COUPLING EFFECTS BETWEEN UNSTRUCTURED WAVEWATCH III AND FVCOM IN SHALLOW WATER REGIONS OF THE GREAT LAKES

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Abstract

The modeling of waves in shallow environments in the Great Lakes is challenging because of irregular coastlines and bathymetry, as well as complicated meteorological forcing. In this paper, we aim to provide insight into the physics of storm surge-wave interaction within shallow water regions of the Great Lakes under strong wind events. Extensive hindcast analysis using the 3D-circulation model FVCOM v3.2.2 and the third-generation spectral wave model WAVEWATCH III v4.18 was conducted on unstructured meshes for each of the Great Lakes. The circulation and wave models are coupled through a file-transfer method and tested with various coupling intervals. We conducted evaluations for four storm events and three long-term (seasonal) test cases. Time series, spatial plots and statistics are provided. Data exchange of radiation stress, water elevation and ocean currents were tested in both two-way and one-way coupling regimes in order to assess the influence of each variable. The meteorological input forcing fields are WRF model at 1-12km resolution. Statistical analysis is performed in order to evaluate the model sensitivity to wind input, physics packages and surge-wave coupling effects.

1, Introduction

The Great Lakes region, the second-largest lake system in the world and largest freshwater lake group, plays an important role in both the environment and U.S. economy. Accurate and reliable wave and storm surge forecast are critical to public safety and the region's economy.

Water level, three-dimensional currents and water temperature forecast guidance for the Great Lakes is provided four times a day by National Ocean Service (NOS), Great Lakes Operational Forecast System (GLOFS). The forecast cycles are driven by North American Mesoscale Forecast System (NAM) and National Digital Forecast Database (NDFD) winds. The core ocean model used by GLOFS has traditionally been the Princeton Ocean Model (POM) and is running on regular grids for each of the lakes, with 20 vertical layers. GLERL is currently developing a new FVCOM-based unstructured mesh circulation modeling system for the Great Lakes.

Schwab et al [1984] have developed the first 2-D wind wave model for the Great Lakes. This model is considered a first-generation wave model, driven by over-lake wind fields interpolated from measurements by technique discussed also in this project. The 3rd generation spectral wave model WAVEWATCH III for the Great Lakes was implemented at NOAA/NCEP for wave predictions in 2005, enabling the representation of both swells and wind seas [Alves et al 2014]. This system, the Great Lakes Wave forecasting system (GLW), was initially driven by the Regional Atmospheric Modeling system (RAM), with later versions driven by NDFD and NAM.

Regionally-driven atmospheric responses in the Great Lakes induce significant hydrodynamic events such like strong wave formation or strong positive or negative surges. These events pose threats to swimmers, navigation and possible inundation flooding. The large water body, highly variated depth and complex coastlines results in largely variated response in terms of both wave and circulation behaviors. Of most interest here are the effects at shallow water open regions and transition zones in and near large bays. A event is Oct 24th 2013 in Lake Erie (shown in Figure 1), during which strong wind blows from west to east, causing strong draw down of water level at Toledo, OH and strong surge at Buffalo, NY.

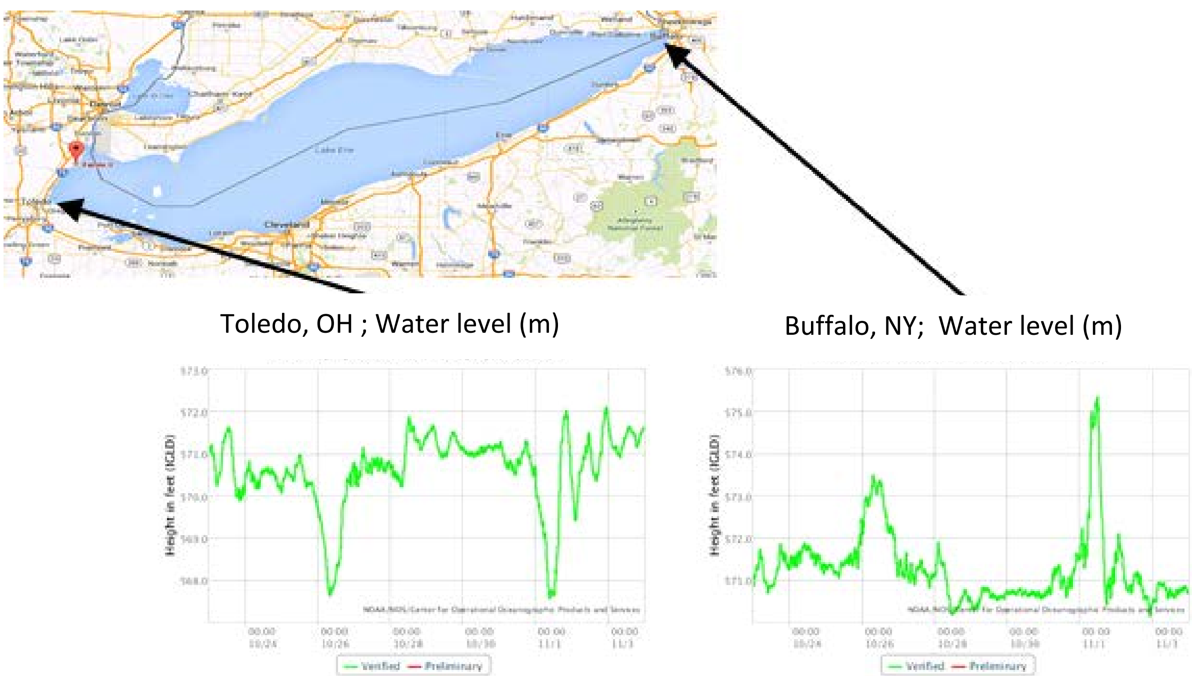


Figure 1. Storm event at Lake Erie starting at Oct 24th 2013

Dietrich et al [2011] developed a tightly-coupled SWAN+ADCIRC model applied to identical, unstructured meshes. In this coupled model, ADCIRC and SWAN share the same parallel computing structure and run sequentially in time. Both model use same wind speed input field data, while water levels, current and radiation stress pass exchanged between models for coupling purpose. Elias et al [2012] implemented a coupled Delft3D and SWAN at Mouth of Columbia River (MCR). MCR is an estuary where tidal currents, river discharge and wave induced currents are of the same level of importance, which make coupled modeling a valuable effort there.

