Estimation of Wave Heights during Extreme Events in Lake St. Clair

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Abstract

Lake St. Clair is the smallest lake in the Great Lakes system, with a maximum depth of about 6 meters and water surface area of about 430 square miles, however not considered one of the "Great" lakes. Even though the west coast of Lake St. Clair is densely populated, no long-term storm wind, wave or surge hindcast has been performed. The Federal Emergency Management Agency (FEMA) initiated a revised Flood Hazard Mapping Project for the Great Lakes. Under this project, identification, generation of long-term (approximately 60-years) storm climatologies (wind, wave, and surge) are being produced to base the potential for flood risks. As part of this study, Lake St. Clair is included. This paper summarizes the development, execution and evaluation of wind field generation, wave model simulation for a small water body. The study highlights maximum storm significant wave heights on the order of 1-m; signal to noise levels contaminating wave measurements; performance of two wind field specification products, (NCEP Climate Forecast System Reanalysis, and the Natural Neighbor Method); and WAM generating wave estimates.

Introduction

Lake St. Clair is located between Lake Huron and Lake Erie in the Great Lakes region. The lake has a surface area of about 430 square miles and a maximum depth of 6-m. The city of Detroit is located on the southwest corner of Lake St. Clair which includes both commercial and residential properties on or near the shores of the lake. The examination of the extreme storm events in Lake St. Clair is a part of the larger Great Lakes FEMA study.

In this paper, the challenges modeling wave conditions in Lake St. Clair are discussed including the paucity and quality of measurements, and the need for adjustments in the description of accurate wind fields. Solutions to these impediments are described including the use of detailed spectral analysis and re-specification of the wind fields based on correlation of over-land and marine exposure adjusting wind magnitude.

Buoy Measurements

In all wave hindcast studies, there is a need to evaluate the wave model's results based on a series of meteorological conditions. Accomplishing this task requires wave measurements. Unfortunately the amount of data residing in Lake St. Clair is limited to one buoy deployed on a yearly basis in late spring and removed in late fall because of icing conditions in the winter months. This buoy maintained by Environment Canada (Buoy 45147, Figure 1) has resided in Lake St. Clair for approximately 10-years and data were extracted from its respective archive. This buoy provides non-directional wave spectra estimates and a battery of meteorological sensors (winds, air/water temperatures, and barometric pressure). It was evident at the onset of the study, the frequency spectra contained low frequency noise at some level in all data records. Energy levels were elevated in frequency bands (0.1-Hz and lower) where, based on the Lake St. Clair domain size, and extreme wind estimates could not produce natural conditions such as these. Figure 2 illustrates the magnitude of the noise level over time and the relative amount of energy, based on the mean significant wave height removed from the data.

Figure 1. Location of Canadian buoy 45147 (red) and CMAN station LSCM4 (orange) in Lake St. Clair.

It is believed the persistent high frequency energy levels and noise is a product of the analysis package used in the buoy, or the response routine translating the hull motion to estimate the free surface. A dialogue between Environmental Canada continues to determine the actual cause of these errors. At the present time, a low pass filter was applied to the spectra for frequency bands below the 0.1-Hz level until the cause of this is determined.

