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THE GREAT LAKES WAVE MODEL AT NOAA/NCEP: CHALLENGES AND FUTURE DEVELOPMENTS[1]

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1. INTRODUCTION

In spite of a notion that the nature of wind waves in the Great Lakes is generally benign, intense storms and rapidly changing weather patterns generate severe sea states that develop into serious hazards to marine activities involving commercial and recreational vessels. The Great Lakes basin aggregates more than 1/10th and ¼ of the populations of United States and Canada, respectively. Several states with large contributions to the American economy, such as Wisconsin and Minnesota, make up the lakes margin. Commercial shipping constitutes one of the most cost-effective means of transporting raw materials and goods to and from these states, as well as provides an important source of jobs for the region's population. Providing accurate forecasts of wind waves associated with severe sea states is a critical service towards ensuring the safety of maritime operations in the Great Lakes, with critical consequences to the American economy and public safety.

The Great Lakes storm of November 1913 is an historic example of how extreme wave conditions can develop within the Great Lakes. Considered the deadliest and most destructive natural disaster ever to hit the lakes (Brown, 2002), the storm developed hurricane-force winds and severe sea states, which allegedly destroyed 19 ships and killed over 250 crew. Ship losses surpassed what would correspond today to more than US$ 100 million. In a dramatic account of the event, the New York Times reported: ``Ship losses equaled those of the Titanic disaster: the incident ought to impress the lesson that the dangers of the lakes rival those of the ocean".

2. THE GREAT LAKES WAVE MODEL

The initial implementation of a Great Lakes model based on NOAA/NCEP's WAVEWATCH III code (henceforth the GLW model), began in late 2004. During the first three quarters of 2005, a wave forecasting system using WAVEWATCH III (Tolman, 2002) was developed and tested, and by late 2005, a pre-operational version of the GLW model was deployed. In August 2006, the experimental GLW system was made operational within the US National Weather Service suite of numerical weather prediction models (Figure 1). The initial operational implementation of the GLW model system was forced with winds from the ETA model (Black, 1994), which was the mesoscale NWP model providing operational forecasts for the NWS on a regional scale circa 2006. The ETA model also provided ice concentrations and air-sea temperatures differences, used in WAVEWATCH III® for wind-speed corrections due to instability. Since its implementation, the GLW has changed its atmospheric forcing inputs following the changes made to NWS's mesoscale operational models. Currently, the GLW system is forced with winds from the NAM model (Janjic, 2003).

An alternate version of the GLW model (the GLWN model) is run with surface winds provided within the National Digital Forecast Database (NDFD). The NDFD (Glahn and Ruth, 2003) is a composite of collaborated gridded forecasts from the NWS Weather Forecast Offices (WFOs). The wind forecasts are a man-machine mix designed to optimize forecast quality by leveraging the collective suite of numerical guidance, rather than committing a priori to a single model input. Wind forecasts are routinely produced at

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a minimum of 4 times daily with complete flexibility to update as conditions warrant. The GLWN model uses a custom Great Lakes sector of the NDFD dataset designed to compliment the GLWN grid configuration. Both GLW and GLWN have similar performance, measured in terms of skill relative to wave measurements made by surface buoys.

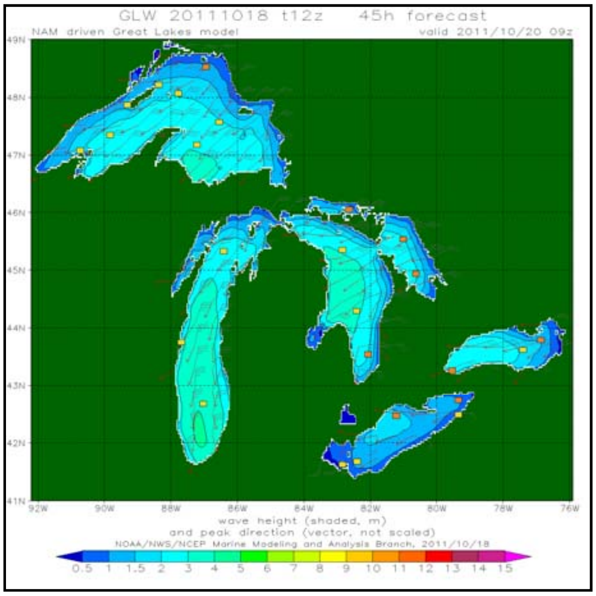

Figure 1 Graphical representation of significant wave heights computed for the 45h forecast from Great Lakes wave model system (GLW) at NOAA/NCEP.