In this study, we developed a coupled FVCOM-WW3 system to provide sensitivity analysis of wave coupling using various test cases and model settings focusing on shallow water regions of the Great Lakes.

Two major events are described, namely Superstorm Sandy and the Oct 2013 storm. Each of the coupling variables are tested individually as well as combined.

The paper is structured as follows: Section 2 presents the configuration of each component of the system (wind input, WAVEWATCH III, FVCOM and coupling process). In section 3, the model results are discussed. Conclusions and recommendations are presented in Section 4.

2. Model Configuration

2.1 WRF wind model

The Weather Research and Forecasting (WRF) model is a numerical weather prediction (NWP) system designed to serve both atmospheric research and operational forecasting needs. WRF features two dynamical cores, a data assimilation system, and a software architecture allowing for parallel implementation. The model was created through a partnership that includes the National Oceanic and Atmospheric Administration (NOAA), the National Center for Atmospheric Research (NCAR), and more than 150 other organizations and universities in the United States and abroad.

Both WAVEWATCH III and FVCOM were driven by WRF model with 1km/4km/12km resolution. The WRF model run on a regular grid covering the entire Lake Region with both original and nudged model settings tested. The wind forcing data updates every 3600 seconds for 4km and 12km WRF; while 600 seconds for 1km. FVCOM was also run stand-alone using interpolated wind in order to validate the performance of the wind model. Wind stress is calculated through Garrett's formula at each element center for FVCOM, while WAVEWATCH III uses U and V wind speed at each node point.

2.2 WAVEWATCH III Model Configuration

WAVEWATCH III was configured with wave components at 50 discrete frequencies from 0.0373 ~ 4.4Hz plus a parametric high-frequency tail; with 36 directions. The non-linear interaction scheme Discrete Interaction Approximation (DIA) was selected. The physics package of Ardhuin et al [2010] is applied.

2.3 FVCOM Model Configuration

FVCOM [Chen et al 2010] was applied with 20 sigma vertical layers activated for each elements of the computing grid. The time step set at 5 second for most event while 2 second and 1 second for Superstorm Sandy to ensure convergence. Smagorinsky mixing scheme was used with coefficient of 0.1. Elevation-specified boundary conditions are set up only at east/west Lake Erie. No boundaries are set up elsewhere. The bottom roughness was set constant spatially.

2.4. Computing grids

Three versions of unstructured meshes were developed, with 200m, 500m and 2000m coastal resolutions. After comparison regarding accuracy and efficiency, we selected 2000m grid for assessment of model coupling. The bathymetry of the grid comes from NGDC 3 arc-sec bathymetry, with resolution of ~ 20m. Figures 2 and 3 show computational grids of 2000m coastal resolution.

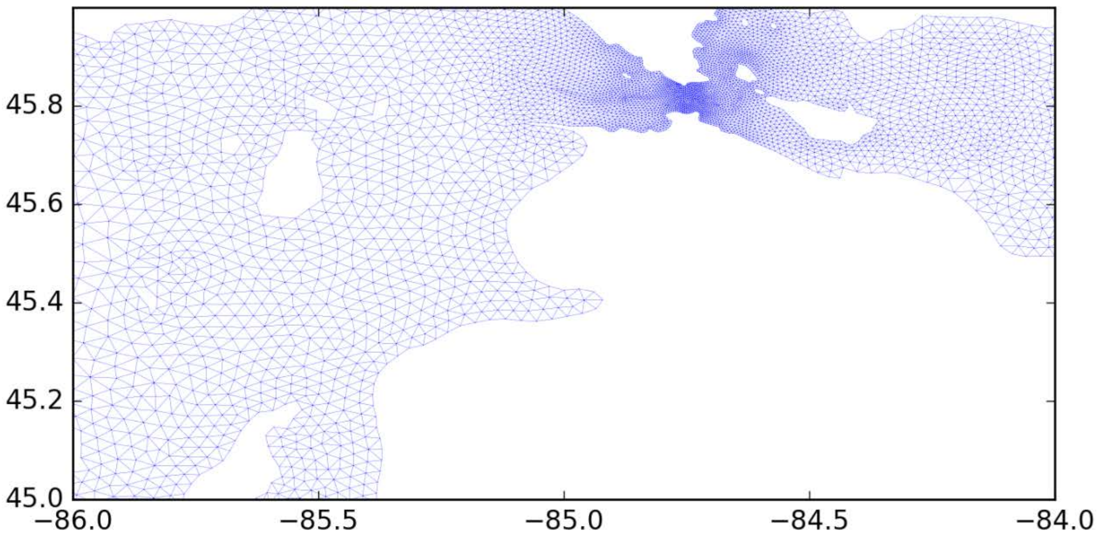


Figure 2. Unstructured grid of Lake Michigan-Huron with detail of Straits of Mackinac

