NCEP NOTES

The Operational Implementation of a Great Lakes Wave Forecasting System at NOAA/NCEP*

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ABSTRACT

The development of a Great Lakes wave forecasting system at NOAA's National Centers for Environmental Prediction (NCEP) is described. The system is an implementation of the WAVEWATCH III model, forced with atmospheric data from NCEP's regional Weather Research and Forecasting (WRF) Model [the North American Mesoscale Model (NAM)] and the National Digital Forecast Database (NDFD). Reviews are made of previous Great Lakes wave modeling efforts. The development history of NCEP's Great Lakes wave forecasting system is presented. A performance assessment is made of model wind speeds, as well as wave heights and periods, relative to National Data Buoy Center (NDBC) measurements. Performance comparisons are made relative to NOAA's Great Lakes Environmental Research Laboratory (GLERL) wave prediction system. Results show that 1- and 2-day forecasts from NCEP have good skill in predicting wave heights and periods. NCEP's system provides a better representation of measured wave periods, relative to the GLERL model in most conditions. Wave heights during storms, however, are consistently underestimated by NCEP's current operational system, whereas the GLERL model provides close agreement with observations. Research efforts to develop new wave-growth parameterizations and overcome this limitation have led to upgrades to the WAVEWATCH III model, scheduled to become operational at NCEP in 2013. Results are presented from numerical experiments made with the new wave-model physics, showing significant improvements to the skill of NCEP's Great Lakes wave forecasting system in predicting storm wave heights.

1. Introduction

The Great Lakes basin aggregates more than 1/10th and 1/4th 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 Great Lakes margins. Commercial shipping constitutes one of the most cost-effective means of

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transporting raw materials and goods to and from these states, as well as providing an important source of jobs for the local population. Consequently, providing accurate forecasts of wind waves is a critical service toward ensuring the safety of maritime operations in the Great Lakes, with consequences of great importance to the American economy and public safety.

Since 1974, marine forecasting in the Great Lakes region has been made in a systematic way following the creation of the National Oceanic and Atmospheric Administration's (NOAA) Great Lakes Environmental Research Laboratory (GLERL). GLERL developed technology for producing wave forecasts for the Great Lakes in the early 1980s, using a parametric, first-generation wave model (Schwab et al. 1984). With the advent of third-generation wind-wave models in the late 1980s, efforts have been made toward using these more advanced models in the Great Lakes, as they have the potential to provide a more effective framework for simulating waves in more complex weather conditions and environments, including the nearshore zone, as well as for coupling with other environmental prediction models.

The current paper describes the challenges faced, and solutions adopted by the wave modeling group at the Environmental Modeling Center of NOAA's National Centers for Environmental Prediction (NCEP), which led to the successful deployment of a Great Lakes wave forecasting system using the third-generation model WAVEWATCH III (Tolman 2002b; Tolman et al. 2002). Performance of the current operational wave forecasting system for the Great Lakes, and the impacts of scheduled upgrades that will soon enter operations at NCEP are evaluated, focusing mostly on predictions of significant wave heights H_s, relative to surface buoys operated by NOAA's National Data Buoy Center (NDBC). For completion, considerations are also made on model predictions of peak periods T_p.

The paper is structured as follows. Section 2 provides a brief historical summary of relevant wind-wave modeling studies made in the last few decades on the Great Lakes. A description of NCEP's current operational system is made in section 3. A validation study of the current operational system at NCEP is presented in section 4, alongside a comparison to the GLERL semioperational wave forecast system. Section 5 provides a discussion centered on recent model upgrades that led to a higher accuracy of severe sea-state predictions relative to the current operational system, and presents associated supporting validation results. Finally, concluding remarks and a summary of planned improvements to NCEP's operational Great Lakes wave forecasting system are made in section 6.

2. Previous Great Lakes wave modeling efforts

Numerical forecasts and hindcasts of wind waves at the Great Lakes have been generated since the early 1970s. Wave hindcasting studies have typically been more likely to use the latest wave modeling trends and techniques. Wave forecasting, however, has usually favored older, less computer-intensive approaches, often based on parametric models. Such approaches have remained feasible at the Great Lakes due to the generally simple wave conditions predominant in that region (e.g., wind-sea-dominated wave climates, with moderate swell contributions).

The more contemporary need for a detailed description of complex wave generation scenarios and shallow-water wave propagation, for both practical applications and for environmental prediction using coupled models, has provided a push toward upgrading wave forecasting systems in the Great Lakes region. In this section we provide a brief, general history of both wind-wave hindcasting and forecasting in the Great Lakes, which outlines this progress in technologies and complexity of products in the wave modeling.

a. *Hindcasts*

The first long-term Great Lakes wave hindcast product generated using a numerical scheme is presented in Resio (1977). The technique was based on overlake wind data estimated from overland measurements and ship anemometers. These early hindcasts covered a 69-yr period (1907–75), and were a useful source of wave data for engineering applications in the Great Lakes during the late 1970s and 1980s.

With the deployment of a two-dimensional model at GLERL, the Ontario Ministry of Natural Resources funded in the mid-1980s the development of a new wave climate database using the latest available technology, as part of its shoreline management plan. The approach consisted of using a first-generation wave model described in Schwab et al. (1984), forced with gridded overlake winds derived from wind measurements employing an estimation technique as discussed in Schwab and Morton (1984).

The U.S. Army Corps of Engineers (USACE) has been generating and constantly upgrading more recent wave hindcast databases in several oceanic basins, and in major inland water bodies such as the Great Lakes. These so-called Wave Information Studies (WIS) have provided two distinct data streams for the Great Lakes region. In the first, the second-generation wave model WISWAVE (Hubertz 1992) was run for a 32-yr period (1956–87) using a 10-mi-resolution grid, and gridded winds derived from land stations via adjustments for the transition between land–water boundary layers, stability, and measurement height. This first WIS database was later extended for the period 1988–97, using improved wind estimates developed in partnership with GLERL that included buoy measurements available in the Great Lakes since the early 1980s. A general description is provided in Lin and Resio (2001).

USACE's WIS has recently upgraded the Great Lakes wind-wave hindcast database with higher-resolution hindcasts for Lake Ontario. Wave simulations were made for a 40-yr period (1961–2000), using an upgraded version of the WISWAVE model named WAVAD (Resio 1993). The hindcasts were generated using a 3-km grid covering Lake Ontario, with wind fields derived from land-based meteorological stations and buoys and ice concentrations assembled from databases developed by Assel et al. (1983), for the first 14 yr, and generated at GLERL for the remaining period. A full description of the Lake Ontario hindcasts, which have been available since 2003, is provided on USACE's Field Research Facility web site (USACE 2011).

b. Forecasts

The first wave forecast product for the Great Lakes based on numerical schemes was implemented in 1974 by the National Weather Service (NWS), which consisted of forecasts of sea state at 64 discrete locations spread over the five major Great Lakes, extending out to 36 h, at 12-h intervals. These early wave forecasts were computed using a nonspectral, automated numerical scheme developed by Pore (1979), based on an adaptation of wind-fetch relationships developed by Bretschneider (1970).

In response to requests made by the forecasting community to expand the wave forecasts generated by the NWS in the 1970s, GLERL developed a two-dimensional wind-wave model, which was later implemented for semioperational forecasting in the Great Lakes region. The deployed model was a first-generation wind-wave model, solving a local momentum balance equation over individual lake grids with resolutions of 10 km (Lake Superior) and 5 km (all other lakes). Ice coverage was ignored. Detailed history and description of the GLERL wave model are provided in Schwab et al. (1984) and Schwab and Morton (1984), whereas the initial validation that led to its operational implementation is reported in Liu et al. (1984).

As pointed out by Liu et al. (1984), the implemented model at GLERL was "not without drawbacks," as it was purely a wind-wave prediction model and had no provision for swell propagation. Liu et al. (1984) also stressed that, in addition, the model was built for deep-water waves, which meant results may not be accurate in shallow-water waves. These concerns summarize the central motivation pushing NOAA/NCEP efforts toward implementing its state-of-the-art, third-generation spectral wind-wave model WAVEWATCH III for Great Lakes wave forecasting, within a framework where not only swell propagation, but also shallow-water and nonlinear processes, may be represented for a full two-dimensional wave energy-density spectrum.

A first implementation of the WAVEWATCH III model for the Great Lakes region was made in an independent effort by the NWS Weather Forecast Office at Marquette, Michigan (T. Hultquist 2004, personal communication). Several case studies were performed, using winds generated with the Regional Atmospheric Modeling System (RAMS) model (Pielke et al. 1992). Results were promising, and established loosely the feasibility of running WAVEWATCH III operationally for wind-wave forecasting at the Great Lakes.

3. The Great Lakes wave models at NCEP

During the first three quarters of 2005, a wave forecasting system using WAVEWATCH III was developed and tested by the Marine Modeling and Analysis Branch of NCEP's Environmental Modeling Center (EMC). A preoperational version of NCEP's Great Lakes wave forecasting system (henceforth GLW), which used forcing fields from NCEP's operational regional atmospheric model, was deployed by late 2005. In June 2006, an experimental web site made available the 4 times daily GLW forecasts for public access. In August 2006, the experimental system was made operational.

In response to requests made by NWS field offices operating in the Great Lakes region, an additional wave model subsystem was added to NCEP's operational wave model suite. The subsystem was an independent model run using identical grid and general configurations as the original Great Lakes wave system, but forced with surface wind fields from the National Digital Forecast Database (NDFD). The new wave model system, designated GLW-NDFD, was implemented experimentally in 2008. NDFD winds consist of a seamless mosaic of digital forecasts from NWS field offices, made in collaboration with NCEP (Glahn and Ruth 2003). After dealing with NDFD data feed issues that required additional adjustments to ensure continuity of the forecasting system over time, the GLW-NDFD was implemented operationally in 2009.

In the subsections below, a detailed description is provided of forcing fields and spectral and spatial resolutions used in both operational Great Lakes wave forecasting systems at NCEP. Since both models share spectral and spatial resolutions, these are described in a single section. Each system is described in its own separate section in what refers to forcing data. In the latter case, for GLW-NDFD a description is made only for system components that differ from the North

American Mesoscale Model (NAM) forced GLW system (e.g., wind forcing).

a. Spectral resolution

Waves can develop over long fetches and propagate long distances in the major oceanic basins, generating wave spectra that may contain measurable amounts of energy in very low frequencies. Therefore, typical wind-wave models resolve discrete energy spectra with frequencies in ranges from 0.03–0.04 up to 0.5–1.0 Hz. In the Great Lakes, geographical features limit the fetch size and propagation distances so that the development of lower frequencies is significantly constrained. On the other hand, it is expected that very short waves will have a more prominent role than in the open ocean.

In the absence of previous records in the literature about typical "Great Lakes spectra," a brief investigation was made using NOAA's National Data Buoy Center (NDBC) measurements in the region, with the objective of determining the optimal spectral range to be used in a Great Lakes wave model. A compilation of "spectral climatologies" was made at all available NDBC buoys. Since many of these buoys are removed during the winter months to avoid damage from heavy icing, it was assumed that the data may lack information on spectra from more extreme winter storms. These gaps were filled via running WAVEWATCH III with strong sustained winds over the longest fetches found in the Great Lakes region. Even if unrealistic, this provided a lower bound for spectral ranges of dominant waves.

