong wind events. The effects of wind field sources, wind drag coefficient bulk formula, and parameterizations of the bottom friction term were explored to understand lake dynamics. Two wave models were calibrated by using alternative wave physics settings under the 2011 northeasterly wind event. Forced by the southwesterly wind event in 2013, the calibrated models using the atmosphere–ocean fully coupled Climate Forecast System Version 2 wind field were further validated. It is found that the northwesterly winds induced 0.57 m setup near the southwestern coast, whereas the southwesterly winds produced 0.28 m setup and −0.43 m setdown near the northern and southwestern coasts, respectively. The WCSI mostly influence waves and storm surge in shallow-water areas near coasts and islands through depth-induced breaking, current-induced frequency shift and refraction, and wave-induced setup/setdown through wave radiation stress. Owing to the adoption of different discretization algorithms and bottom friction formulations, the modeled storm surge and waves exhibit some variation between the paired models. Even though the storm surge difference with and without WCSI is smaller than that between the two WCSI-coupled models, both circulation models adopt WCSI considering their consistent improvement on model accuracy under both wind events. The analysis of water transport indicates that wind speed, direction, and coastal geometry and bathymetry are also important factors in storm surge.

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1. Introduction

Storm winds generate large waves, high surges, and strong currents (Kerr et al., 2013a,b), which further create complex wave–current–surge interactions (WCSI) in the extremely dynamic and shallow regions (Benetazzo et al., 2013; Xie et al., 2008). Longuet-Higgins and Stewart (1964) established the WCSI theory by introducing the concept of two-dimensional (2D) depth-averaged wave radiation stress (WRS) to account for wave-induced setup and setdown. Based on the conservation of wave energy flux, wave height and its steepness become greater when they propagate into shallower regions. The shallow-water wave process is dominated by depth-induced breaking; the momentum flux is then transferred to the water column and raises the water levels adjacent to the coast (Holthuijsen, 2007). Based on the wave–current observations near the southern coast of the North Sea, Wolf and Prandle (1999) proposed that wave propagation and dissipation processes are also affected by variations in local water depth and ambient current velocity. The analytical solution to account for the effect of currents on waves in the absence of the breaking process was given by Phillips (1977): $\frac{A}{A_0} = \frac{c_0}{\sqrt{c(c+2U)}}$, where A, c, and U are the wave amplitude, phase speed, and ambient current velocity, respectively; A_0 and c_0 refer to the wave amplitude and phase speed without the inclusion of ambient currents. The modification of wave frequency by current is achieved through the Doppler shift effect kU_n, where k is the wave number, and U_n is the current component in the wave direction. This formula relates the absolute frequency ω in a fixed frame of reference with the relative frequency σ in a frame of reference moving with the current through the expression of $\omega = \sigma + kU_n$. From sites A to B, the variations of wave directions (θ_A and θ_B) and wavenumbers (k_A and k_B) on a spatially varying current field are determined by Snell's law, which is expressed as $k_A \sin(\theta_A) = k_B \sin(\theta_B)$ (Holthuijsen, 2007; Longuet-Higgins and Stewart, 1964; Wolf and Prandle, 1999). On the basis of linear wave theory, Mellor (2008) derived the depth-dependable WRS formulation, which further elucidates the underlying physics of WCSI in a three-dimensional (3D) space.

Previous works have laid the foundation of WCSI theory and stimulated intensive numerical studies of wave, storm surge dy-

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namics, and complex WCSI process. With the inclusion of wave effects in a circulation model, Xie et al. (2008) made a significant improvement on simulating the surge peak in Charleston Harbor, South Carolina, during the passage of Hurricane Hugo (1989). Liu and Xie (2009) further pointed out that the increase (decrease) of significant wave height (SWH) is highly dependent on the positive (negative) variation of water depth caused by storm surge in shallow-water regions. Using the surge–wave–tide coupled model, Kim et al. (2010) demonstrated that wave-induced setup accounted for 40% of the magnitude of the total surge height in close proximity to the open coast of Tosa Bay, Japan, during Typhoon Anita (1970). Relative to the studies of wave effects on storm surge, significant effects of storm surge on waves in shallow-water regions are less frequently investigated and require further research (Osuna and Monbaliu, 2004). More recently, Olabarrieta et al. (2011) identified wave-induced setup as the primarily factor in the significant wave effect on circulation in the inner part of the Willapa Bay, Washington, during a storm event in October 1998. By applying a Coupled–Ocean–Atmosphere–Wave–Sediment Transport (COAWST) modeling system to the U.S. East Coast and the Gulf of Mexico, Warner et al. (2010) determined that surface waves were highly sensitive to the oceanic and atmospheric coupling processes that occurred during Hurricane Isabel (2003). Subsequently, Benetazzo et al. (2013) applied the COAWST system to the shallow Gulf of Venice during 2011 Bora and Sirocco events, which are fetch-limited northeasterly and long-fetch southeasterly winds, respectively. These works demonstrated that the modeled SWH was substantially enhanced (reduced) due to the inclusion of opposite (unidirectional) currents. Because of coarse grid resolution in resolving the complex coastline and islands and the numerical or physical error introduced by intra-model interpolation along nested boundaries, previous structured-grid-based circulation models using the nesting technique (e.g., Benetazzo et al., 2013; Kim et al., 2010; Liu and Xie, 2009; Osuna and Monbaliu, 2004; Xie et al., 2008) may have inaccuracies (Dietrich et al., 2011; Zijlema, 2010).