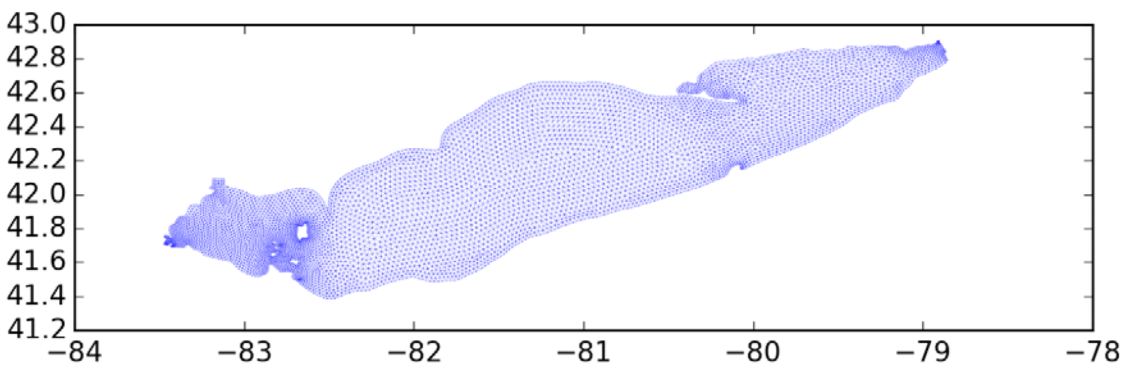


Figure 3. Unstructured grid of Lake Erie, overall

2.5 Coupling physics

Two models are coupled through a file-transferring method. In every coupling interval, all the input and transferring (come from another model) variables are stored in a netCDF4 file serving as input forcing file for both models. The storm surge and wave model runs sequentially, similar to the protocol of ADCIRC+SWAN. First, WAVEWATCH III starts and runs for a certain amount of time, which called "coupling interval", then a script extracts radiation stress, and to calculate stress gradient. Radiation stress gradient is calculated at each element center using the following formula used by Dietrich et al

[2011] in ADCIRC+SWAN. Then added to wind stress accordingly to calculate total surface forcing and. FVCOM execution starts instantly after the forcing was calculated.

According to the nature of finite volume model, vector field input and output are calculated at element center instead of vertexes. Also, wind stress input is selected for FVCOM instead of wind speed, which is using by WAVEWATCH III. The reason of using stress is easier manipulation of stress, such as wave radiation stress addition.

After the execution of FVCOM, the script extracts water level at each node point and water currents at each element center. An interpolation script calculates water currents value at each node point. Then water level and currents are written into forcing file which is readable for WAVEWATCH III preprocessing programs.

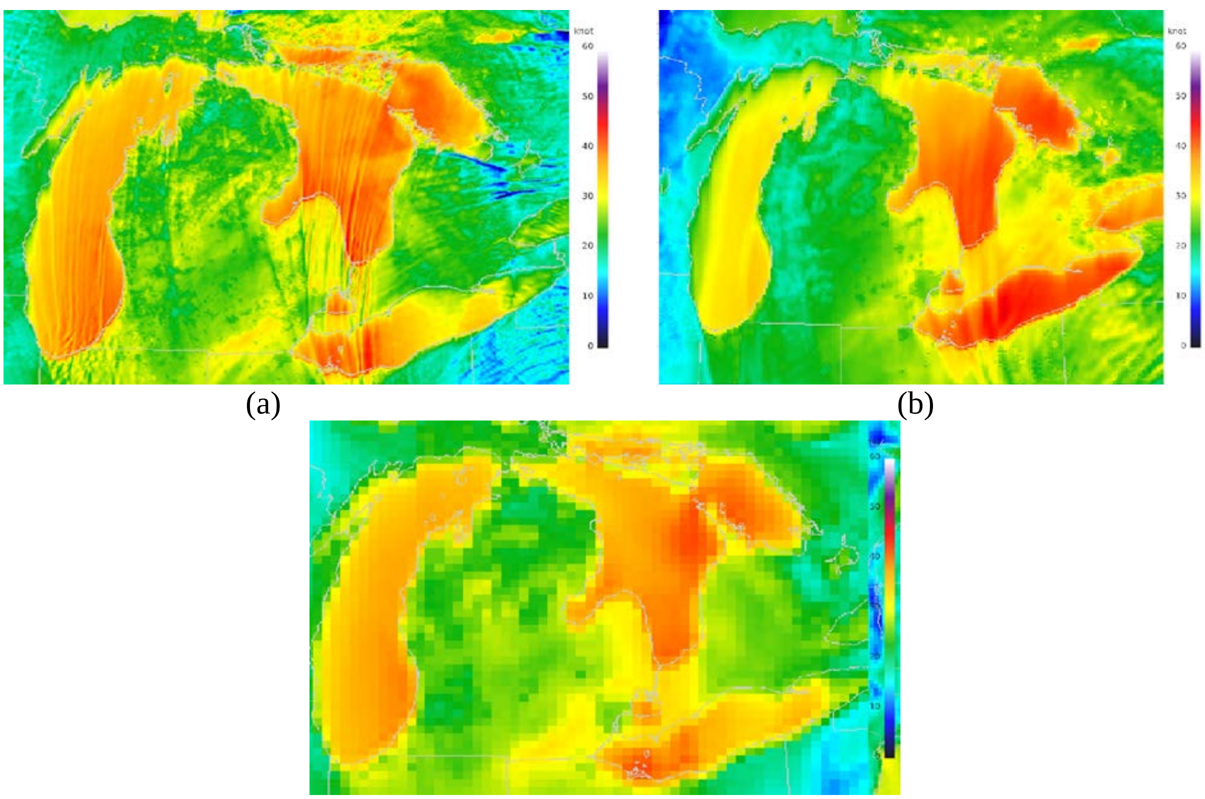
The coupling interval was set at 3600 seconds, while 1800 seconds and 900 seconds are also tested. We've also investigated the effect of each transferring variable by running "partially coupled" model, in which only one of radiation stress, water level or water currents are activated for coupling, along with stand-alone model and fully coupled model.

Figure 4. Map showing validation points for all events. Yellow: wave buoys; Red: tide gauges for water level.

List of validation points

1*	45142, Erie	1	Buffalo, NY; Erie
2	45005, Erie	2	Toledo, OH; Erie
3	45008, Huron	3	Cleveland, OH; Erie
4	45149, Huron	4	Lakeport, MI; Huron
5*	45163, Huron	5	Harbor Beach, MI; Huron
6	45002, Michigan	6	Essexville, MI; Huron
7	45007, Michigan	7	Mackinaw City, MI; Michigan
8*	45161, Michigan	8	Calumet Harbor (Chicago), IL; Michigan
9*	45028, Superior	9	Milwaukee, WI; Michigan
10	45006, Superior	10	Green Bay, WI; Michigan
11*	45025, Superior	11	Duluth, MN; Superior
12	45004, Superior	12	Oswego, NY; Ontario
13	45135, Ontario		
14	45012, Ontario		

*: Shallow-Intermediate depth buoys



(a) (b)

(c)

Figure 5. WRF wind speed map for Superstorm Sandy on 2012/10/31. Panel (a) 1.5km; (b) 4km; (c)12km.