After building a "design" Great Lakes spectrum via merging the NDBC climatology with the extreme-forcing model results, it was decided that a discrete spectrum with 29 frequencies ranging from 0.05 to 0.72 Hz would be computationally feasible. This resolution would also be physically appropriate to represent the relevant wave scales expected to occur in the Great Lakes basins.

b. Spatial grids

Land-boundary constraints make coastline resolution an issue as important as wind field resolutions in building a forecasting system for the Great Lakes. Coastline shape determines fetch geometry, and coastline features are important when computing sheltering. Another strong constraint for defining spatial grid resolutions is the available computer time for operational forecasting at, initially, a forecast horizon of up to 84 h in the NAM-driven GLW (a 90-h-long model run, since a 6-h hindcast is run at every model cycle), and up to 144 h for the GLW-NDFD.

This led to a spatial wave model grid resolution of 0.035° in latitude by 0.05° in longitude, which provided a roughly square grid cell with approximately 4-km resolution, and a total mesh with 235 × 327 points in latitude and longitude, respectively. The five major Great Lakes basins are described in a single grid to provide optimal load balancing while running the WAVEWATCH III model in a parallel computing environment. More details of the latter are provided in Tolman (2002a).

The bathymetric grid for NCEP's Great Lakes wave models was initially designed using depths obtained from GLERL's operational wave model. Resolutions of the original GLERL wave model grids were on the order of 5 km, except for Lake Superior, which had a 10-km grid, and was inadequate for the higher-resolution grid used in NCEP's system. High-resolution bathymetry data were obtained from NOAA's National Geophysical Data Center (NGDC), allowing the development of a bathymetric grid that was fit for operational purposes. Figure 1 illustrates the Great Lakes bathymetry currently used operationally in NCEP's wave models.

c. Forcing fields

1) Wind fields

The initial operational implementation of NCEP's Great Lakes wave model system was forced with winds from the Eta Model (Black 1994). Thereafter, the GLW system has changed its atmospheric forcing inputs following the changes made to NWS's operational mesoscale systems, so that at any time the forcing winds would come from the most contemporary atmospheric model system available. Currently, it is forced with winds, air–sea temperature differences, and ice concentrations obtained from outputs generated by the NAM implementation of the Weather Research and Forecasting Model (WRF) at NCEP, which is described in Janjić (2003). A more detailed description of forcing fields used in the NAM-forced GLW system (henceforth GLW-NAM) is provided next.

(i) GLW-NAM system

Horizontal resolutions of the NAM model at the time of implementation of the new wave modeling system were $1/12$°. A preliminary evaluation of NAM winds was made against several buoys, on all five major Great Lakes, with the objective of investigating if any adjustments would be needed for wave modeling. Results revealed two major sources of error: a generalized bias, which varied with classes of wind speeds, and a bias associated with wind direction and distance to shore (fetch geometry).

Such preliminary assessments also indicated that NAM surface winds had systematic biases for wind speeds under 15 m s^{-1}, and were in good agreement or slightly higher than measured winds at stronger intensities.

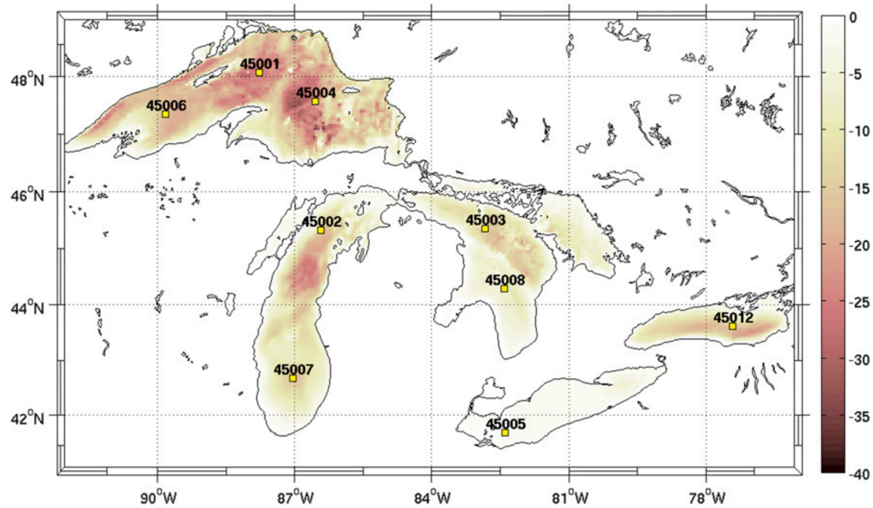


FIG. 1. Bathymetric grid used by NCEP's Great Lakes wave model systems. Also indicated are locations of NDBC buoys used for model validation.

Analyses of individual locations indicated a similar trend, but also revealed the existence of a consistently higher bias of surface winds near the coast. Figure 2 summarizes the percentage biases found at selected locations, as a function of distance to the shoreline.

Strategies for correcting bulk and distance-to-shoreline NAM wind biases were investigated independently. Bulk bias correction was attempted using the average slope of linear regression lines through zero. Validation statistics indicated that model results were generally insensitive to the bulk correction, so that a decision was made to go ahead with a future operational implementation without a bulk surface wind correction component.

A distance-to-shoreline correction scheme was initially computed using an empirical fetch-dependent formula derived from error statistics for NAM surface winds relative to buoy data. Error diagrams at selected locations, as a function of wind speed and direction, were generated, as seen for station DBLN6 in Fig. 3. Global statistics were then derived from associated error matrices in an attempt to define a generalized relationship between wind speed biases and wind-fetch geometry.

Obtaining generally consistent relationships for correcting wind speeds, based on fetch geometry, was encouraging. However, the relatively small number of buoys available in the Great Lakes region, and the fact they are removed during winter months, limited

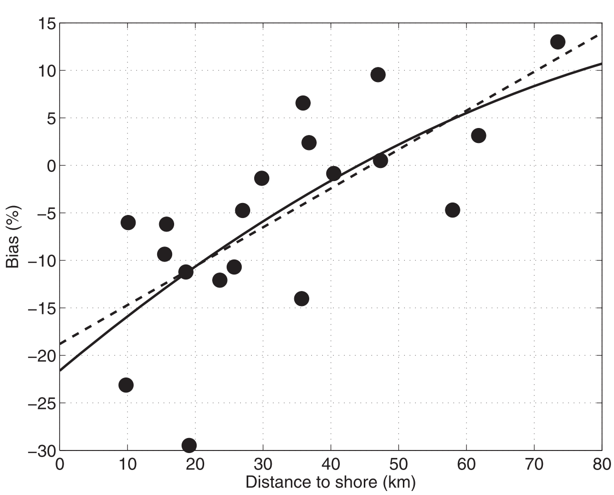


FIG. 2. Percentage bias of NAM winds relative to NDBC buoys (filled circles) in the Great Lakes as a function of upwind distance to the shoreline in km. Also shown are lines indicating the linear (dashed) and second-order polynomial (solid) curves fitted to data.

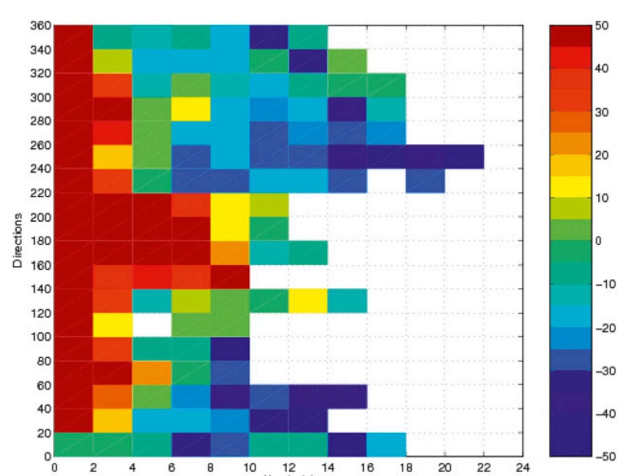


FIG. 3. Directional distribution of biases as a function of wind speeds at coastal station DBLN6. Colors indicate percentage bias with the rhs color bar.

the reliability of the derived relationships. Furthermore, as will be explored in more details below, the WAVEWATCH III model physics available at the time of the initial GLW implementation, which had been developed mostly for deep-water applications, showed significant limitations in simulating waves in short-fetch scenarios. The latter appeared to be the more significant source driving the observed biases.

As a consequence, it was decided that the GLW-NAM system would not include a distance-to-shoreline correction scheme, until the WAVEWATCH III model package included physics characterizations more adequate for dealing with short-fetch wave generation. The GLW-NAM system was, therefore, implemented using NAM 10-m-height winds provided at 1-h intervals, up to a 84-h forecast horizon.

(ii) GLW-NDFD system

The NDFD winds are a composite of collaborated gridded forecasts from the NWS field offices. The collaborated grids are stitched together at NOAA's Meteorological Development Laboratory (MDL) every hour, as a compilation of changes made by the field offices. Forecasters create forecast grids via a graphical editor using a multitude of numerical weather prediction guidance options (including ensemble and bias-corrected data sources). The end result is a wind forecast product generated through a man–machine mix, designed to optimize quality by leveraging the collective suite of numerical guidance, rather than committing a priori to a single model input.

NDFD wind forecasts are routinely produced at a minimum of 4 times daily with complete flexibility to update as conditions warrant. WAVEWATCH III uses a custom Great Lakes sector of the NDFD dataset designed to match the spatial grid used by NCEP's wave models, and include Canadian waters, which were initially left out of the operational NDFD products. NDFD winds are regularly available at 3-h intervals (as opposed to hourly NAM winds) at all forecast cycles, up to a 144-h time stamp. This allows the NDFD-forced GLW to be run beyond the current 84-h cutoff of the GLW-NAM, which has been limited by the availability of the underlying NAM winds. The GLW-NDFD, therefore, runs a 144-h cycle when NDFD winds are available, but is cutoff at 84 h when the NDFD winds are not found, and the system falls back to using NAM forcing. NDFD data are provided on a Lambert conformal grid with ~5-km resolution, which is interpolated onto the wave model grid.

2) ICE CONCENTRATIONS

NCEP's Great Lakes wave model systems use ice concentrations obtained directly from the NAM model output. The latter has a land–sea mask that is slightly different from that used in the GLW grid, so that corrections are made that also address inconsistencies in ice coverage close to land boundaries. Whenever offshore ice is present at a distance smaller than a given threshold, ice concentrations are extended from offshore to the land boundary.

3) AIR–SEA TEMPERATURE DIFFERENCES

WAVEWATCH III has the capability of adjusting input winds taking into account the stability of the near-surface environment. The latter can change significantly the growth rates of waves. Winds are adjusted if the differences between the near-surface air temperature and the sea surface temperature (SST) exceed a given threshold (for the default source terms, the threshold is 0.9°C). Steeper lapse rates result in stronger 10-m winds, while more stable lapse rates result in weaker winds than those determined with a neutral profile. The GLW-NAM system uses such a stability correction approach on the basis of differences between the 2-m air temperature and SST extracted from NAM model data. Corrections are not made within the GLW-NDFD system, since at the time of its operational implementation there were no available sources of real-time SST data matching the NDFD winds.

d. Operational forecast schedule

The GLW-NAM system's operational runs follow the usual operational scheduling at NCEP: 4 times per day, every 6 h, at the 0000, 0600, 1200, and 1800 UTC cycles. The GLW-NDFD system also runs four daily forecasts, but at the 0300, 0900, 1500, and 2100 UTC cycles. The 3-h lag relative to GLW-NAM, and to most other operational products at NCEP, is used to accommodate time requirements set by NWS field offices, and the later delivery–availability of NDFD winds. Computational costs are relatively small, both codes run using 10 nodes and 160 processors, taking on the order of 10 min to complete one forecast cycle. The GLW-NAM system runs a 6-h hindcast prior to actual forecasts, using atmospheric and ice fields from the NAM Data Assimilation System (NDAS). Therefore, it is initialized with spectral wave data at −6 h from the nowcast of a previous cycle. Since NDFD products focus only on forecast fields, the GLW-NDFD does not yet include a hindcast phase. Restart files used for initialization of a GLW-NDFD cycle include spectral wave data from the 6-h forecast of a previous cycle.