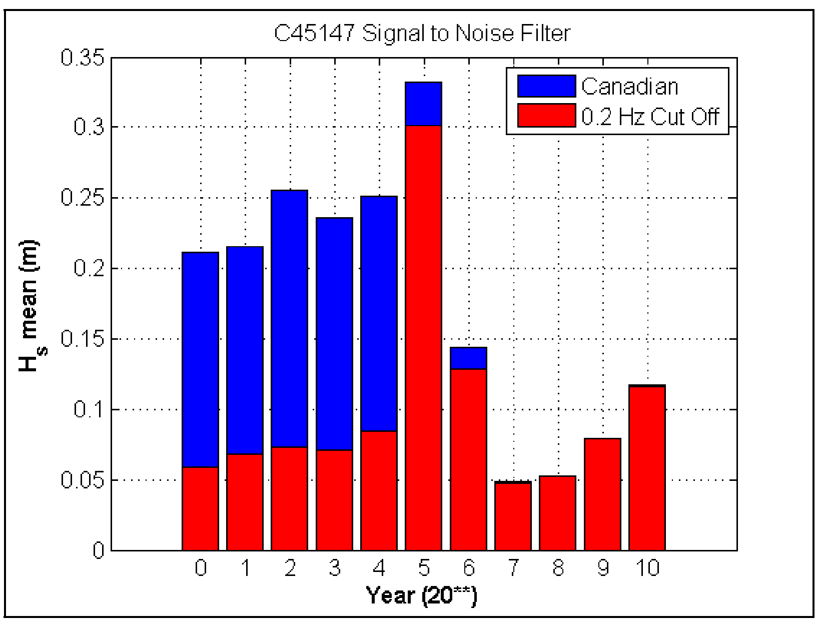

Figure 2. Noise levels in the Canadian wave buoy data for mean wave height estimates.

CFSR Wind Fields

Specification of accurate wind fields to drive wave and surge models becomes a major challenge for any of the Great Lakes domains. Recently, the CFSR 30-year data set (Saha et al., 2010) became available, containing wind, and pressure fields defined on a approximately 38-km globally at a time interval of one-hour. The original wind and pressure fields were spatially interpolated to a fixed spherical grid at a resolution of 0.02-deg (about 2.2-km). The only consequence of this interpolation was to slightly smear the land-sea boundary. These wind and pressure fields were used extensively for a similar FEMA project in Lake Michigan (Jensen et al., 2010) to drive wave and surge models. Evaluation of the resulting wave and water level estimates to buoy and gauge data revealed these fields were accurate in the depiction of fast moving synoptic, and meso-scale meteorological events as they crossed Lake Michigan. Because of these results the CFSR wind and pressure fields were selected as the forcing for Lake St. Clair.

It was determined at the onset of this study that Lake St. Clair was located in the land portion of the land-water mask for the CFSR winds. Hence, all wind estimates derived from the CFSR fields would be considered as over-land exposure winds, rather than marine exposure. The consequence of this yield lower wind speeds relative to the water surface area. This is shown in Figure 3, where the area inside the solid blue line is considered to be marine exposure winds. .