3. Model Results and analysis

3.1. Validation points

Figure 4 is a map illustrating all validation points for the couple model. Most of the wave buoys are maintained by NDBC and GLERL, while most tide gauges are set up by COOPS.

3.2. Field input/forcing assessment

Figure 5 is spatial map of wind speed for Superstorm Sandy on 2012/10/31 from WRF 1.5km, 4km and 12km-resolution output. According to these images, wind speed increases dramatically over water body. Apparently, 1.5km resolution WRF resolves more detailed wind feature than 4km WRF; while 12km WRF is coarser than 4km. Since low resolution wind field lose some amount of details of wind character, it often leads to an artificial increase of wind fetch, which will results in unrealistic over estimation of storm peak of FVCOM. Figure 6 is a sample time series of WRF input wind. We can see that the 12km WRF wind captures well in terms of amplitude as well as direction of the wind.

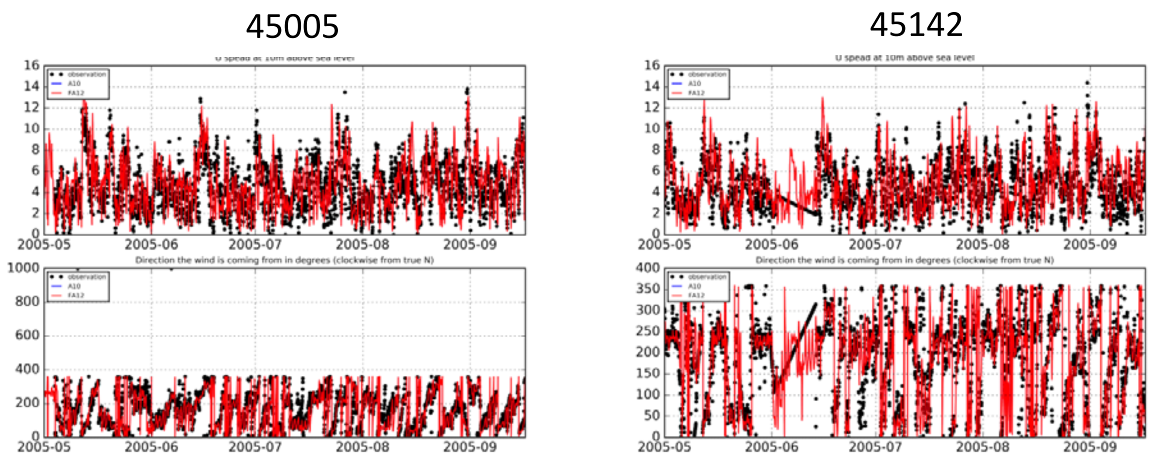
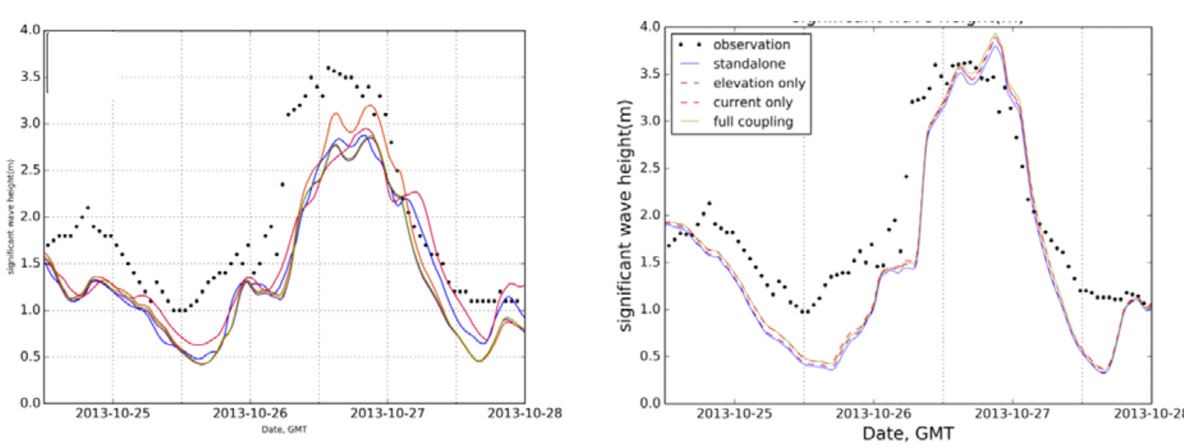


Figure 6. 12km resolution WRF wind speed and angle direction at buoy 45005 (left) and 45142 (right) from 2005/05/01-2005/10/01; Red line: WRF model; Black dot: buoy observations.



(1) (2)

Figure 7. Buoy 45142, Lake Erie, 2013/10/24-2013/10/28. H_sig using different wind input (1) and H_sig using different coupling setups (2)

3.3 Coupling effect: wave model

Figure 7 illustrates the sensitivity of H_sig from wind field and coupling effects at buoy 45142 at eastern Lake Erie. (1) is the H_sig output from WAVEWATCH III using different sets of wind forcing; (2) is the H_sig output from WAVEWATCH III using different coupling set ups ("stand-alone", "elevation only", "water current only" and "fully coupled"). From the model outputs from various locations and events, taking buoy location 45142 during 2013/10/24-2013/10/28 Lake Erie as an example, we found that overall speaking, the influence of coupling effect on waves is much smaller than which of the wind field. Regarding coupling effects due to water current and water level, we can see that the influence of water current is significant throughout the entire event, while water level influence mainly exist only during storm peak period, when water level is elevated the most.