Gridded wave field outputs from NCEP's Great Lakes wave models are made available to the NWS field offices via the Advanced Weather Interactive Processing System (AWIPS), and to the general public via NCEP's ftp server (ftp://ftpprd.ncep.noaa.gov) and NOAA's

TABLE 1. List of acronyms used to describe wave models, related atmospheric forcing sources, and other relevant information for identifying wave model runs.

Acronym	Wave model	Atmospheric forcing	Source term
GLW-TC96-NAM	WAVEWATCH III	WRF North American Mesoscale Model	Tolman and Chalikov (1996)
GLW-TC96-NDFD	WAVEWATCH III	National Digital Forecast Database	Tolman and Chalikov (1996)
GLW-TC96-ANL	WAVEWATCH III	GLERL wind analysis	Tolman and Chalikov (1996)
GLW-A10-ANL	WAVEWATCH III	GLERL wind analysis	Ardhuin et al. (2010)
GLERL	Donelan–GLERL	NAM, NDFD	Schwab et al. (1984)
GLERL-ANL	Donelan–GLERL	GLERL wind analysis	Schwab et al. (1984)

National Operational Model Archive and Distribution System (http://nomads.ncdc.noaa.gov). Outputs include files with fields of wave parameters at the entire computational grids, and full frequency–direction wave energy density and derived wave parameters at selected output locations. Selected outputs and nonoperational data are also made available via NCEP/EMC's public web site (http://polar.ncep.noaa.gov/waves). These include map plots of field outputs, and point-output data in the form of graphics depicting wave spectra and spectral source terms, or bulletins listing the time evolution of integrated wave parameters. A full description of output parameters, file types, and sources of data is also provided on that web site.

e. *Recent upgrades to GLW-NAM and GLW-NDFD*

Other than changes to the forcing fields, NCEP's Great Lakes wave model systems have been upgraded in other aspects, including

- all WAVEWATCH III model codes were updated from version 2.22 to version 3.14;
- systems now include multigrid capabilities and are ready for planned upgrades to grids, including two-way nested nearshore domains;
- a more efficient algorithm for partitioning wave spectra into coherent coexisting wave systems is now available for generating partitioned data at all wet grid points;
- depth-induced breaking was added, as well as wetting and drying capabilities; and
- the format of operational output data files was changed from Gridded Binary format 1 (GRIB1) to format 2 (GRIB2).

4. Results: Performance of current systems

The two critical components of a wave forecast system that determine its skill are the model for surface winds and the underlying wave model itself. Skill is best measured through computing statistics relative to measured data. In the present study, validation of winds and waves is made on the basis of computing bulk statistics of modeled wind speed 10 m above mean sea level U_{10}, significant wave heights H_s, and peak periods T_p, relative to NDBC buoy measurements in the five Great Lakes: Lake Superior, Lake Michigan, Lake Huron, Lake Erie, and Lake Ontario. Figure 1 identifies the locations of the nine NDBC buoys selected for wave model validation, as well as a performance assessment made in the next sections.

Validation of surface wind fields focuses on wind speeds, since these have a dominant effect on wave model error. Wind directions are not considered as they tend to display random rather than systematic errors. In fact, a qualitative assessment of wind directions in the Great Lakes indicated that both NAM and NDFD products are in close agreement with observations, not demonstrating any significant trend or bias. The assessment of the 10-m height wind speeds is made at the 24- and 48-h forecast outputs.

Wave model validation is made with a focus on H_s, as this is the primary parameter used in operational forecasting. Attention is directed, in particular, to forecasts of storm wave heights, as this has been the major limitation of the current implementation of WAVEWATCH III in the Great Lakes (this issue is discussed in detail below). To provide a more complete view of model performance, an assessment of predictions of T_p relative to observations is also provided. Wave model outputs are assessed at the 0-h nowcast, as well as the 24- and 48-h forecast horizons.

Several acronyms describing wave model systems are used extensively throughout this and the next sections. To support a clearer view of what the acronyms represent, Table 1 is provided. It includes the acronym used, a description of the corresponding models, their particular configurations, and any other relevant information that allows the reader to clearly identify the used acronym. In the same context, to make a clear distinction between the current operational Great Lakes wave systems at NCEP, and a new version of the GLW system that is scheduled to become operational in 2013, the wave model descriptive acronyms used up to here are, henceforth, expanded to GLW-TC96-NAM and

GLW-TC96-NDFD. As indicated in Table 1, the abbreviation TC96 refers to the wave-growth physics parameterizations used in the Tolman and Chalikov (1996) source-term package.

The underlying validation statistics used for performance assessment are bias, standard deviation, scatter index, correlation coefficient, root-mean-square error, and slope of a linear regression forced through the origin. Goodness of fit and skill are visualized through the assistance of time series, scatterplots, quantile–quantile plots, and an adaptation of the Boer–Lambert–Taylor (BLT) diagram (Boer and Lambert 2001). The latter consists of a mirrored Taylor diagram, where the origin is translated to the right-hand side, providing more flexibility toward zooming into data clouds when points are tightly clustered, which was the case in the majority of the results presented here.

Validation of winds and waves was made using periods of NDBC buoy deployment—typically April–November—during 2008 and 2009. During 2008 the NDFD underwent upgrades that affected the homogeneity of the results and, thus, provided inconsistent validation statistics. Consequently, 2009 winds were considered more representative of NDFD's current wind product quality for the Great Lakes. Therefore, only results for that year were retained for model intercomparison. It was assumed that the selection of only 1 yr is representative of general wave model performance in terms of bulk quantities and typical conditions, on the basis that wave simulations from the GLW-TC96-NAM system for 2008 were very similar to those from simulations for 2009.

Buoy data were obtained directly from NDBC's online data archives. Buoy measurements of U_{10}, H_s, and T_p were filtered using a 3-h moving mean to reduce random sampling variability. Buoy and model data were collocated whenever the latter fell within a $\pm$1-h window centered at the buoy measurement time stamp. Examples of resulting collocated data and associated time series, scatterplots, and quantile–quantile plots are provided in triple-set plots (such as Fig. 4, for U_{10}, and Figs. 6 and 7, for H_s and T_p, respectively).

The validation procedure for model performance assessment included visual inspection of a complete ensemble of triple-set plots, as well as a comparison of tabulated values for validation statistics for all variables, at all NDBC buoy locations. In addition to an assessment of this site-based analysis, the joint performance at all locations was determined via visual inspection of the BLT diagrams shown later (see Figs. 5, 8, and 13). Model performance in predicting storm conditions was examined through bar plots, indicating the ratio of predicted to observed upper quantiles of U_{10} (Figs. 12 and 11) and H_s (Figs. 10 and 14).

BLT diagrams for U_{10}, H_s, and T_p provide a concise summary of validation statistics, simultaneously at all buoy locations. Inspection of the BLT diagrams below indicates that the statistical behavior of model results at most buoys is very similar, on a model-to-model basis – while models differ considerably, a same model performs similarly at all validation sites. Therefore, our description of validation statistics is summarized in the text by ranges of minimum–maximum values, and averages, where applicable. Since general statistical behavior at all buoys is summarized in BLT plots and upper-percentile bar plots, examples of triple-set plots are given at a single buoy location (45001), which qualitatively represents all of the other validation sites for illustration purposes.

a. *Wind and wave forecasts*

1) SURFACE WIND SPEEDS

Inspection of plots and tabulated validation statistics at the majority of selected NDBC buoy locations indicates that both NAM and NDFD overestimate the observed wind speeds by 5%–10% through all wind speed ranges, with larger overestimations observed in the lower and higher wind speed percentiles. NAM provides a slightly better description of wind speeds in the upper percentiles (above 95%). Both models present an accurate, nearly unbiased representation of surface wind speeds at the location of NDBC buoys 45006 (Lake Superior) and 45012 (Lake Ontario).

Total RMS errors, biases, scatter indices, and coefficients of determination (correlations squared) for modeled U_{10} are summarized in Table 2. NAM and NDFD surface winds present mean positive biases of 0.77 and 0.72 m s^{-1}, respectively. Table 2 shows larger values of the scatter index (SI), which reflect the relatively low mean observed wind speeds in the Great Lakes region (on the order of 5 m s^{-1}). Table 2 also reveals that NAM provides a reasonable–fair representation of the observed variance more than 64% (24 h) and 50% (48 h) of the time, on average, whereas NDFD has a poorer level of performance, with mean r^2 values of 56% (24 h) and 45% (48 h).

Although validation statistics for the NAM model are slightly better, particularly in its ability to represent observed surface wind speed patterns and total variability, the results above indicate that both the NAM and NDFD models have nearly identical levels of skill in terms of forecasting surface wind speeds in the 24–48-h ranges. The similar performance is not totally unexpected, since NDFD forecasts are heavily based on NAM model data. Conclusions are supported through visual inspection of the BLT diagrams shown in Fig. 5, and suggest that both NAM and NDFD provide surface winds that may be considered adequate for wave modeling applications.