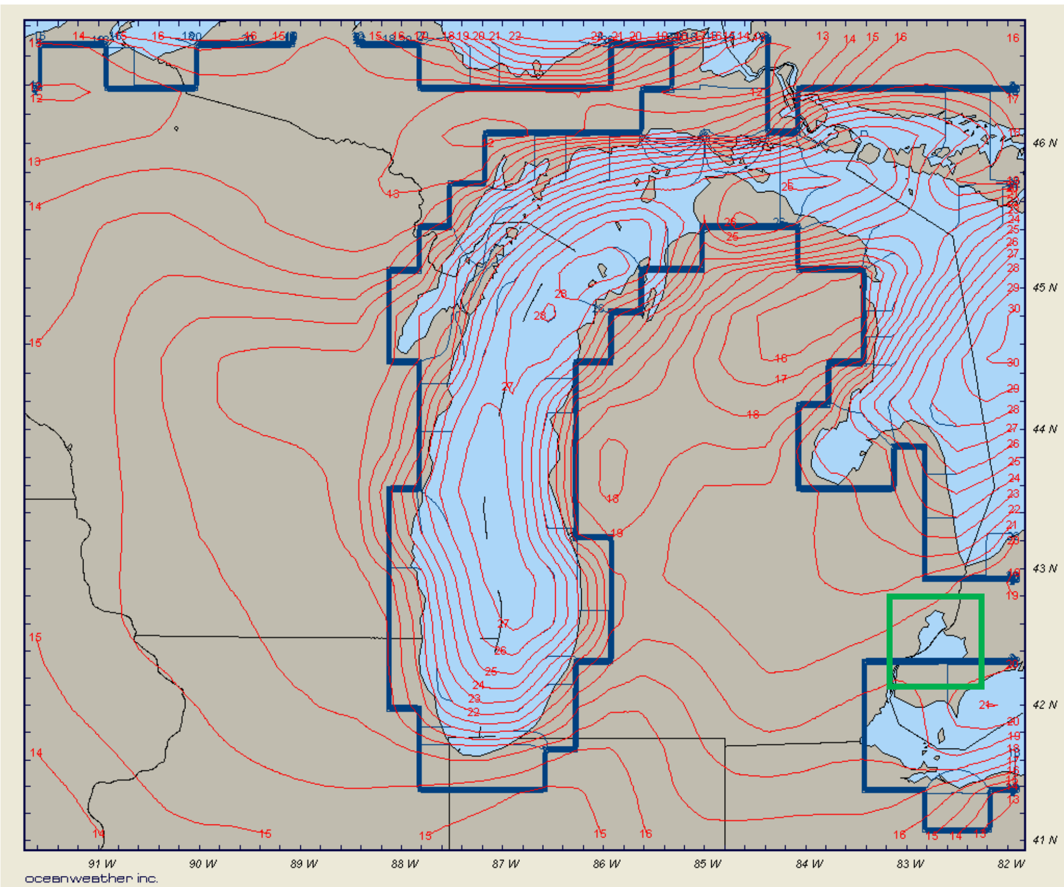

Figure 3. Land-water mask for CFSR wind fields. Lake St. Clair is in the land mask inside the green box.

Preliminary wave model simulations demonstrated the lack of agreement between the CFSR wind estimates and that of two stations in Lake St. Clair. Based on information contained in Figure 3, an adjustment was required to better approximate wind speeds for marine exposure. The analysis focused on time-paired modeled (CFSR) and wind data obtained at a NOAA/National Data Buoy Coastal-Marine Automated Station (C-MAN) nearly centrally located in Lake St. Clair (see Figure 1, the orange symbol). The station is representative of over-water winds, fully exposed in all directions, with no land effects nearby. The data set used spans nearly 10-years (2001 through 2009), and unlike the wave buoy was fully operational during the winter months. Rather than adjust the winds based on, for example a simple bias derived from a mean wind, Quartile-Quartile analysis methods better illustrate any differences in the overall distribution of wind speeds. The results for this technique are found in Figure 4, where there is a strong tendency in the CFSR over the entire range in wind speeds to under-estimate the measurements. This under-estimation (6-m/s at 18-m/s) also grows as the wind speed increases. In addition, there are two distinct trends in the data sets where the transition occurs at approximately 3.5-m/s. Two linear fits were generated to remove the negative biases in the CFSR wind speeds. The two formulations were used to adjust the input CFSR winds. The results are plotted (blue symbols) in Figure 4. The fit of the adjusted CFSR wind speed shows excellent agreement to the LSCM4 data set. The monthly and yearly mean CFSR wind speeds in Figure 5 (note the CFSR wind speed is plotted on the ordinate, opposite to that found in Figure 4) demonstrate the change in the relationship between CFSR and LSCM4 measurements for the old CFSR and the adjusted CFSR wind speeds. There is a persistent leveling off in the adjusted CFSR wind speeds for high values during some of the monthly/yearly Quartile-Quartile plots that may require further investigation. However, the fit to the time paired adjusted CFSR and LSCM4 data is very good, and should provide an increased quality in the wind fields to drive the wave and surge modeling efforts.