3. BUILDING PARTNERSHIPS

The development of the GLW system has allowed a closer interaction between NCEP, several US National Weather Service Forecasting Offices (WFOs) in the Great Lakes region, and NOAA's Great Lakes Environmental Research Laboratory (GLERL). The latter has provided high resolution bathymetries used in the generation of the GLW model's spatial grids. GLERL has also provided an extensive database of surface wind analyses, which has been essential for the verification and continuous development of the GLW model. However, the major contribution made by GLERL to NCEP's GLW system has been the insight towards establishing WAVEWATCH III model configurations more suitable to the Great Lakes basins.

GLERL has been running, on a semi-operational basis, a wave modeling system that has been very successful as a consequence of its development made on the basis of decades of experience from Laboratory staff in measuring sea states, and other parameters describing the geophysical fluid dynamics in the Great Lakes. Due to its well-established success, the GLERL wave model (Schwab et al., 1984), part of the Great Lakes Coastal Forecasting System (www.glerl.noaa.gov/res/glcfs), is used as one of the major sources of wave forecasts used at NWS Weather Forecasting Offices in the Great Lakes region. The high quality now- and forecasts generated by the GLERL wave model have provided a robust and challenging benchmark, which has been extensively used in the development of the GLW system at NCEP.

4. CHALLENGES

The Great Lakes basins provide a unique framework for testing the skill of wind-wave models. The region is exposed to intense storms with complex evolution patterns, as a result of their interactions with similarly complex land topography, irregular basin geometries, ice-concentration patterns, as well as with other storms. Combined, these factors result in wave generation scenarios that are commonly dominated by rapidly changing wind fields, with the occurrence of slanting fetches, intense wind direction/speed gradients, sudden changes in overlake thermal structure etc.

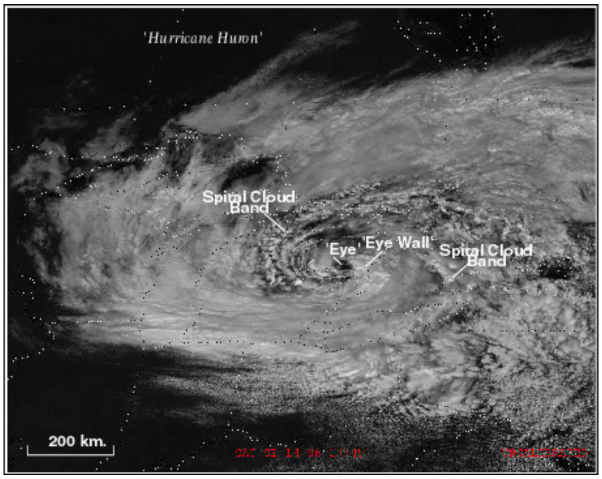

Figure 2 Satellite image of the "Hurricane Huron".

An example of how the Great Lakes meteorology may contribute to developing severe storms, with a potential of generating extreme waves, is the "Hurricane Huron" (Figure 2), an intense cutoff low that developed between 11 and 15 of September 1996. According to Miner et al. (2000), "the low generated sustained winds of 18 m s−1, wind gusts of 23 m s−1, and waves on the Great Lakes near 3 m" (Figure 3).