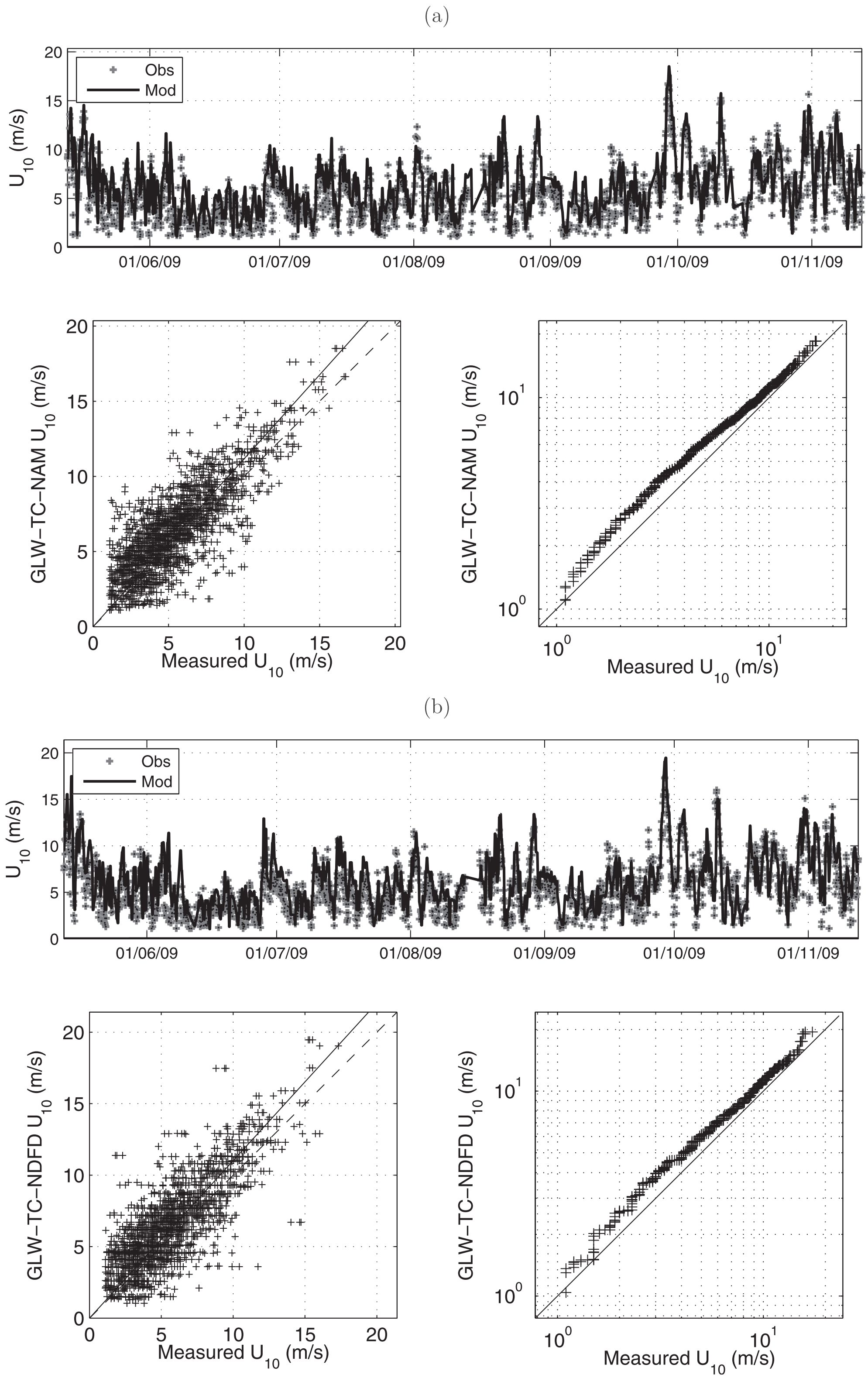


FIG. 4. Validation statistics of 24-h forecast surface wind speeds from the (a) NAM model and (b) NDFD, at the location of NDBC buoy 45001 (Lake Superior), during 2009. Panel groups show (top) time series, (bottom left) scatterplots, and (bottom right) quantile–quantile plots.

TABLE 2. Summarized validation statistics of wave model forecast data (24 and 48 h) relative to NDBC buoy measurements in the Great Lakes. Statistics for U_{10}, H_s, and T_p from indicated models are presented as ranges of minimum to maximum values at all buoy locations. Parameters tabulated are the root-mean-square error (ϵ_{RMS}), the bias, the scatter index (SI), and the coefficient of determination r^2 (U_{10} and H_s) or correlation coefficient r (T_p). A list of abbreviations is provided in Table 1.

		24 h		
U_{10}	ϵ_{RMS} (m s^{-1})	Bias (m s^{-1})	SI	r^2
NAM	[1.99, 2.25]	[0.25, 1.07]	[0.35, 0.41]	[0.53, 0.71]
NDFD	[2.07, 2.32]	[0.20, 1.00]	[0.37, 0.42]	[0.53, 0.60]
H_s	ϵ_{RMS} (m)	Bias (m)	SI	r^2
GLW-TC96-NAM	[0.23, 0.32]	[−0.04, 0.09]	[0.39, 0.52]	[0.72, 0.84]
GLW-TC96-NDFD	[0.26, 0.37]	[−0.06, 0.05]	[0.49, 0.63]	[0.64, 0.74]
GLERL	[0.25, 0.37]	[0.02, 0.13]	[0.48, 0.68]	[0.66, 0.76]
T_p	ϵ_{RMS} (s)	Bias (s)	SI	r
GLW-TC96-NAM	[0.82, 1.01]	[−0.75, −0.44]	[0.14, 0.17]	[0.75, 0.82]
GLW-TC96-NDFD	[0.89, 1.21]	[−0.87, −0.47]	[0.17, 0.19]	[0.66, 0.75]
GLERL	[0.91, 1.22]	[−0.69, −0.22]	[0.19, 0.26]	[0.53, 0.75]
		48 h		
U_{10}	ϵ_{RMS} (m s^{-1})	Bias (m s^{-1})	SI	r^2
NAM	[2.30, 2.59]	[0.56, 1.16]	[0.39, 0.48]	[0.46, 0.57]
NDFD	[2.28, 2.56]	[0.60, 1.00]	[0.40, 0.47]	[0.35, 0.54]
H_s	ϵ_{RMS} (m)	Bias (m)	SI	r^2
GLW-TC96-NAM	[0.28, 0.42]	[−0.01, 0.11]	[0.50, 0.64]	[0.62, 0.74]
GLW-TC96-NDFD	[0.30, 0.42]	[−0.08, 0.04]	[0.55, 0.72]	[0.52, 0.65]
GLERL	[0.30, 0.44]	[0.01, 0.11]	[0.53, 0.73]	[0.49, 0.71]
T_p	ϵ_{RMS} (s)	Bias (s)	SI	r
GLW-TC96-NAM	[0.91, 1.06]	[−0.70, −0.46]	[0.17, 0.19]	[0.65, 0.78]
GLW-TC96-NDFD	[1.04, 1.27]	[−0.92, −0.47]	[0.18, 0.21]	[0.59, 0.68]
GLERL	[1.10, 1.44]	[−0.89, −0.30]	[0.23, 0.26]	[0.50, 0.72]

2) SIGNIFICANT WAVE HEIGHTS

Forecasts of significant wave heights H_s at the 24- and 48-h horizons indicate a general tendency of NCEP's Great Lakes operational wave models to consistently overestimate smaller measured H_s, generated either during weaker wind speed periods or in the earlier storm-generation stages, and to underestimate larger observed values associated with the mature stages of more intense storms. This is evident through inspections

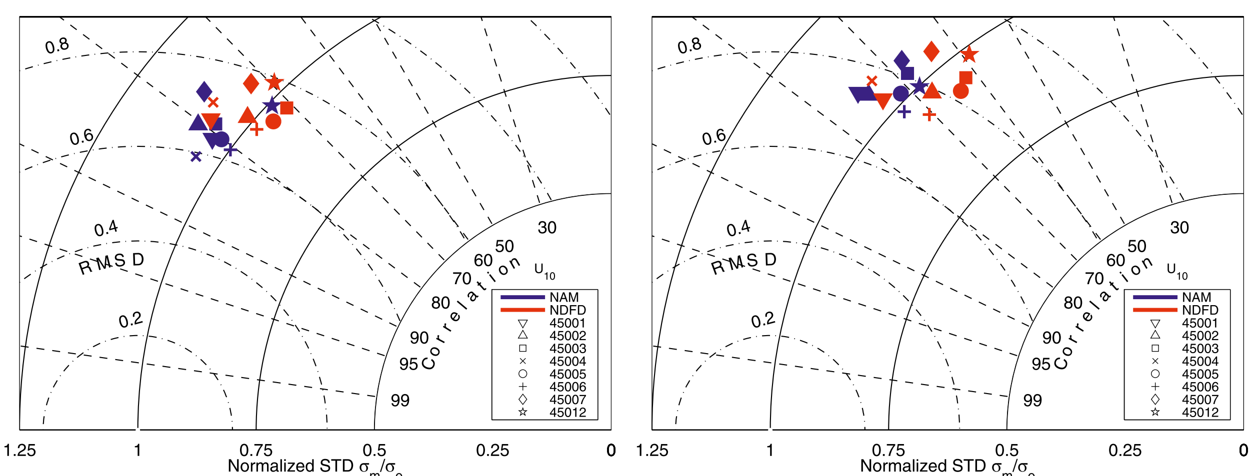


FIG. 5. BLT diagrams summarizing the validation of NAM (blue) and NDFD (red) surface wind forecasts at (left) 24 and (right) 48 h, relative to NDBC buoys in the Great Lakes. Correlation levels in percentage points appear as radial lines emanating from the bottom right-hand corner, standard deviations normalized with buoy values are circles centered at the bottom right-hand corner, and root-mean-square deviations are circles centered at the bottom left-hand corner.

made of triple-set plots, such as in Fig. 6, at most NDBC buoy locations, and is in contrast to the corresponding trends identified for surface wind speeds, which indicate that the wave model may not be accurately representing the generation and development properties of the observed wave climate. This limitation will be explored more extensively in forthcoming sections.

Validation statistics for H_s are shown in Table 2. Data are summarized into ranges of values (minimum to maximum) at all NDBC buoys. RMS errors are similar for GLW-TC96-NAM and GLW-TC96-NDFD, with the former presenting slightly better scores. On average, GLW-TC96-NAM has a slightly positive trend, with 0.02 m (24 h) and 0.04 m (48 h) mean biases, whereas GLW-TC96-NDFD presents a slightly negative trend, with −0.01 m (24 h) and −0.03 m (48 h) mean biases. Since the Great Lakes wave climate is dominated by relatively small waves (mean H_s values range from 0.5 to 0.8 m), tabulated scatter indices were large. Coefficients of determination reveal that the GLW-TC96-NAM system provides reasonably accurate representations of the observed variance more than 80% (24 h) and 68% (48 h) of the time, on average, and the GLW-TC96-NDFD system performs less accurately with mean r^2 values of 69% (24 h) and 58% (48 h).

The strong similarity between NAM and NDFD in their forecasts of wind speeds (e.g., Table 2) is reflected in most validation statistics for wave heights simulated by NCEP's Great Lakes systems. This is particularly true in terms of biases and random errors. The differences are more significant in terms of their differential ability in representing wave-height patterns and the total observed variance of the wave heights at selected NDBC buoys. The GLW-TC96-NAM model, forced with NAM winds, has a noticeably better degree of performance. Whereas this has significance for practical applications, it may also be a result of deficiencies in the slightly stronger NAM wind fields compensating for limitations in wave model parameterizations of wave-generation physics.

The two most striking features of the validation of H_s forecasts are the consistent overestimation of smaller observed wave heights, and the opposite trend of underestimating larger measured H_s values. Overestimation of smaller H_s is consistent with a systematic high bias in both NAM and NDFD surface winds. This may be associated with improper treatment of land–sea transition effects, as discussed in section 3c, and poor representation of the atmospheric boundary layer over the lakes. Solutions to these problems require improvements in NAM and NDFD, which are currently being discussed with NCEP's mesoscale modeling group. Further improvements may be obtained via a data assimilation scheme, operating in tandem with a wave ensemble system for the Great Lakes, both under development at NCEP. The latter could, furthermore, allow exploring statistical optimization via ensemble Kalman filtering (Kalnay 2002), and the reduction of H_s biases via new techniques, such as the approach proposed in Galanis et al. (2009).

The underestimation of larger observed H_s values by NCEPS' Great Lakes models, in a range where corresponding NAM and NDFD surface winds slightly overestimate the observations, suggests a systematic bias related to the wave model behavior during more intense storms. This problem is also associated with limitations in the choice of wave-growth parameterizations used in NCEP's current Great Lakes operational wave modeling systems, and will be explored in greater detail below.