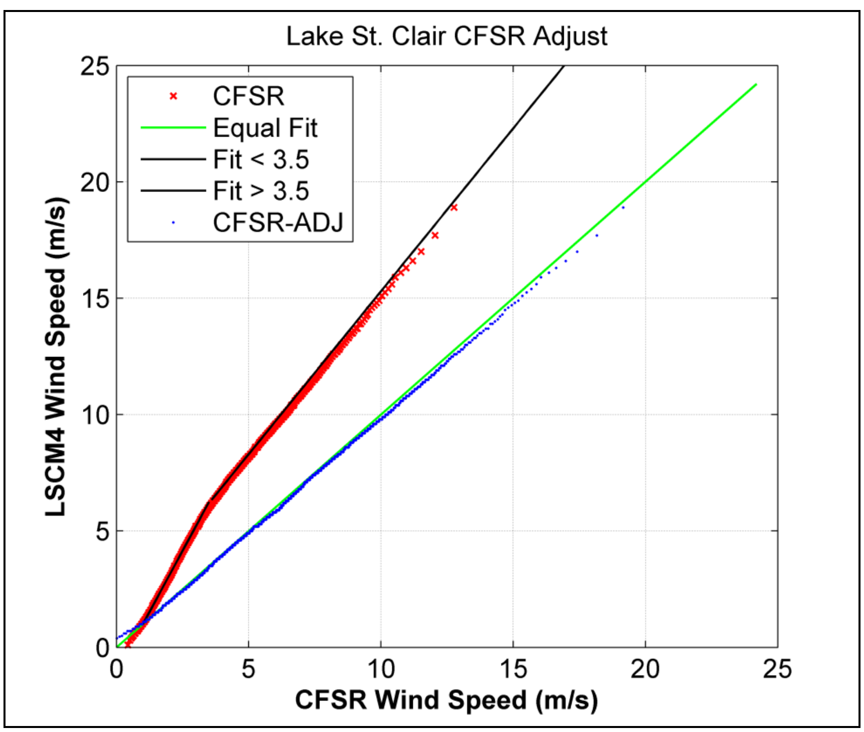

Figure 4. Adjustment of CFSR wind speed at station LSCM4 using two linear trend lines.

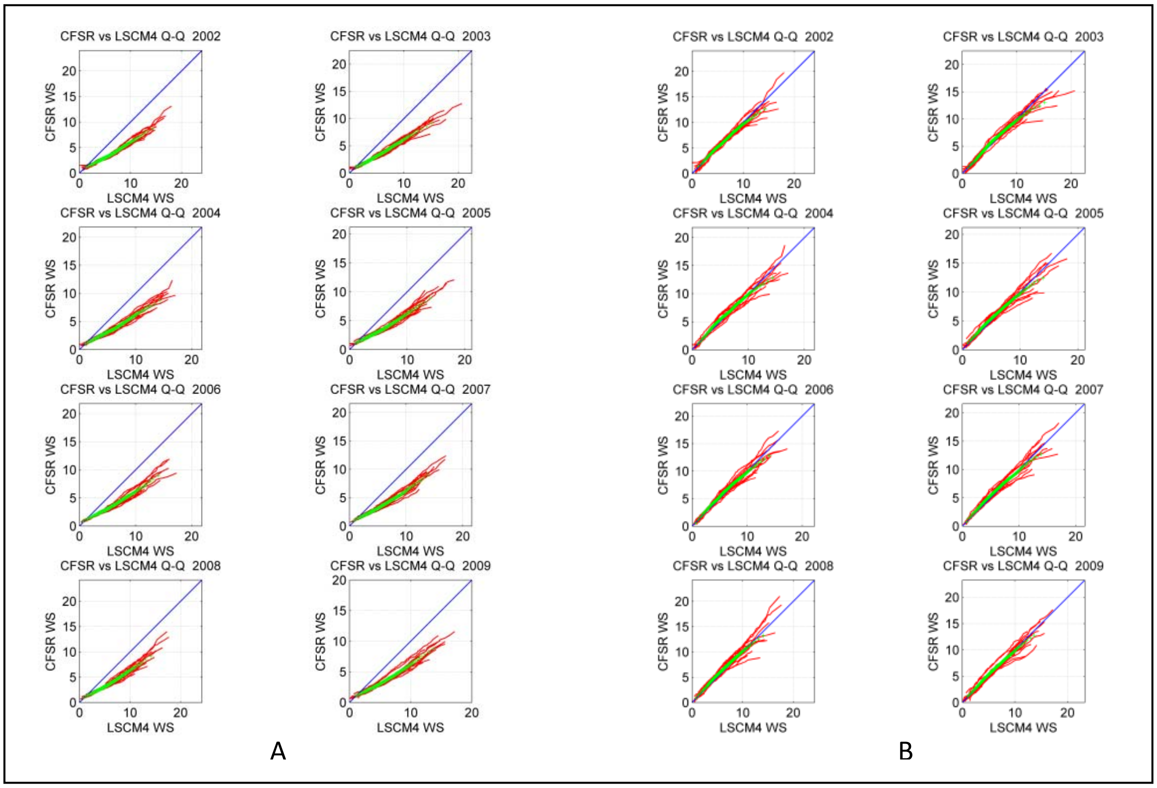

Figure 5. Monthly and yearly mean of CFSR wind speed. A) Original CFSR wind speeds. B) Adjusted CFSR wind speeds.