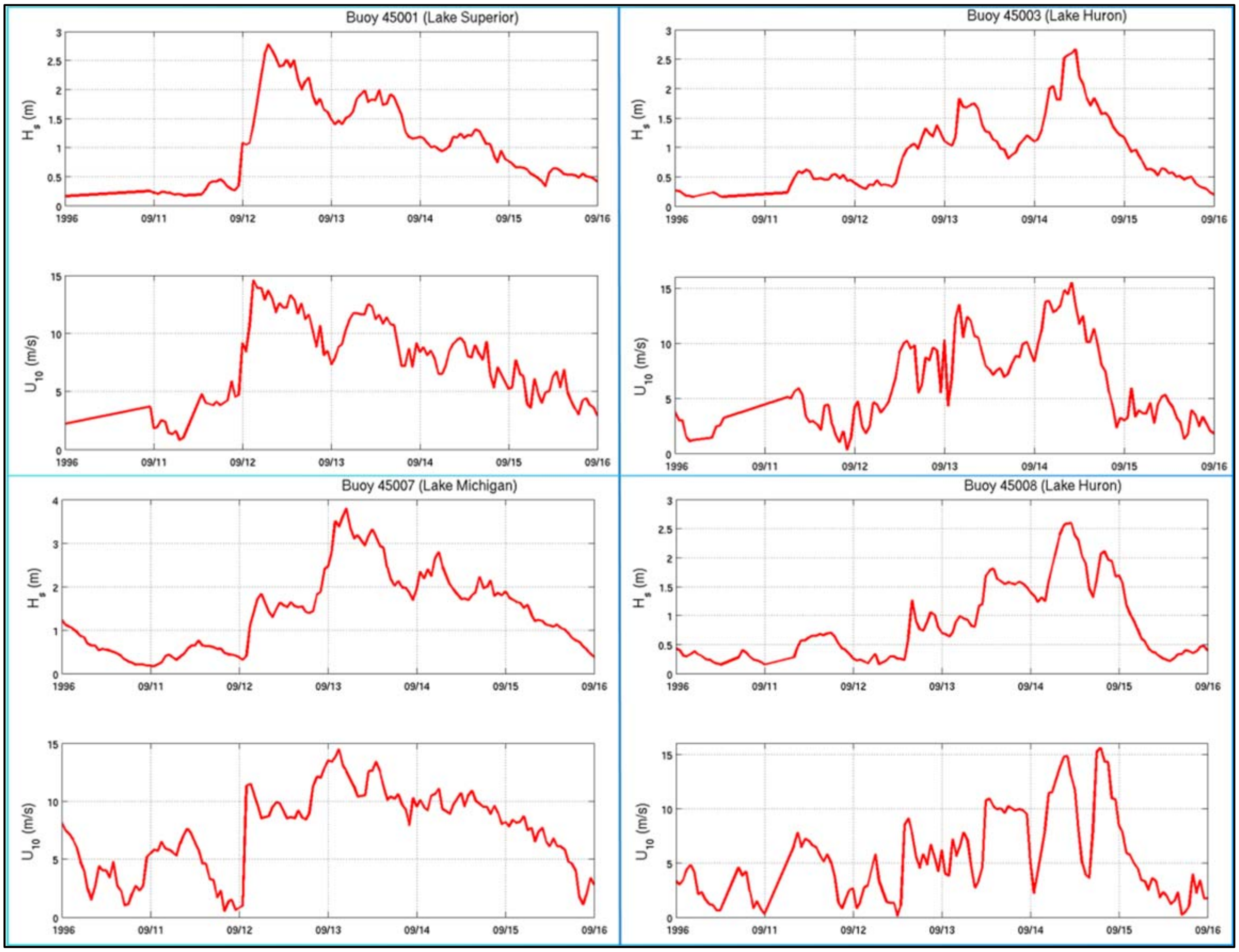

Figure 3 Wave heights and wind speeds at NDBC buoys in three of the Great Lakes recorded the passage of the "Hurricane Huron".

5. CURRENT PERFORMANCE

The GLERL wave forecasting system is based on an implementation of a simple parametric wave model developed by Donelan (1977), as cited in Schwab et al. (1984). Further than its successful deployment in the Great Lakes region, the model has been shown to perform well in semi-enclosed basins, such as the Chesapeake Bay (Lin et al., 2002). Such good performance in areas with significant land-boundary constraints to the development of wind fetches, is due to a very good response of the GLERL/Donelan model to changing wind conditions regardless of other factors that may characterize the surface wind field on a larger scale.

In contrast, earlier versions of WAVEWATCH III, implemented using the source terms for growth and decay proposed by TC96 (Tolman & Chalikov, 1996), have shown limitations in simulating waves generated in short/slanted fetches (Ardhuin et al., 2007), as well as in predicting the early growth stages of waves in rapidly changing/intensifying winds, such as during hurricanes (Alves et al., 2004; Chao and Tolman, 2010). The TC96 source terms were initially tuned in WAVEWATCH III to provide good predictions of deep-water waves. This is typically used as a justification for its poorer performance in basins with short, irregular wind fetches, such as in the Great Lakes. Such limitations, however, have been the major obstacle in making the GLW model system a reliable source of wave forecasts in the Great Lakes, particularly during the occurrence of severe sea-states.