3) PEAK PERIODS

Predictions of peak periods T_p from both of NCEP's Great Lakes wave models systematically underestimate the observed values, particularly at the smaller T_p range. This is illustrated in Fig. 7. As with the case of H_s, the GLW-TC96-NAM system provides consistently better predictions of T_p. On average, both NCEP wave models have a consistent negative trend in predicting T_p. Mean biases for GLW-TC96-NAM were −0.58 s (24 h) and −0.59 s (48 h), whereas for GLW-TC96-NDFD they were −0.70 s (24 h) and −0.81 s (48 h). NAM-based GLW forecasts have significantly higher correlation with observations than GLW-TC96-NDFD, which suggests a better level of performance for the NAM model winds, relative to NDFD data, in capturing the spatial coverage, as well as the intensity of observed surface winds. A summarized view of the wave model validation results for both H_s and T_p predicted by NCEP's Great Lakes systems is provided in the BLT diagrams shown in Fig. 8. Validation statistics are also summarized in Table 2.

In combination with the discrepancies observed in the previous section regarding predictions of H_s, the results for T_p suggest that the parameterization of wave development currently used in NCEP's operational Great Lakes implementations of the WAVEWATCH III model may have limited application for modeling wave development in geographically restricted basins. This idea will be explored in greater detail in section 5.

4) PERFORMANCE RELATIVE TO GLERL FORECASTS

The semioperational GLERL wave modeling system has been successfully used in forecast guidance in the Great Lakes region for more than 25 yr, providing a solid reference for evaluating the forecasting skill of

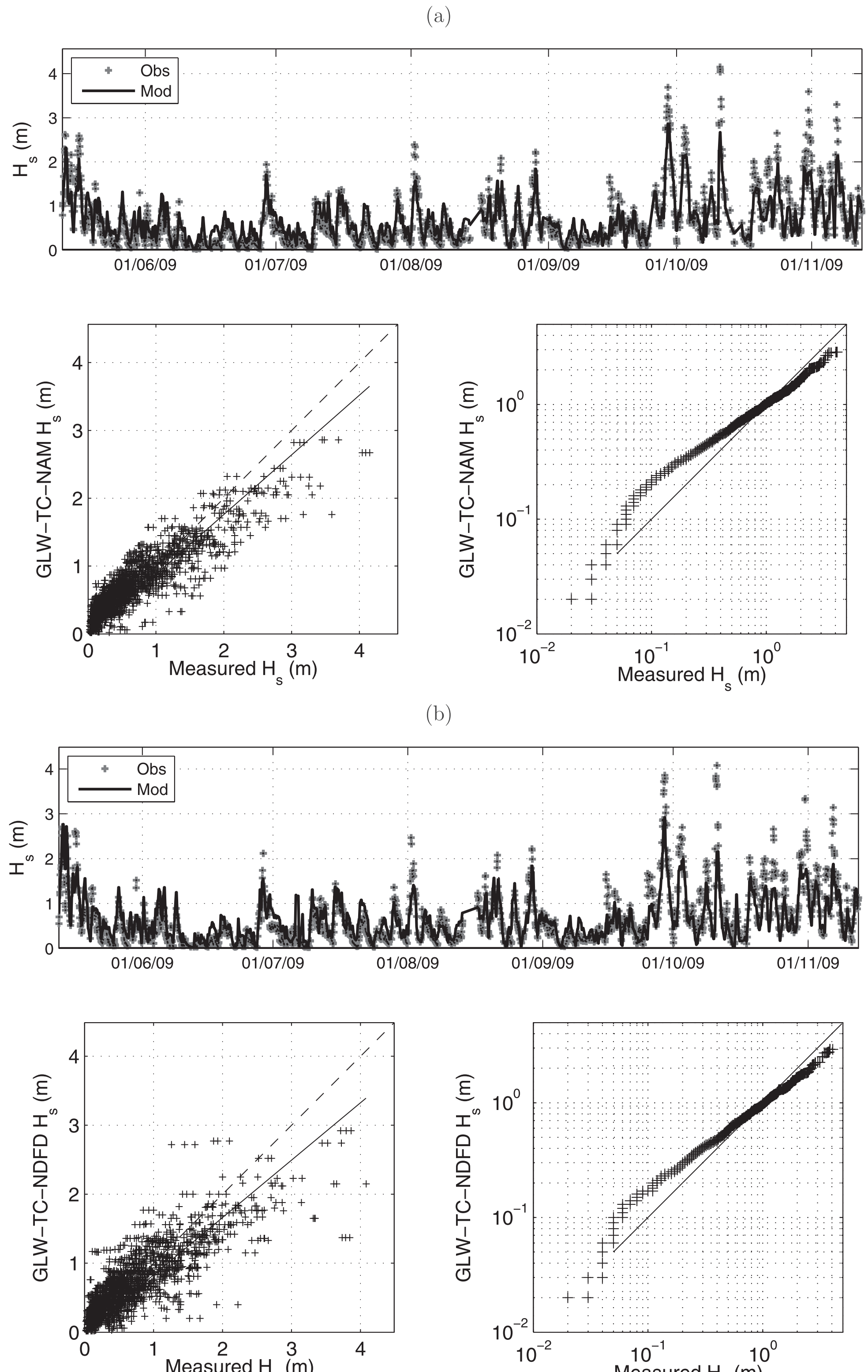
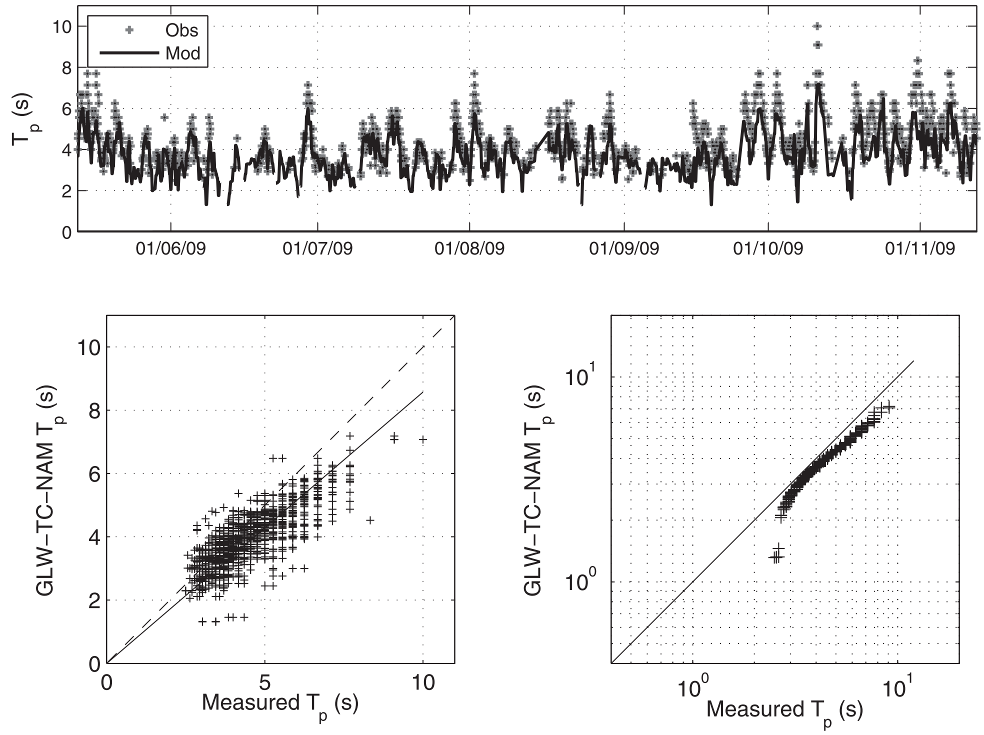


FIG. 6. Validation statistics of wave heights H_s from (a) GLW-TC96-NAM and (b) GLW-TC96-NDFD 24-h forecasts during 2009, at the location of NDBC buoy 45001 (Lake Superior). Panel groups show (top) time series, (bottom left) scatterplots, and (bottom right) quantile–quantile plots.

(a)



(b)

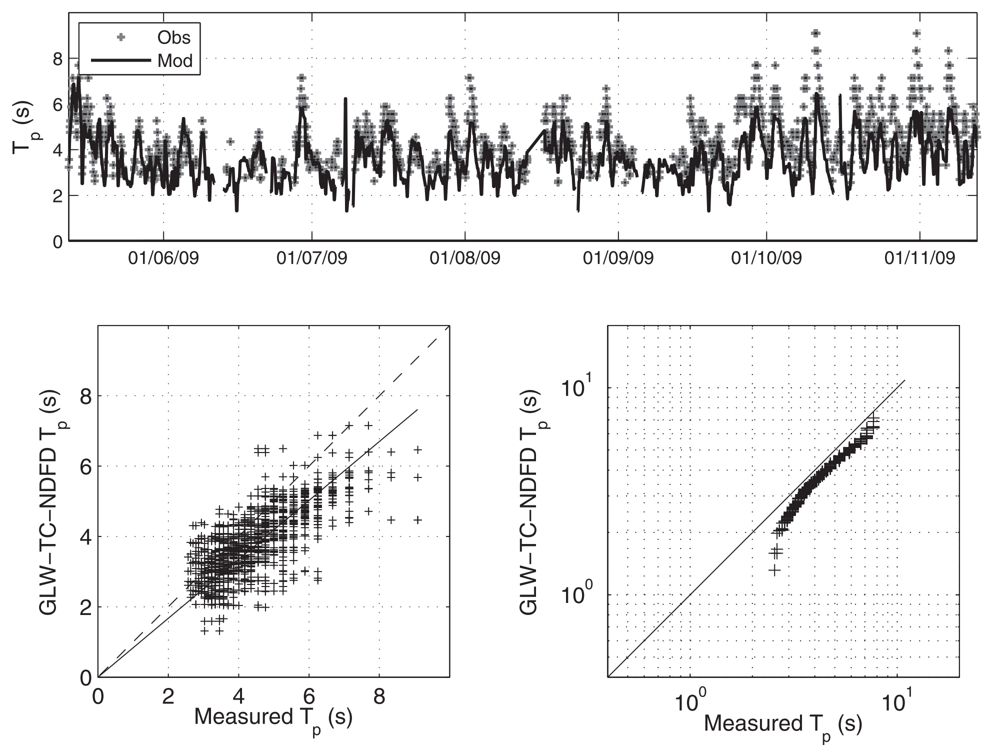


FIG. 7. As in Fig. 6, but for peak periods T_p.