The recent emergence of unstructured methods, however, provides an opportunity to better resolve the complex bathymetry and highly irregular coastline and islands in shallow-water regions, which enhances the computational accuracy and efficiency (Dietrich et al., 2011). Such methods have triggered the development of various unstructured-grid-based models, including MIKE3 + MIKE21 SW (MIKE3/21 SW; Bolaños et al., 2014), Advanced Circulation Model + Simulating Waves Nearshore (ADCIRC/SWAN; Bunya et al., 2010; Dietrich et al., 2010, 2011, 2012), and Finite Volume Coastal Ocean Model + Surface Wave Model (FVCOM/SWAVE; Chen et al., 2003; Qi et al., 2009; Sun et al., 2013; Wu et al., 2011). Inclusion of WCSI in the modeling system enables computation of the wave action spectral balance equation in the wave model with the inclusion of water surface elevation (WSE) and current velocity fields and simultaneously passes the 2D/3D WRS gradients back to the circulation model to account for momentum flux. Chen et al. (2013) reported that the WCSI intensity was relatively appreciable inside Scituate Harbor, Massachusetts, during the 2007 Patriot's Day Storm. They further attributed the difference in modeled SWH and WSE between ADCIRC/SWAN and FVCOM/SWAVE to the application of different discretization algorithms and bottom friction formulations. With the inclusion of WCSI, the FVCOM circulation model reduced the underestimation of the 0.9 m high storm surge from 23 cm to 15 cm during the December 2010 nor'easter event in Scituate (Beardsley et al., 2013).

Although WCSI was successfully tested by model-to-model comparisons (Chen et al., 2013), direct evaluation of the unstructured-grid-based model's performance using field observations has been barely reported. By using adequate data collected during Hurricanes Ike (2008) and Rita (2005) in the Gulf of Mexico, Kerr et al. (2013b) determined that although both circulation-only and wave-only models satisfactorily reproduced storm surge and surface waves, respectively, the two-way coupled ADCIRC/SWAN yielded the most accurate results. Given that FVCOM and SWAN are one-way offline coupled, however, a direct comparison of fully and dynamically coupled modeling systems is still lacking. Most importantly, no consensus has been reached regarding the intensity of WCSI, which was shown to be relatively strong in the shallow Harbor and weak in the deep Gulf. Therefore, it would be worthwhile to explore the significance of WCSI with additional numerical applications and model calibration and validation. Considering the dominant role of wind forcing both in circulation and wave dynamics in a semi-enclosed basin (Benetazzo et al., 2013), sensitivity tests to explore the key factors influencing surface wind stress, including various wind field sources and wind drag coefficients, are likely important. By using the wind field derived from alternative data sources (e.g., the Global Environmental Multiscale (GEM) and North American Mesoscale models) in ADCIRC, Chittibabu and Rao (2012) detected different spatiotemporal patterns of WSE and storm surge in Lake Winnipeg, Canada, during the October 2010 storm. For the Great Lakes system, Jensen et al. (2012) hindcasted seven storms passing over Lake Michigan in 1989–2009. By replacing the observation-based Natural Neighbor Method (NNM) winds with the atmospheric modeled data from the Climate Forecast System Reanalysis (CFSR), a higher skill level in storm surge simulation was achieved. Based on the storm surge simulation of an Ivan-like storm in Tampa Bay, Florida, Weisberg and Zheng (2008) illustrated that surge height is positively related to surface wind stress according to the wind drag coefficient bulk formula.

In this study, we configured a pair of coupled modeling systems to simulate storm surge, wave dynamics, and WCSI processes in Lake Michigan. Overall, three main questions are addressed: (1) How sensitive is the storm surge simulation in response to various wind forcing and wind drag coefficient bulk formulae? (2) How do storm surge and waves develop under strong wind conditions in Lake Michigan? (3) How will the simulations differ by using alternative WCSI-coupled modeling systems and those with and without WCSI? The remaining sections of this study are organized as follows. The following section introduces the methodology, which includes descriptions of the study domain and model meshes, coupling system, data sources, numerical experiments, and skill metrics. Sensitivity and calibration results are described and analyzed in Section 3, followed by a validation experiment in Section 4. In Section 5, numerical results addressing the aforementioned question (3) are reported, and dynamic responses of the depth-integrated water transport flux (DWTF) to the synergistic effect of wind forcing and coastal bathymetry and geometry are discussed. A summary and conclusions are given in Section 6.

2. Methodology

2.1. Study domain and model meshes

Lake Michigan is the third largest lake in the Great Lakes system by surface area (58,000 km^2). At about 494 km long and 190 km wide, the elongated semi-enclosed basin is delimited by land boundaries on three sides and conjoins at the northeastern corner with Lake Huron via the Straits of Mackinac at a mean depth of ~20 m (Fig. 1a and b). From north to south, the smooth and deep mid-lake area includes the Chippewa Basin, Mid-Lake Plateau, and South Chippewa Basin. Two island chains, Beaver Island and North Manitou Island, and two bays, the shallow and elongated Green Bay and the deep Grand Traverse Bay, are located in the middle and on the flanks of the Chippewa Basin, respectively. Green Bay and Grand Traverse Bay meet Lake Michi-

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