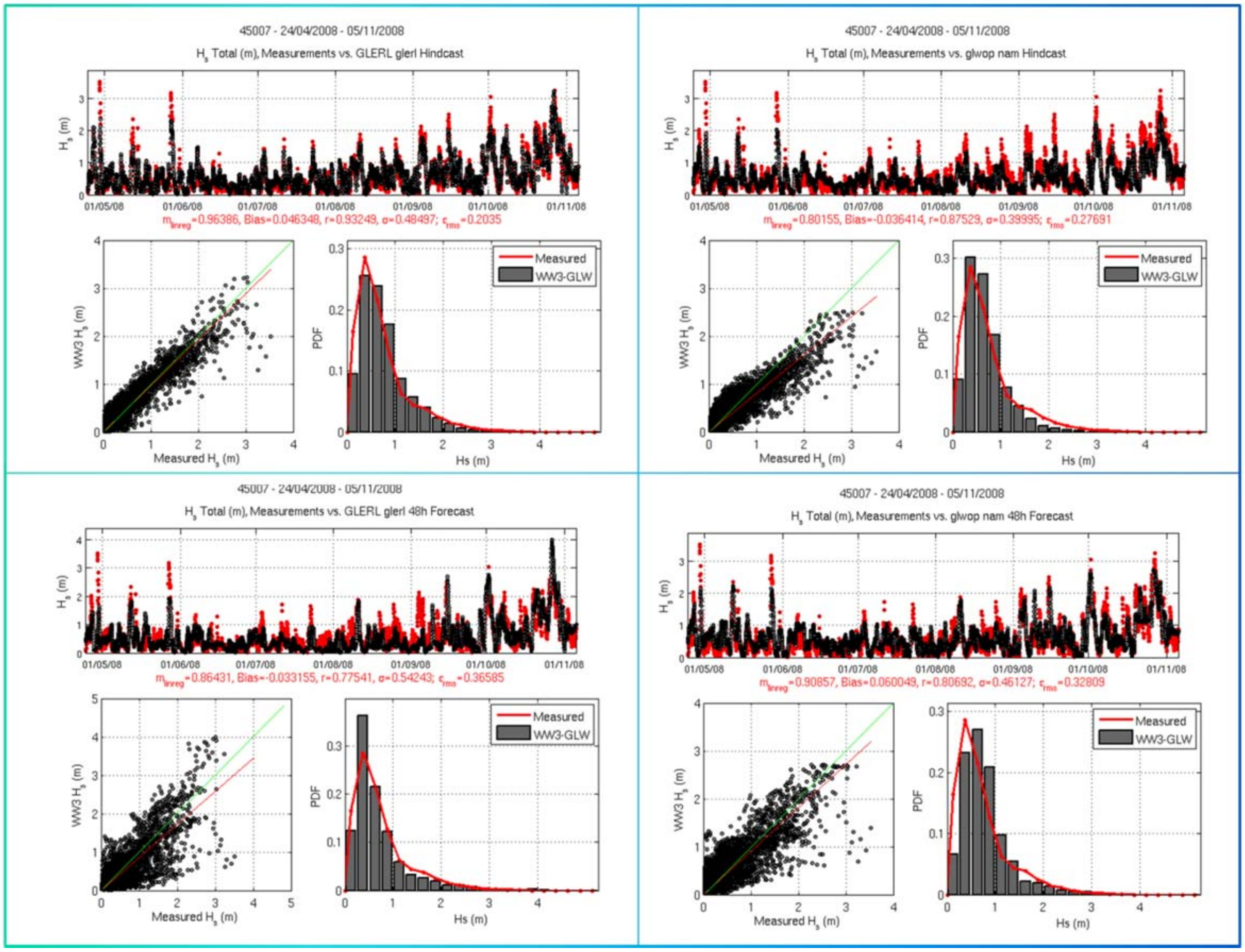

Figure 4 Wave heights from the GLERL model (left) and from NCEP's GLW model (right). Hindcasts (top) and 48h forecasts (bottom) are shown. Panels: time series (note that in winter buoys are removed), scatter plots and probability density functions.

Validation of wave heights computed with the GLERL wave model, and with NCEP's GLW model was made relative to NDBC buoy measurements from the five major lakes that compose the Great Lakes basin: 45001, 45004, 45006 (Lake Superior), 45002, 45007 (Lake Michigan), 45003, 45008 (Lake Huron), 45007 (Lake Erie) and 45012 (Lake Ontario). Results confirm the very good performance of the GLERL model, particularly when hindcast winds are used. They also confirm the significant underestimation of more severe sea states by the GLW model, despite the fact that validation statistics reveal a performance comparable to the GLERL model in the majority of sea state conditions, characterized by moderate to low wave heights (Figure 4).

The contrast between models is particularly evident in wave hindcasts. The reason for larger discrepancies in hindcasts of wave heights is explained by the fact that the GLERL wave model is forced by a wind analysis product developed at GLERL, specifically aiming at providing forcing data for hydrodynamic models in the region, with high quality in representing the observed surface wind fields (Kelly et al., 1998). The GLW model hidncasts, on the other hand, are generated via forcing provided by the data assimilation cycle of the NAM model (NDAS) which is not particularly weighed towards minimizing biases near the lakes wet surface. The differences between GLERL and GLW models become less pronounced in the forecast ranges because both use products derived from the NAM model forecasts, including the gridded wind products available through the NDFD.