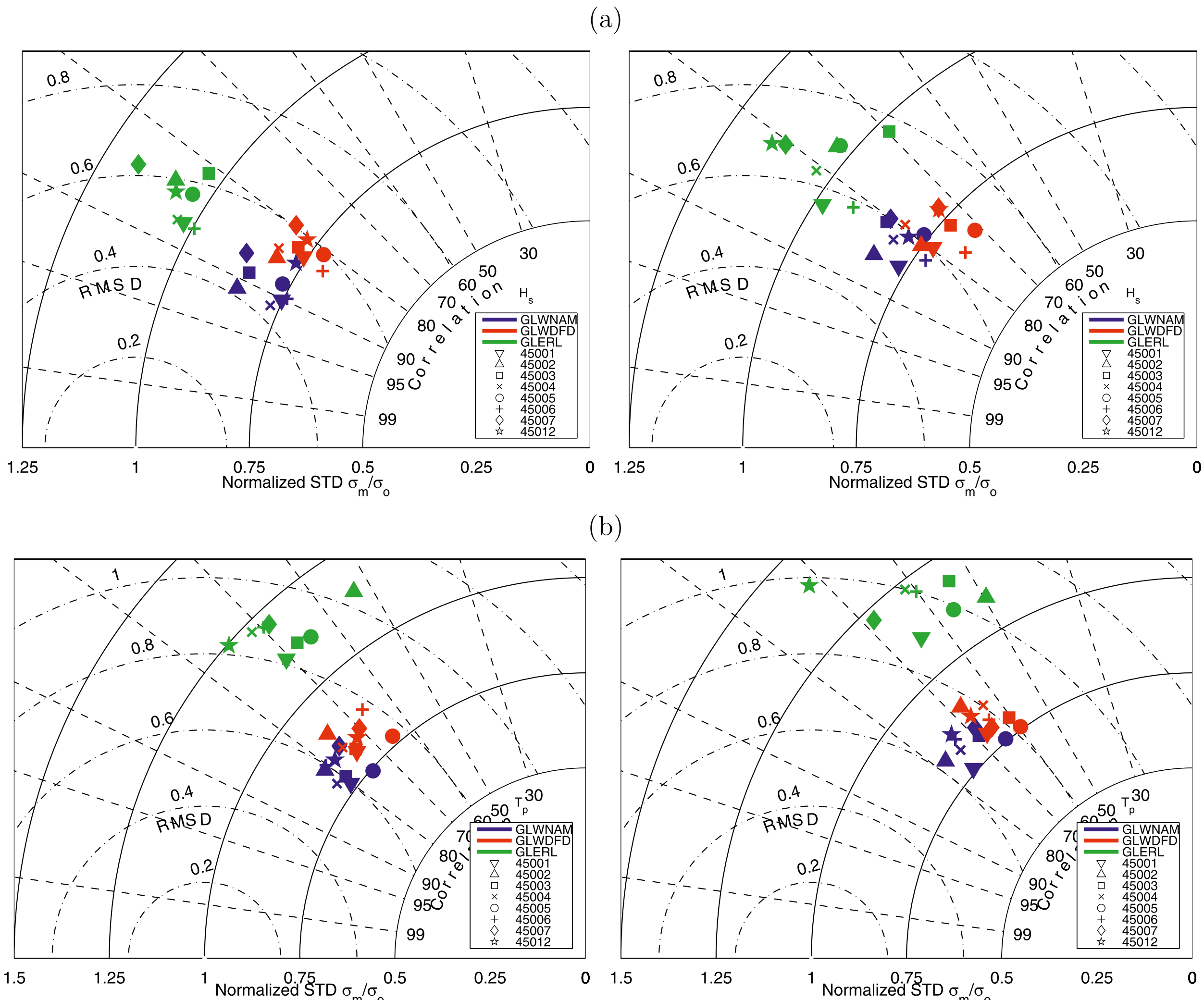


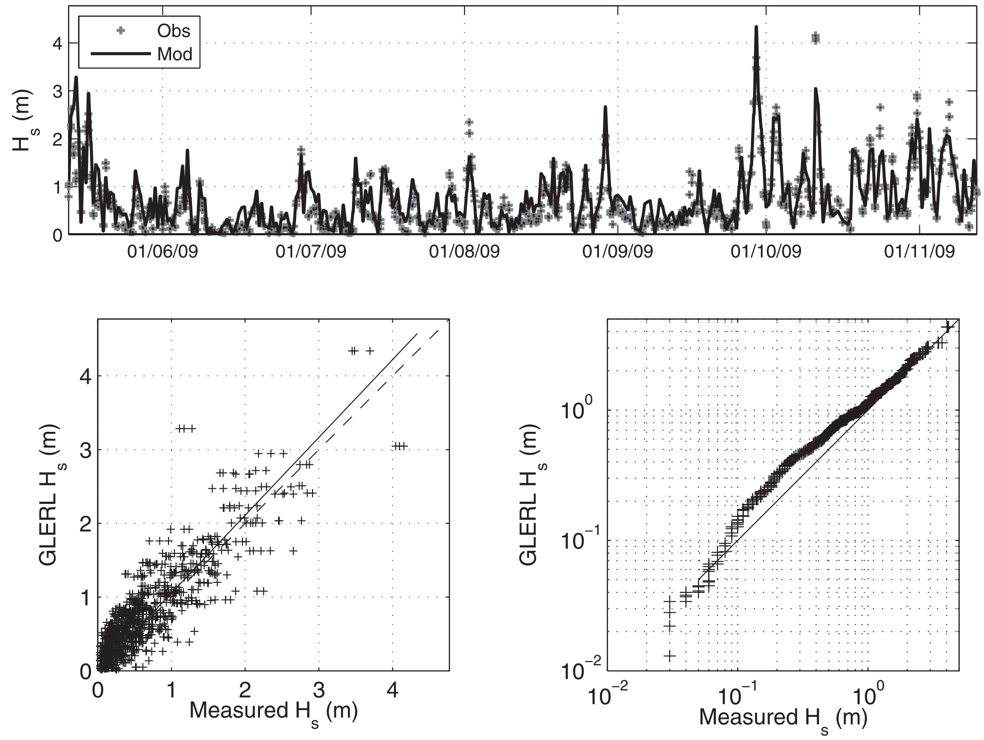
FIG. 8. BLT diagrams summarizing the validation of GLW-TC96-NAM (blue) and GLW-TC96-NDFD (red) systems relative to NDBC buoys in the Great Lakes, for (a) wave height H_s and (b) peak periods T_p. See Fig. 5 for a description of the BLT structure. Green markers indicate validation statistics for the GLERL wave model, referred to in section 4b.

NCEP's Great Lakes wave model systems. A brief description of the GLERL wave model is provided in section 2b. GLERL wave forecasts are run primarily with NDFD winds and NAM model data, whenever the former are not available. Therefore, forcing winds are nearly identical to those used to force the GLW-TC96-NDFD system, and a separate validation of atmospheric forcing fields is not necessary.

A brief examination of GLERL predictions of H_s and T_p is made, providing a basis for comparison relative to the forecast skill of NCEP's operational Great Lakes models. Examples of collocated H_s and T_p data from the GLERL wave system, and associated time series, scatterplots, and quantile–quantile plots, are provided in Fig. 9, for NDBC buoy 45001. Table 2 summarizes the ranges of validation statistics relative to all nine NDBC buoys used presently for model validation. In addition to the tabulated statistics, it was found that the average trend of GLERL H_s predictions was positive, with 0.09-m (24 h) and 0.07-m (48 h) mean biases. Mean coefficients of determination indicate the GLERL wave model captures the observed variances of H_s 72% (24 h) and 62% (48 h) of the time. Mean GLERL T_p forecast biases were −0.48 s (24 h) and −0.59 s (48 h), revealing a negative trend.

Both NAM- and NDFD-driven wave models at NCEP outperform the GLERL in most bulk validation statistics for H_s. NCEP's GLW-TC96-NAM has a clearly superior level of performance relative to both GLW-TC96-NDFD and GLERL, reflecting the better

(a)



(b)

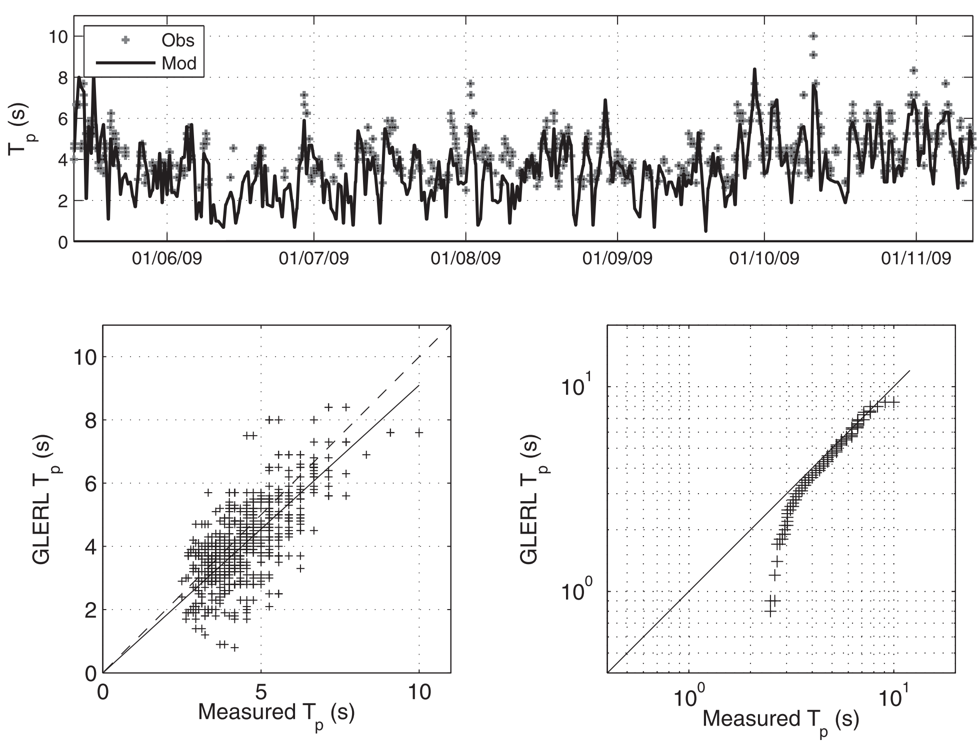


FIG. 9. Validation statistics for (a) wave height H_s and (b) peak periods T_p from the GLERL model's 24-h forecasts in 2009, at the location of NDBC buoy 45001 (Lake Superior). Panel groups show (top) time series, (bottom left) scatterplots, and (bottom right) quantile–quantile plots.

performance of the NAM surface winds relative to the NDFD wind product. One possible reason for this superior performance is the fact that hourly NAM winds are used, whereas NDFD data are made available only at 3-hourly intervals. The same may be said about T_p, where the two NCEP wave models outperform the GLERL model in all validation parameters except biases. The results presented above show that the NCEP wave model systems provide Great Lakes wave forecasts that may be considered at least as good as, and generally better than, forecasts issued by GLERL. It should be stressed, however, that such assessment is valid only for the bulk of the sea states observed in the Great Lakes, which generally consist of calm conditions, with relatively small waves. This is very important for planning and determining weather windows in several applications.

Storm events, with large significant waves that can reach several meters in the Great Lakes, are of a more crucial importance to operational weather guidance during critical weather periods. Large waves pose risks to navigation and are associated with incidents that result in the loss of property and lives. A bulk parameter that provides a first hint of how well a wave model behaves in predicting more extreme values is the standard deviation, as it is very sensitive to the presence (or absence) of larger values.

Buoy-normalized standard deviations for H_s from the GLW-TC96-NAM system range from [0.74, 0.87] (24 h) and [0.73, 0.84] (48 h), averaging 0.80 for both the 24- and 48-h forecast horizons. For GLW-TC96-NDFD, ranges are [0.71, 0.81] (24 h) and [0.67, 0.81] (48 h), with means of 0.77 and 0.74, respectively. Normalized standard deviation ranges for the GLERL wave model were [1.00, 1.17] (24 h) and [0.92, 1.15] (48 h), with means equal to 1.06 and 1.03, respectively. Values close to unity indicate better skill. Estimated ranges of normalized standard deviations reveal that the current operational Great Lakes wave models at NCEP consistently underestimate the measured variance at all NDBC buoys. The GLERL wave model, on the other hand, generally overestimates the measured data. The latter, however, provides a much closer degree of agreement with the observations.