WAM Wave Modeling

In all wave modeling activities there are certain steps required to a reasonable amount of success in the project. WAM (Komen et al., 1994) was selected to be used for the Lake St. Clair FEMA project. This was based on original work using WAM for Lake Michigan, and the quality of the wave estimates when compared to measurements. Secondly, the original CFSR wind fields have been re-specified to account for marine exposure, and as previously mentioned compared favorably to a wide range of wind speeds. The next step is to construct a model grid. This was done based on 3-arc second digital data based posted at the NOAA National Geophysical Data Center (http://www.ngdc.noaa.gov/mgg/greatlakes/erie.html). The data were used to construct a series of fixed grids (longitude/latitude), ranging from 36-s to 18-s. Frequency bands (28 discrete) ranged from 0.06- to 0.80-Hz, while the directional resolution was selected at 5-deg (used in the Lake Michigan Study). A series of academic tests were performed, running WAM with constant winds (20-m/s, at N, NE, E, SE, S, SW, W, and NW) for a period of 48-hours. This would provide insights to the selection of the final grid resolution, balancing *value added* to the results and computational load required to run the simulation. Ultimately an 18-s grid resolution was selected for the Lake St. Clair domain. Also, the maximum wave height obtained from these tests was about 2.5-m and resided in an area southwest of the wave measurement site (Figure 1).

The adjusted CFSR winds were evaluated using WAM on the top four storm wave producing events defined in the buoy (Station 45147) archive. The top wave event (in the 10-year record) is here to illustrate not only the quality of the WAM results, but also the adjustment made to the CFSR wind forcing. The results from WAM forced with the original CFSR and the modified CFSR winds found in Figure 6 confirm the adjusted CFSR wind speed is a better fit to the measured wind speeds than the original CFSR. However, the significant wave height estimates from WAM for the adjusted CFSR winds consistently over-estimates the measured wave heights at buoy 45147.

Buoy-Model Comparison

We examined the energy density spectrum, S(f), from 45147 and WAM in Figure 6 for Storm03, occurring in October 2009. The WAM frequency bands start at 0.06 Hz and extend to 0.8-Hz (identified in blue). All the energy below 0.2-Hz in the spectra from 45147 was filtered out during our initial evaluation of the buoy data because of signal to noise factors. Investigating the reasoning why WAM consistently over-estimated the significant wave heights, while the winds appeared to be consistent, it was discovered that all energy greater than 0.3-Hz was zeroed out of energy spectrum from 45147. The excess energy found in the WAM spectra in frequencies greater than 0.3-Hz is the cause of the over-estimation in wave heights. The location is generally on the rear face of the spectra, where the atmospheric input source is effectively working, and seems to be reasonable considering the forcing.

Time series of wave heights integrated over the entire spectra from WAM (blue symbol) and 45147 (red symbol) in Figure 7 confirms the over-estimation in wave heights by WAM. Integrating the energy spectrum for frequencies greater than 0.3-Hz in the WAM results (green line) illustrate the wave heights calculated from the differences in the cutoff locations between the model and the buoy. To compare similar frequency domains, the WAM energy spectra were integrated from 0.2- to 0.3-Hz. The resulting time series of wave heights (black line) WAM results now show good agreement to the measured wave heights. This result suggests WAM forced with the adjusted CFSR accurately estimates wave heights. Also, it is recommended the complete spectra derived from WAM simulations be used to approximate the wave climate in Lake St. Clair.