Despite being smaller, the discrepancies in wave hindcasts are also present in forecasts, which indicates that the GLW model has a systematic source of biases affecting its skill in predicting severe sea states. Strong evidence supports the idea that the main source of bias are TC96 source terms, used in the version of WAVEWATCH III deployed within the GLW system, due to their limitation in simulating waves under short fetches and rapidly changing wind conditions, which are prevalent in generating severe sea states observed in the Great Lakes.

6. FUTURE DEVELOPMENTS: THE IMPROVED GLW SYSTEM

New findings in both theoretical and empirical fields have allowed the development of new source term parameterizations which have shown to be promising in representing more accurately wave growth and decay. International partnerships involving NOAA/NCEP have allowed us to integrate more rapidly such new development into the WAVEWATCH III model. As a consequence, the availability of new source-term packages, such as that based on parameterizations of Ardhuin et al. (2010) [A+10], has provided the opportunity of achieving breakthrough-level improvements in the GLW model skill towards predicting severe sea states in the Great Lakes. This hypothesis has been tested through a series of experiments made recently, where the GLERL model was again compared to NCEP's GLW model, now using alternatively the TC96 and A+10 source term packages. Experiments were made using the GLERL surface wind analyses, to minimize uncertainties and emphasize differences between model runs. Results indicate that the GLW model matches the skill of the GLERL model in predicting wave heights in more severe sea states, also matching its ability to represent well the total variance of the wave field. Further to that, the new A+10 source term package has led the GLW model to produce superior results to the GLERL wave model, in terms of wave-height bias, root-mean-square error and correlations, relative to data measured in most NDBC buoy sites (Figure 5).

Further experiments are currently being made at NOAA/NCEP to determine the best configuration of the new source term packages available via WAVEWATCH III, that will provide improvements in forecast skill at an appropriate level. It is estimated that such improvements would become operational in the second half of 2012. At that time, a new implementation of the GLW and GLWN wave models would include not only physics upgrades, but also increased spectral and spatial resolutions. Further expansions may include high-resolution nearshore grids, fully integrated to larger-scale domains via WAVEWATCH III's mosaic grid capabilities (Tolman, 2008)

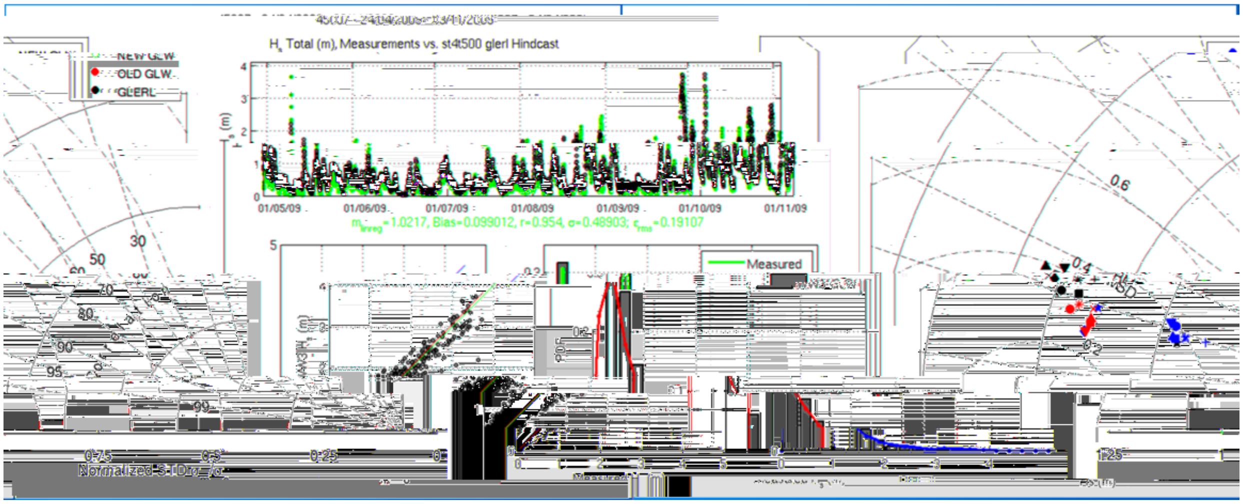

Figure 5 Validation plots showing GLW model results with A+10 source terms, relative to data from buoy 45007 (left). Right: an inverted Taylor diagram comparing data from the GLERL model (black), with GLW model data using the TC96 (blue) and A+10 (red) source terms.

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