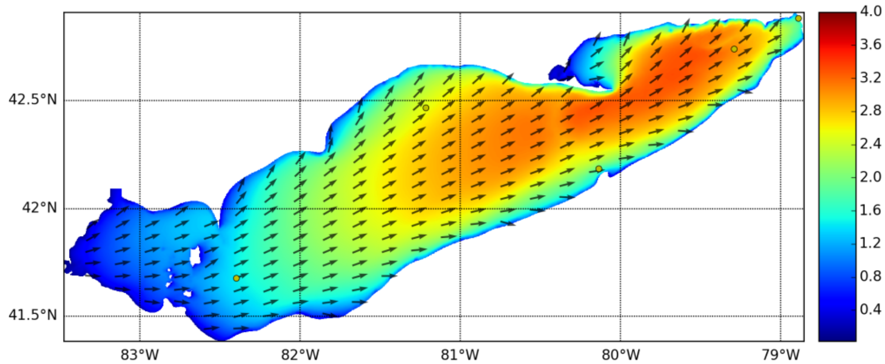


Figure 8.1 Spatial plot of H_sig (m) from WAVEWATCHIII-FVCOM using 4km WRF model during storm peak 2013/10/26 at 17Z; Black arrow: wave propagating directions

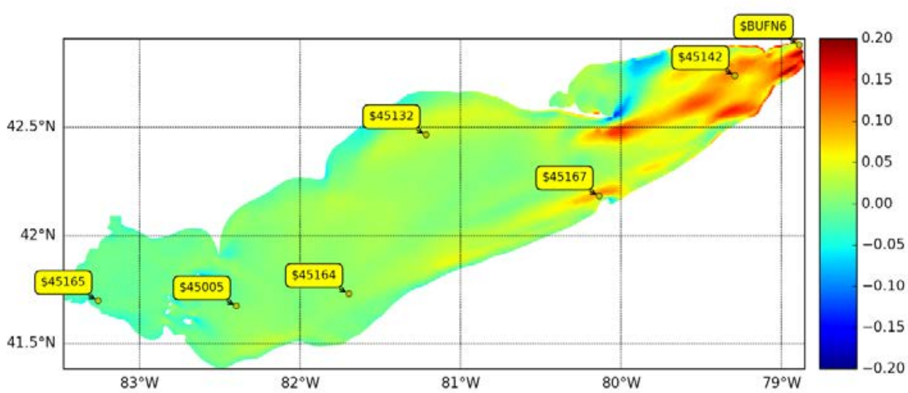


Figure 8.2 Spatial plot of H_sig change (m) due to coupling effect using 4km WRF model during storm peak 2013/10/26 at 17Z.

From Figure 8.1 and Figure 8.2, we know that the wave at mid-lake of eastern Lake Erie has been significantly elevated due to water currents flowing westward, opposing wave propagation direction. There's also considerable increase for nearshore wave at the eastern Lake Erie, which is because of the elevated water level there, since the relative increase of water level is much larger at nearshore region than deep water.

In contrast, wave height decreased at north shore of Lake Erie, especially at regions around Long Point, OT, where strong currents flows as the same direction as wave propagation. When coupling included in this current feature, wave length is enlarged, wave speed is increased and wave heights is decreased.

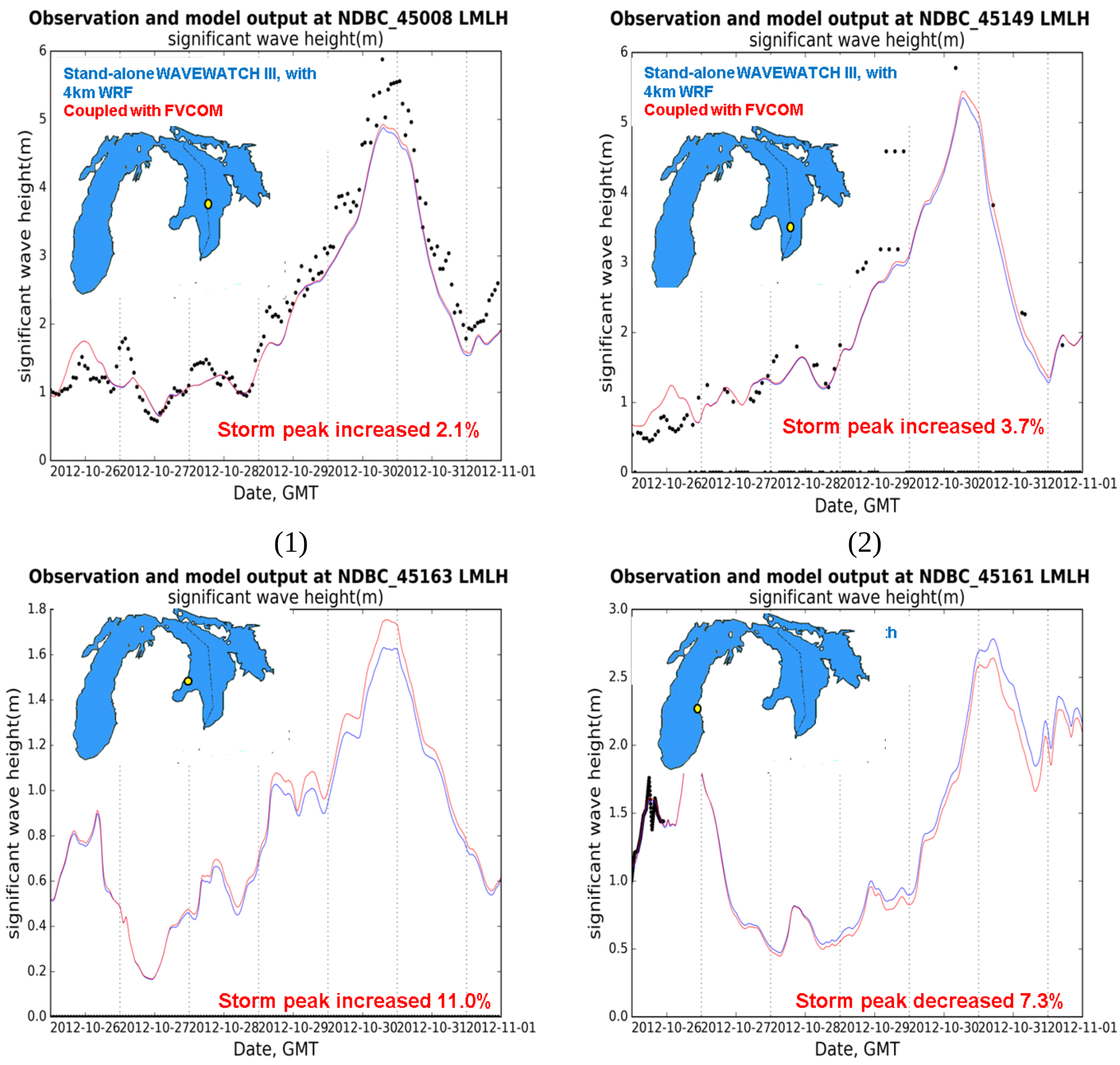


Figure 9. Storm surge impact on waves at various locations within Lake Michigan-Huron red: significant wave height output from the fully coupled model (elevation, current and radiation stress all activated); blue: stand-alone WAVEWATCH III..