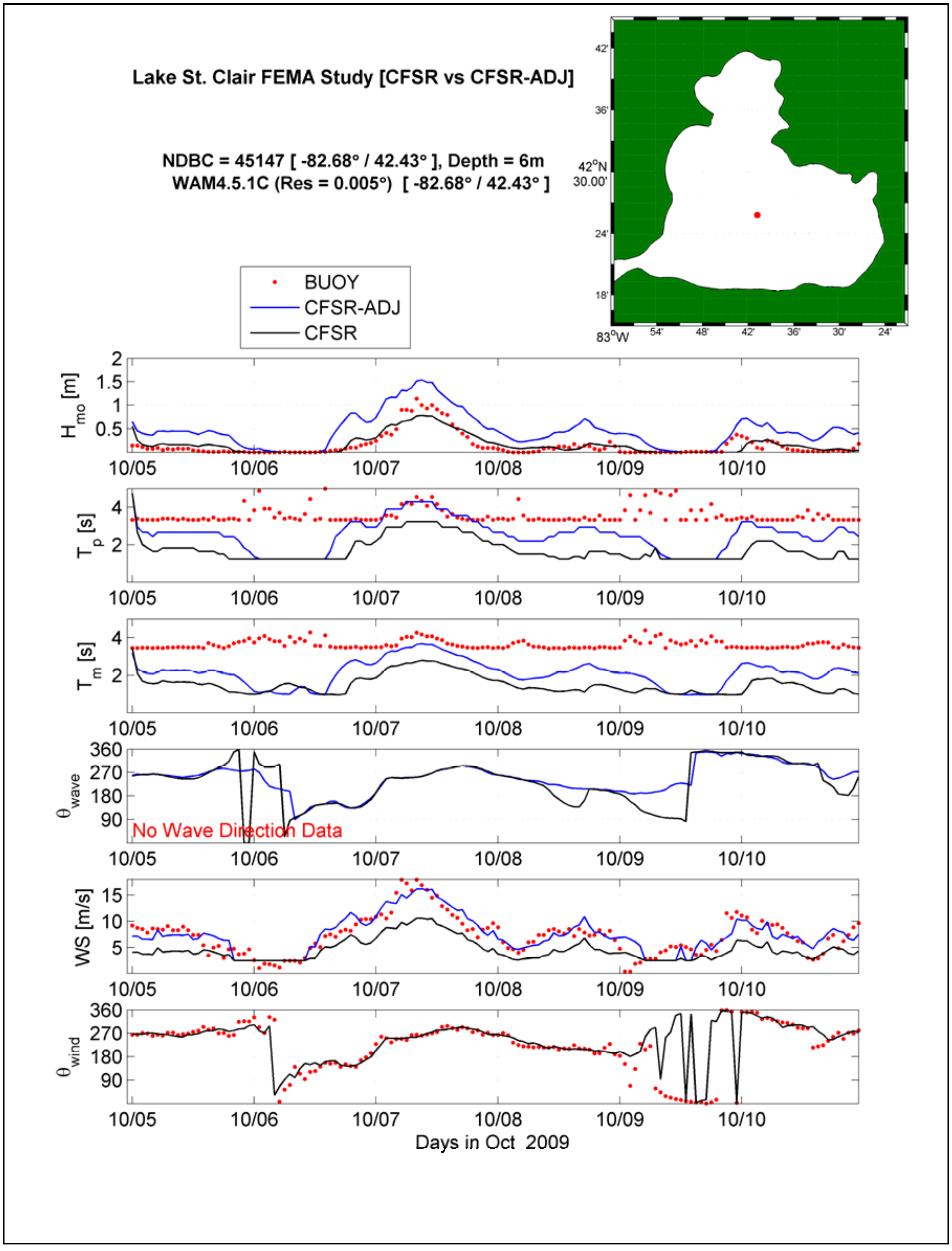

Figure 5. Time series of WAM results for CFSR and CFSR-ADJ wind forcing on October storm in 1999.