The 95th and 99th percentile H_s values (H_s^{95} and H_s^{99}) from modeled and measured data provide an even closer view of the wave model performance in terms of extreme wave predictions. Figure 10 shows plots of H_s^{95} and H_s^{99} from NCEP and GLERL wave models at each NDBC buoy location. Again, normalization by the measured value means that values close to one indicate better performance. Figure 10 clearly shows that both NCEP GLW wave model systems consistently underestimate the higher measured H_s quantiles. In contrast, the GLERL model provides a closer agreement to the observations, in spite of the fact it shows a tendency toward slightly overestimating the highest measured waves.

Figure 11 shows the 95th and 99th U_{10} percentiles from NAM and NDFD, normalized with NDBC surface wind measurements. Both atmospheric model winds provide reasonably good agreement with the observations (values close to one at most buoy locations). Because GLERL wave forecasts closely represent larger observed waves, as they use the same source of wind forcing as the GLW-TC96-NDFD, the wind data do not provide an indisputable mechanism that explains the discrepancies found in the forecasts of larger storm waves, which are generally underestimated by the Great Lakes wave models currently in operations at NCEP. Such discrepancies are examined further, through an intercomparison of wave model skill made via forcing the NCEP and GLERL wave model systems with high quality surface wind analyses for the Great Lakes. This allows us to investigate in a more conclusive manner if differences in the treatment of forcing winds may be ruled out as a cause for the observed discrepancies.

b. *Assessment of wave model skill*

High-resolution surface wind analyses are generated routinely at GLERL and at NOAA's National Ocean Service (NOS), as part the Great Lakes Operational Forecast System (GLOFS). These analyses are currently the most accurate representation of the observed overlake wind fields, and are used to force semioperational hydrodynamic models at GLERL and operational services at NOS. More detailed descriptions of the GLERL–NOS wind analyses and associated validation studies are presented in Chu et al. (2011) and Liu et al. (1984).

A summary of validation statistics associated with the current study is presented in Table 3, which confirms the high quality of GLERL wind analyses in mean conditions. Deviations from observations are a result of adjustments made to analyzed winds to remove stability effects from measured data assimilated into the wind analyses. An illustration of how well the GLERL wind product represents the upper measured wind speed percentiles is provided in Fig. 12. The figure clearly shows that GLERL surface wind analyses provide an accurate representation of the measured upper wind speed percentiles as well and, it may be assumed, are appropriate for modeling the regional wave climate, including more severe sea state events.

The availability of accurate surface wind data provides the opportunity to investigate the skill of the wave models, focusing on the effect of their numerics and

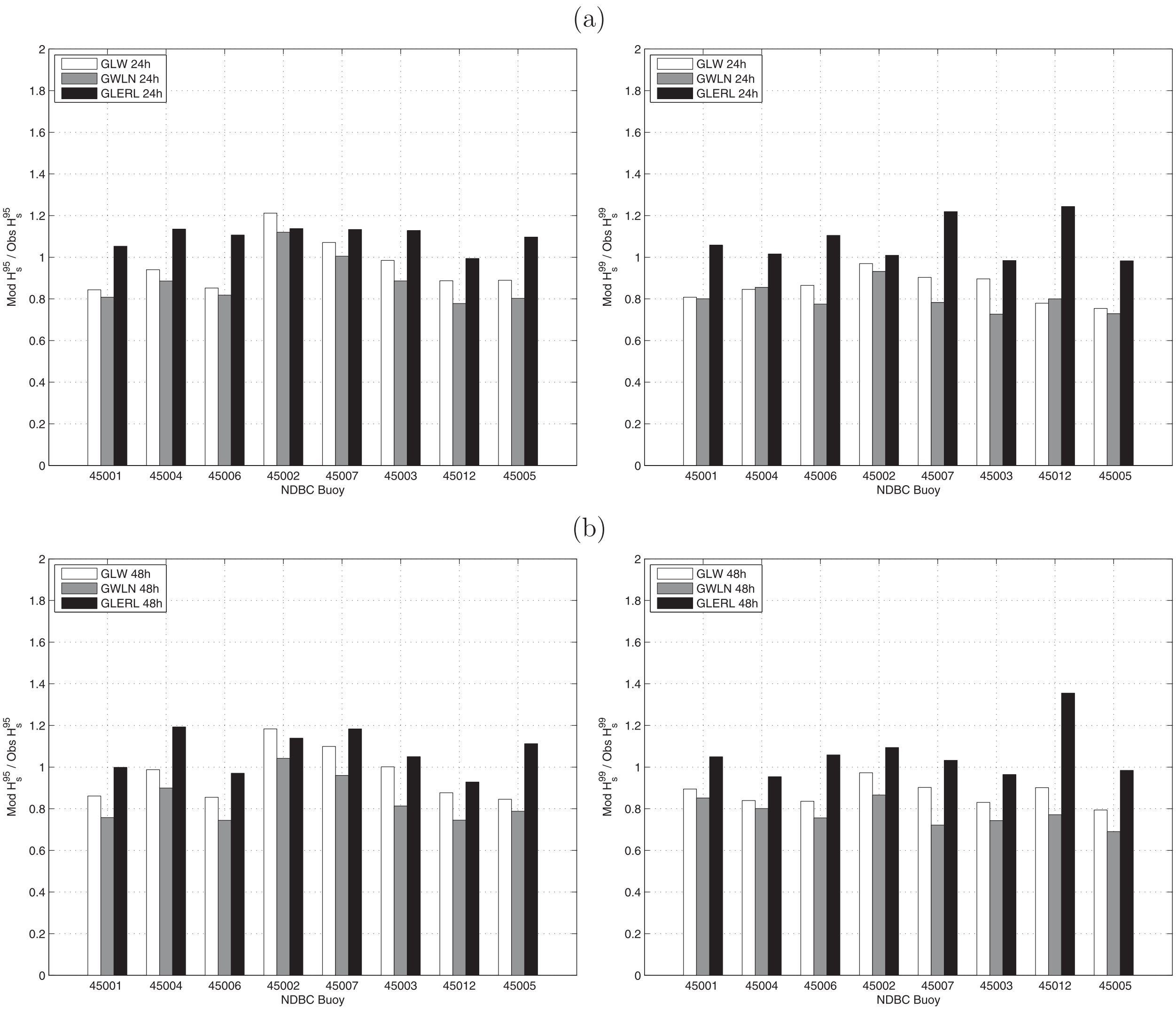


FIG. 10. Bar graphs comparing normalized (left) 95th and (right) 99th H_s percentiles at selected NDBC buoy locations: (a) 24- and (b) 48-h forecasts. Model H_s quantiles are normalized by the observed quantile-level H_s at each buoy location.

parameterizations of wave-development physics. For relatively small bodies of water such as in the Great Lakes, differences between the GLERL wave model and WAVEWATCH III numerics are assumed to be not significant. Consequently, the more significant distinctions in wave model skill will be the result of the differences in their parameterizations of wave growth (source terms).

Bulk validation statistics were computed for model runs made with NCEP's GLW and the GLERL wave systems, forced with GLERL wind analyses. As per Table 1, these two wave model configurations are henceforth referred to as GLW-TC96-ANL and GLERL-ANL, respectively. Table 3 summarizes the resulting validation statistics. An illustration of the relative performance of wave model hindcasts is provided below (see Figs. 15 and 16). Bulk statistics for wave hindcasts confirm the assessments of wave forecasts: the wave model skill of NCEP's wave model generally outperforms GLERL-ANL, for the more typical, calm sea states observed in the Great Lakes.

Examination of the BLT plots shown in Fig. 13 reveals a few other subtleties. BLT plots for T_p indicate that GLW-TC96-ANL provides predictions that are generally more consistent with measurements than GLERL-ANL for all validation statistics. For H_s, the BLT plots suggest that although GLW-TC96-ANL has slightly better scores in terms of RMS error and correlation, the skill is significantly poorer in terms of standard deviations, whereas GLERL-ANL standard deviations are in close agreement with the measurements.

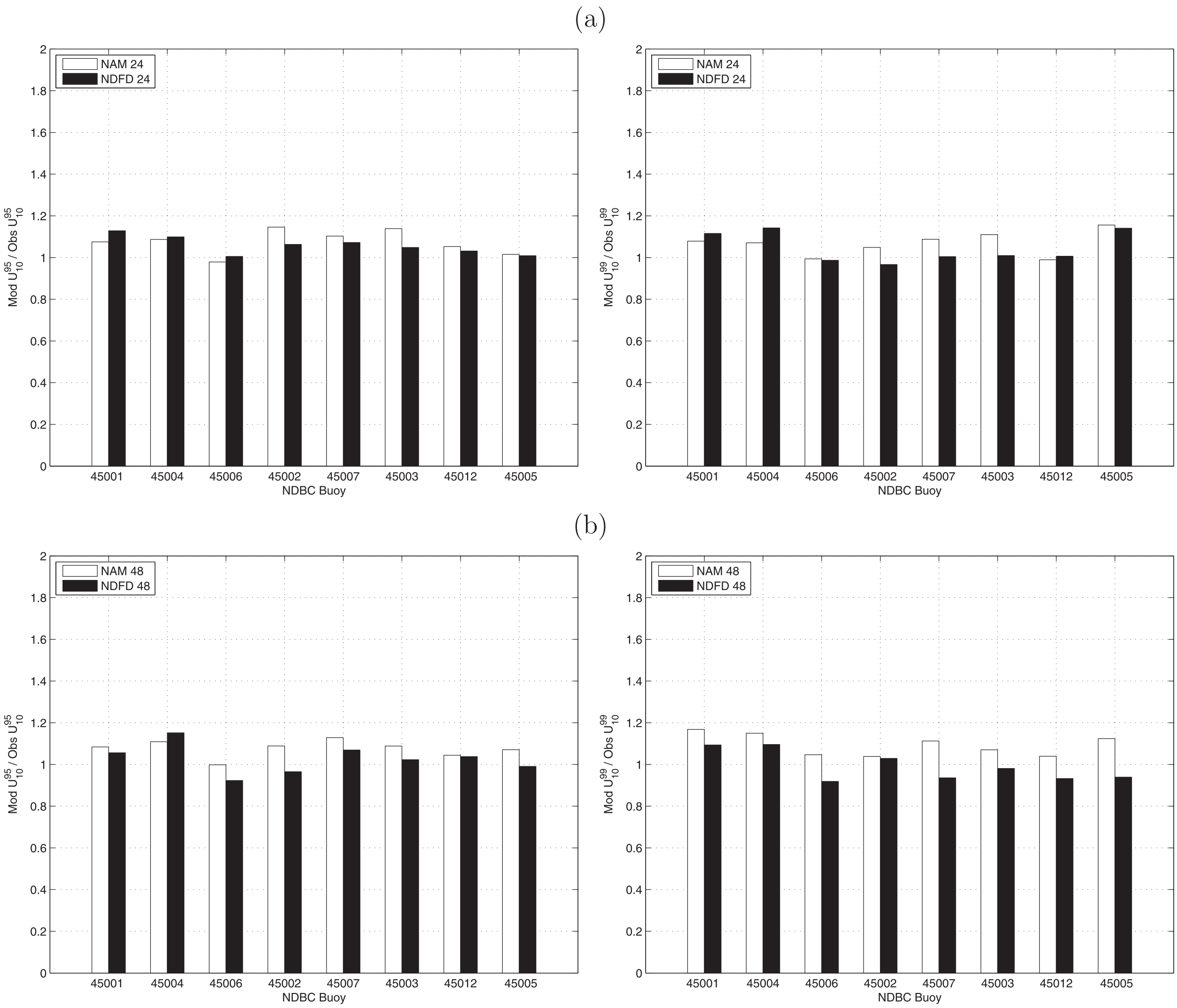


FIG. 11. As in Fig. 10, but for U_{10}. Winds speeds from NAM and NDFD are shown.