Figure 9 consists of 4 time series plots illustrating the effects of coupling on wave heights at various locations. Buoy 45008 is a mid-lake wave buoy. The water depth is 54.3m at this location. The peak wave has increased only 2.1% when coupled with FVCOM. The wave at this location is dominated by deep water wave generation and dissipation laws. Buoy 45149 is also mid-lake deep water buoy (58m depth). However, the effect of coupling is almost doubled (3.7% increase) comparing to 45008. The reason is because, since it is located further south, the wind fetch is significantly longer than 45008, therefore the water level from the circulation model (FVCOM) is much more elevated than 45008, therefore posing a bigger impact on the wave field. The comparison was conducted during -2h~+2h of the maximum value of significant wave height of each model.

Buoy 45163 is a shallow water buoy located at the edge of Saginaw Bay. The impact of wave coupling is a 11.0 increase of peak wave, which is significantly higher than the deep water buoys. This is an effect of elevated water level in addition to the long fetch similar with 45149, which is amplified in shallow water region because the relative increase of water level is higher than which of deep water zones.

Buoy 45161 is also a shallow water buoy located at the east side of Lake Michigan. The coupling impact, however, decreases the peak wave by 7.3%. This is due to the strong longshore current flowing from north to south along east Lake Michigan. In this region, wave propagates toward the same direction as water current, so that the wave get less steep as compared with stand-alone model. Thus wave length is amplified, and wave height decreases.

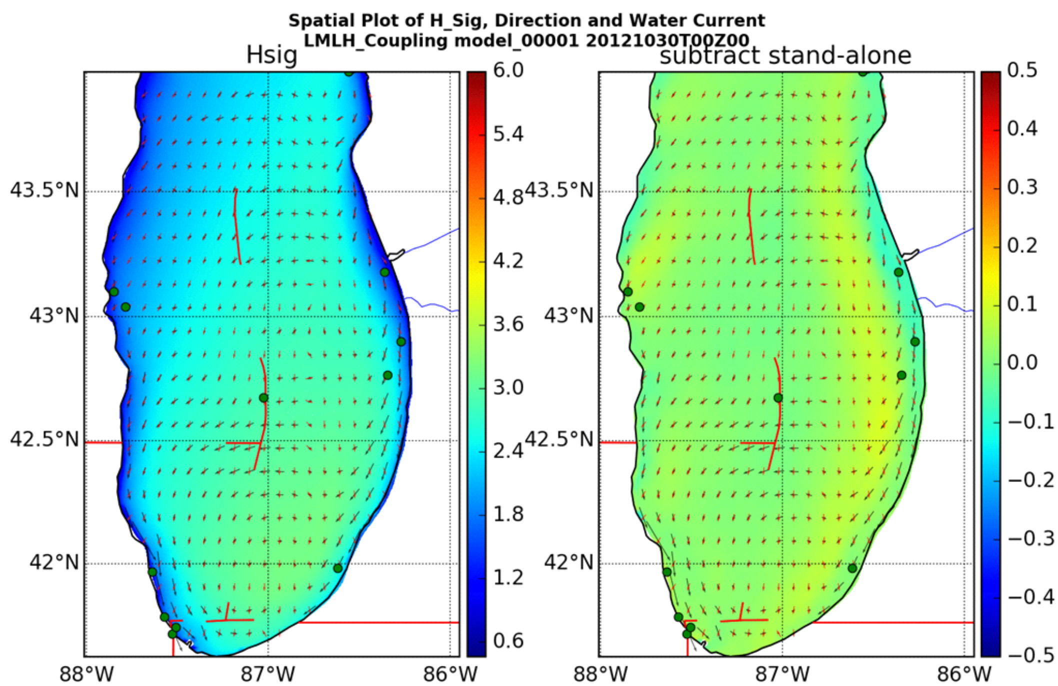


Figure 10. Left: wave height at storm peak in the coupled model (m); Right: Difference between coupled and stand-alone (m); both sides: dark arrow represents the water currents; red arrow represents wave propagation.

From the Figure 10 above, we know that currents have significant effects on waves in all regions, especially deep water. These effects are stronger during the ramping up period of storms, because wave frequencies are higher and thus more sensitive to interactions with currents. In the Great Lakes region, where longshore current is a typical phenomenon under severe meteorological events, significant wave height can varies up to 10% due to water current, especially high frequency waves. Wave propagate against currents will be elevated and waves propagate along current will be decreased. This effect can increase wave steepness significantly, thus could challenge the safety of human activity over the lake for am extended period of the storm.

We can also find increased wave height occurs at the near shore area of peak surge region. Though the overall amplitude of difference is smaller than deep water, the relative difference is usually larger. For example, around east coastline of Lake Erie during 2013/10/24 (figure 8), wave height is elevated at the surf zone when WAVEWATCH III is couple with FVCOM. On the contrary, at west side of Lake Erie, near shore wave was lower than the stand-alone WAVEWATCH III. This effect is closely related to the elevated water level. See section 3.5 for statistics regarding impact of circulation model on nearshore waves.

3.4 Coupling effects, storm surge model

In general, the coupling of wave radiation stress has a positive impact on the peak surge. However, the influence varies from location to location. Surge comparison based on various wind field during Superstorm Sandy event (2012). Dark line represents observation.