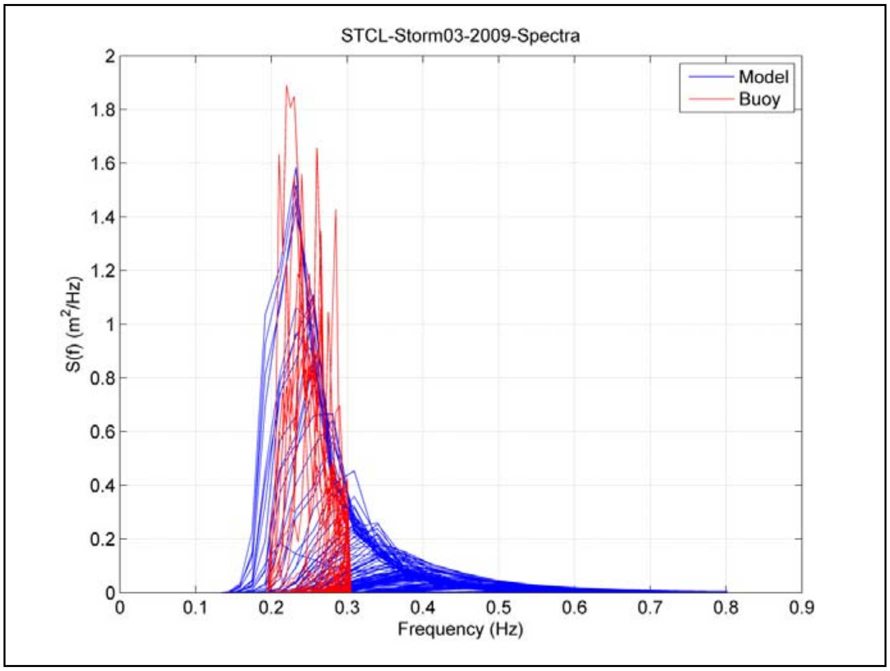

Figure 6. Energy density spectrum for WAM and buoy 45147 during Storm03, October 2009.

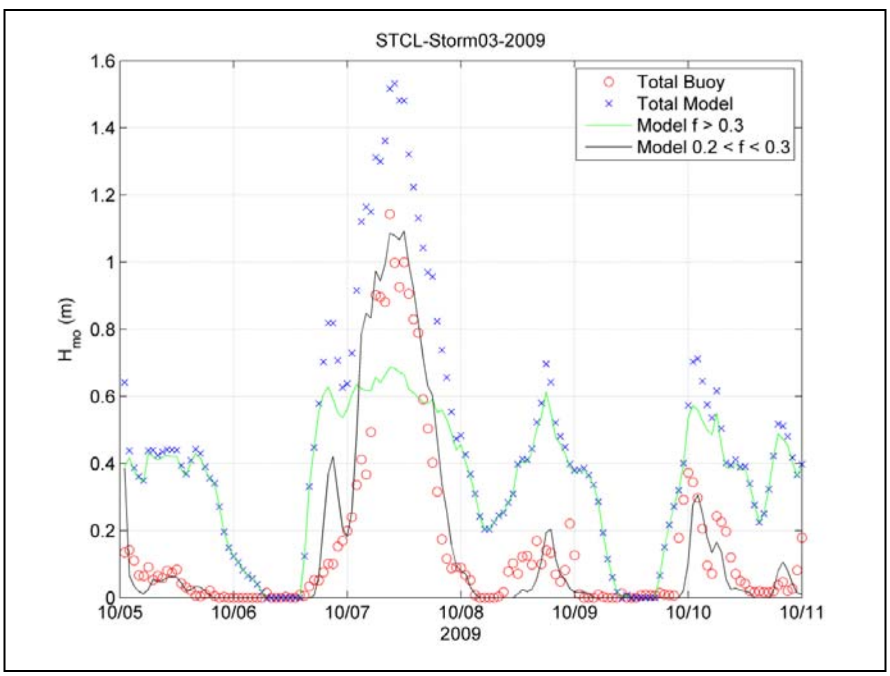

Figure 7. Time series of wave heights calculated for 45147 (o) and WAM (x) for Storm03. WAM wave height results calculated using frequencies greater than 0.3 Hz (-) and between 0.2 and 0.3 Hz (-).

Conclusions

Accurately estimating extreme storm event wave conditions in a small water body possess many challenges to a wave model. Specification of accurate wind fields is critical to the success of the study, as well as having wave measurements to perform model evaluations. Assuming all wave data are error free could eventually become problematic, seeking to change the input wind fields, tuning a wave model to better approximate questionable measurements. Extensive evaluations have been necessary to determine the source of errors between the measured data and model results. The latest evaluation supports the use of the adjusted CFSR winds to better fit the measured winds at both 45147 and LSCM4 and the use of WAM to calculate wave heights at buoy 45147. The discrepancies observed in results from WAM forced with the adjusted CFSR winds appear to be caused by differences in energy levels above 0.3-Hz. The energy cutoff applied to the existing, and archived spectra removed a large amount of energy that most undoubtedly be real. The evaluation of the results from Storm03 confirmed our suspicions the differences were caused by indiscriminately zeroing frequency ranges containing real wave energy.

References

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