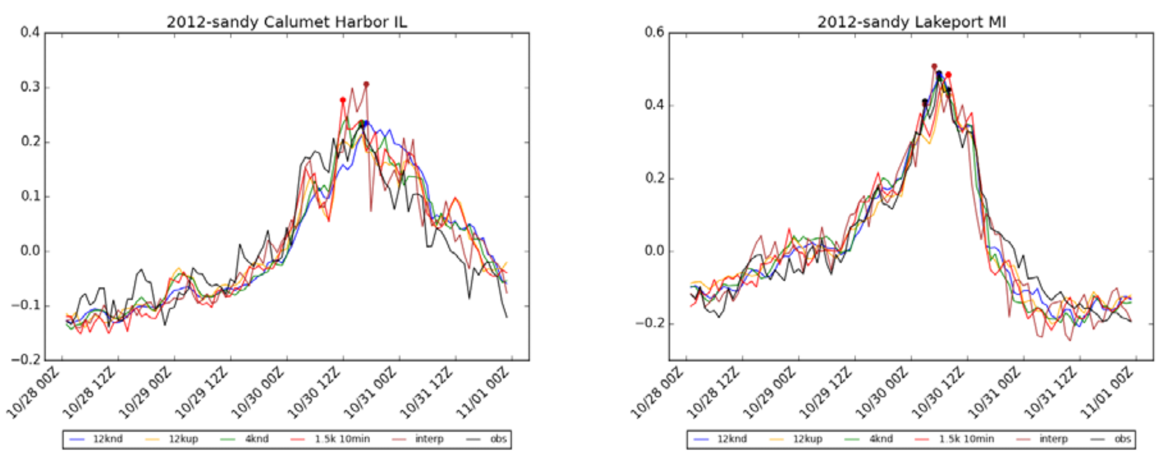
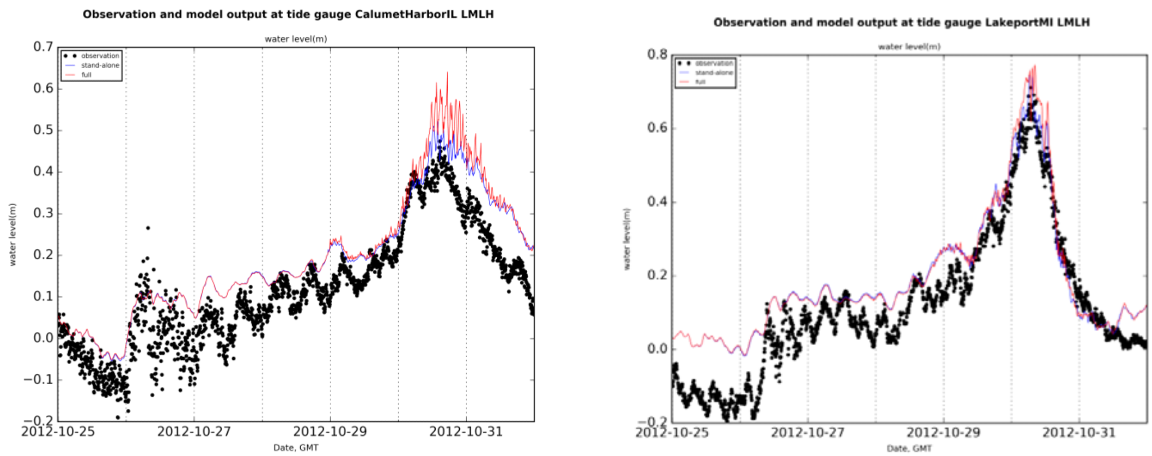


Figure 11. Stand-alone FVCOM results comparison with different wind field. Dark line represents observation.



(1) (2)

Figure 12. Water level at (1) Calumet Harbor (Chicago) IL and (2) Lakeport MI. Red line represents significant wave height output from the fully coupled model (elevation, current and radiation stress all activated) while blue line represents stand-alone FVCOM.

The water level increase due to wave coupling at Calumet Harbor, IL (Chicago) is significantly higher than which of Lakeport MI. From the wind map in the previous section, we know that during Superstorm Sandy, wind blowing primarily from NE to SW. So that Calumet Harbor has a longer fetch than Lakeport, which contributes to a bigger wave height and larger radiation stress.

Comparing with the coupling effects on wave side, storm surge model are more sensitive to coupling than wave model. Since the sensitivity of coupling at the storm peak is comparable or even exceed which of the wind input.

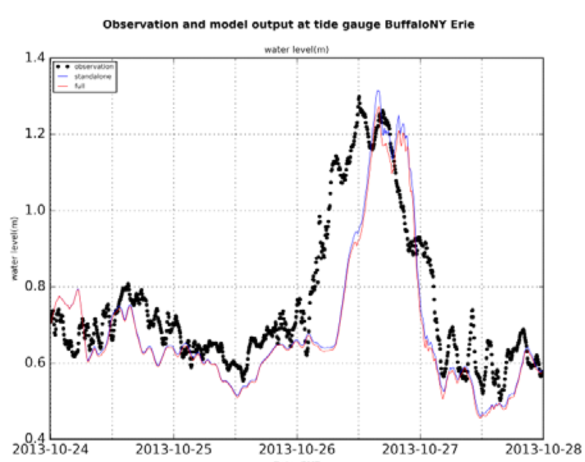


Figure 13. Coupling effect on water level (m) at Buffalo from WAVEWATCH III-FVCOM. Red: Coupled; blue: Stand-alone; black dot: observation

In Figures 13 and 14, we can find that in eastern Lake Erie, WAVEWATCH III-FVCOM coupling gives slightly but constantly lower peak when wave radiation stress is included. This effect was tested using 4km and 12km wind field, and also cross-verified by using ADCIRC+SWAN using the same domain and forcing. The reason of this effect is closely related to the water current feature of the eastern Lake Erie. Strong long-shore currents flow along both north and south shore of Lake Erie, whereas wave also propagates from west to east. From the zoomed-in current feature of eastern Lake Erie, we can find that the longshore current is being enhanced when wave radiation stress is included in the simulation. The direction of the water current is also being altered to be more toward the center of the lake (getting offshore). From the current features we know that there's significant amount of momentum goes into water current at this region. These effects in total, has transported significant amount of mechanical energy of water offshore. In other words, the set-up effect of wave radiation stress has been offset by the effect of current.

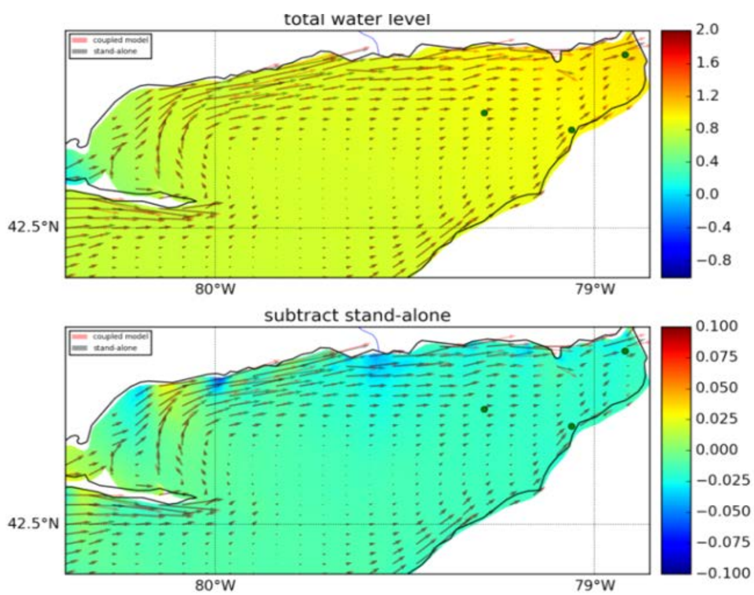


Figure 14. Top: Total water level from the coupled model at eastern Lake Erie; Bottom: Differential map (total water level subtract stand-alone). Red arrows: water current from coupled model; Black arrows: water current from stand-alone FVCOM

From the figure 14, we can see that wave radiation stresses have significant effects on storm surge. However this effect is strongly modified by the presence of current along the complex coastline of the Great Lakes. At most locations, the introduction of wave radiation stresses results in a positive impact on water levels. However, in places where water depth is shallow and longshore current is dominant, like eastern Lake Erie in this project, the effect of wave radiation stress may lead to enhancement/modification of current field and a lower water level.

3.5 Summary

The following tables illustrate places where coupling is making a significant difference for wave model (WAVEWATCHIII) and storm surge model (FVCOM). Coupling effects was calculated as percentage difference of storm peak (-2h~2h of maximum/minimum water level; -2h~2h of maximum H_sig) from fully coupled model versus stand-alone model. The "Significant?" column represents whether the difference made by model coupling is comparable with the error with observations.

Buoy Name	Lake	Event	Coupling effects	Significant?
45142*	Erie	2013/10/24-2013/10/28	3.9%	Y
45005	Erie		0.8%	Y
45008	Huron	2012/10/25-2012/11/01	2.1%	N
45149	Huron		3.7%	Y
45163*	Huron		11.0%	N/A
45002	Michigan		0.4%	N
45007	Michigan		0.0%	N
45161*	Michigan		-7.3%	N/A
45028*	Superior	2014/09/09-2014/09/12	-6.8%	Y
45006	Superior		-2.1%	Y
45025*	Superior		-5.4%	Y
45004	Superior		0.7%	N
45135	Ontario	2014/11/17-2014/11/22	2.6%	Y
45012	Ontario		1.1%	Y

*: Shallow-Intermediate depth buoys

Tide Gauge Name	Lake	Event	Coupling effects	Significant?
Buffalo, NY; Erie	Erie	2013/10/24-2013/10/28	-3.9%	Y
Toledo, OH; Erie*	Erie		2.1%	Y
Cleveland, OH; Erie*	Erie		1.6%	Y
Lakeport, MI; Huron	Huron	2012/10/25-2012/11/01	10.6%	Y
Harbor Beach, MI; Huron	Huron		-2.9%	Y
Essexville, MI; Huron	Huron		-1.1%	N
Mackinaw City, MI; Michigan*	Michigan		2.5%	N
Calumet Harbor (Chicago), IL; Michigan	Michigan		18.2%	Y
Milwaukee, WI; Michigan	Michigan		7.2%	N
Green Bay, WI; Michigan	Michigan		1.8%	N
Duluth, MN; Superior*	Superior	2014/09/09-2014/09/12	-5.2%	Y
Oswego, NY; Ontario	Ontario	2014/11/17-2014/11/22	2.3%	Y

*: Negative Surge

4. Conclusions

This paper investigated coupling effects between FVCOM and WAVEWATCH III in the Great Lakes region using 2 significant events. From the results of the study, the following conclusions can be drawn:

a. Wind field quality is the dominating factor for both circulation and wave model. Regardless of coupling or not, the peak of both wave and surge are mostly affected by wind strength, duration and direction (which determines the fetch length). In addition, the timing of the storm peak is also controlled by the timing of wind field. Though the bathymetry contour, coastline and coupling physics do have some effects on both amplitude and timing of the storm peak, these effects combined are minimal comparing to which due to wind field quality.

b. Effects of wave radiation stress elevates storm surge at the coastal region at most, but in some case it can also lead to a lower water level at storm peak at both coastal and deep water region. This effect is closely related to the feature of water currents.

c. Currents have significant effects on waves in all regions, especially deep water. The effect of water current on wave depends on its strength and direction related to wave propagating directions. While water level effects the waves at the nearshore regions mostly.

Recommendation and Future work:

a. In terms of the quality of wind field, 1km/4km WRF wind produces the lowest bias and best timing for both wave model and compared to 12km, while 1km WRF wind gives lowest bias and best timing for storm surge model. Recommend 1km for coupled modeling system.

b. Vertical mixing, turbulence coupling with FVCOM, which may have additional impact on water level and coastal physics.

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