Normalized standard deviations for hindcast H_s from GLW-TC96-ANL were in the range [0.73, 0.86], with 0.81 mean value, whereas GLERL-ANL wave height hindcasts had normalized standard deviations in the range [0.97, 1.09], with a mean value of 1.03. Figure 14 shows the skill of GLW-TC96-ANL and GLERL-ANL in predicting the upper percentiles (95% and 99%) of H_s. Again, most hindcast H_s results from NCEP's GLW

TABLE 3. Summarized validation statistics of wave model hindcast data relative to NDBC buoy measurements in the Great Lakes. See Table 2 for a description of table structure and statistical parameters, and Table 1 for a list of acronyms.

U_{10}	ϵ_{RMS} (m s^{-1})	Bias (m s^{-1})	SI	r^2
GLERL-ANL	[1.05, 1.15]	[0.47, 0.68]	[0.16, 0.19]	[0.94, 0.95]
H_s	ϵ_{RMS} (m)	Bias (m)	SI	r^2
GLW-TC96-ANL	[0.18, 0.27]	[−0.08, 0.02]	[0.34, 0.44]	[0.88, 0.92]
GLERL-ANL	[0.18, 0.23]	[0.05, 0.10]	[0.29, 0.40]	[0.85, 0.90]
GLW-A10-ANL	[0.14, 0.20]	[0.02, 0.10]	[0.23, 0.32]	[0.90, 0.94]
T_p	ϵ_{RMS} (s)	Bias (s)	SI	r
GLW-TC96-ANL	[0.66, 0.78]	[−0.45, −0.18]	[0.13, 0.16]	[0.78, 0.88]
GLERL-ANL	[0.57, 1.18]	[−0.61, −0.23]	[0.13, 0.23]	[0.59, 0.85]
GLW-A10-ANL	[0.49, 0.69]	[−0.28, 0.00]	[0.12, 0.16]	[0.78, 0.97]

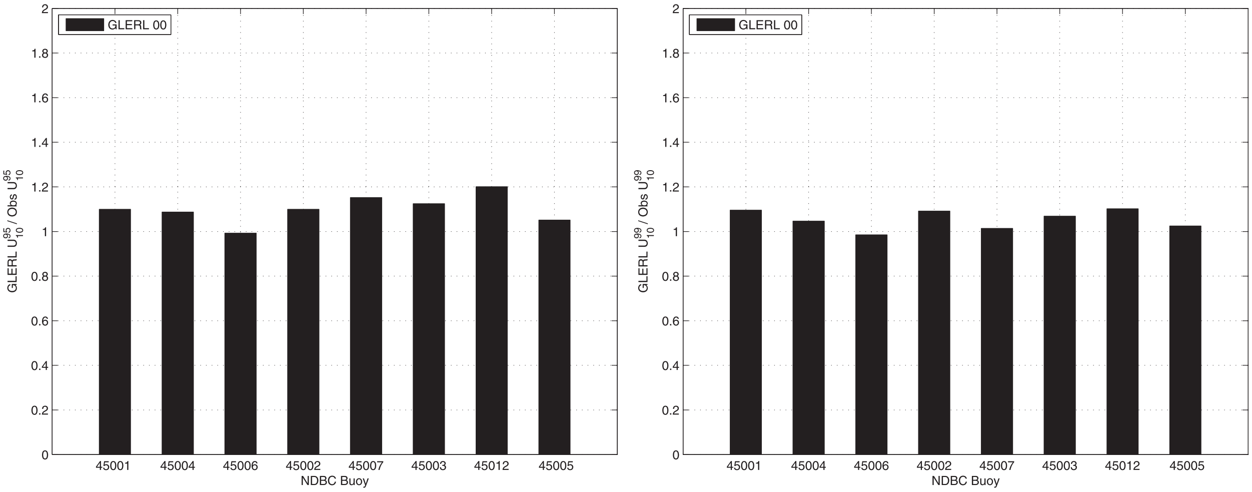


FIG. 12. As in Fig. 10, but for U_{10}. Model U_{10} quantiles are normalized by the observed quantile-level U_{10} at each buoy location. Winds speeds from the GLERL surface wind analyses are shown.

model underestimate by more than 20% the measured upper percentiles, while GLERL-ANL hindcasts provide a more accurate representation of the highest measured waves. The poorer skill of the NCEP wave model system in terms of hindcasting more severe wave heights mirrors the relative performance of NCEP and GLERL wave model forecasts presented in section 4.

Validation of Great Lakes wave hindcasts generated with NCEP and GLERL wave model systems using identical wind forcing (GLERL surface wind analyses) supports the hypothesis that the discrepancies in their relative levels of skill in predicting severe sea states stems from differences in their treatment of wave growth. These findings, and the results of studies reported elsewhere (e.g., Ardhuin et al. 2007; Chao and Tolman 2010), fueled significant efforts toward investigating the impact of improved source terms on the performance of the WAVEWATCH III model. Successful outcomes of such efforts have allowed the development of an experimental Great Lakes wave prediction system at NCEP, with improved skill in predicting severe sea states. Relevant outcomes from this initiative are discussed next.

5. Discussion: Improved wave model physics

Current operational implementations of the WAVEWATCH III models at NCEP, including the

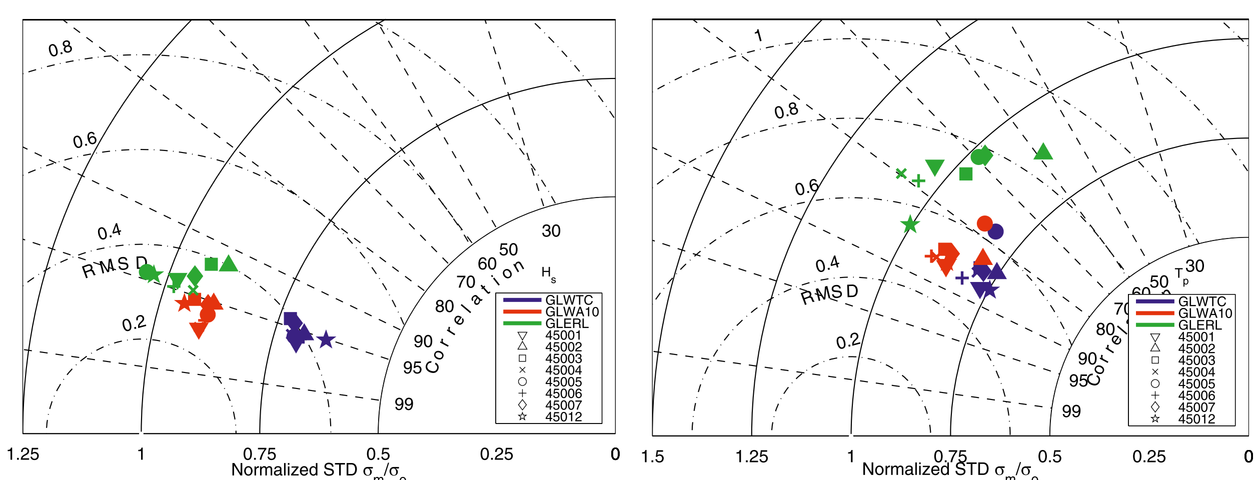


FIG. 13. BLT diagrams summarizing the comparative skill assessment of the current operational GLW-TC96-ANL system (blue), the upgraded experimental GLW-A10-ANL system (red), and the GLERL-ANL wave model (green), relative to NDBC buoys in the Great Lakes, for (left) wave height H_s and (right) peak periods T_p. See Fig. 5 for a description of the BLT structure. All model runs are made with GLERL surface wind analyses for 2009.

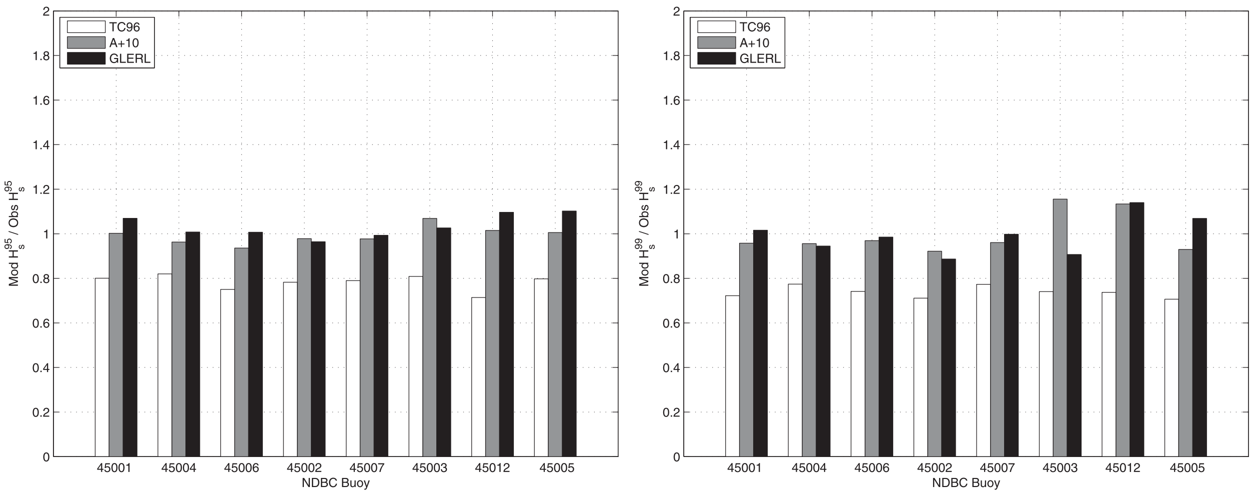


FIG. 14. Bar graphs comparing normalized (left) 95th and (right) 99th H_s percentiles at selected NDBC buoy locations. Model H_s quantiles are normalized by the observed quantile-level H_s at each buoy location. Wave heights from GLW-ANL hindcasts runs using TC96 and A10 (labeled as A + 10) source terms are compared to hindcasts generated by the GLERL-ANL wave forecasting system.

Great Lakes wave forecasting systems, use the source terms of Tolman and Chalikov (1996, hereafter TC96). The TC96 parameterizations of wave growth and dissipation were developed for wave modeling on oceanic scales, without particular consideration for enclosed basins, areas with land constraints, or more severe forcing scenarios. It is therefore not surprising that the TC96 package has shown limitations in simulating waves under short/slanted fetches (Ardhuin et al. 2007), as well as in predicting the early growth stages of waves in rapidly changing winds (Chao and Tolman 2010).

Results presented in section 4 above confirm the general findings of these investigations. They also indicate that a model with a physics parameterization that addresses wave growth in short-fetch environments, such as the GLERL wave model, has the potential to provide better predictions of storm waves in the Great Lakes. This hypothesis is tested through using an improved physics package coded into the WAVEWATCH III model, developed for rapid growth under local wind-wave generation. A positive outcome would bridge the gap between the good performance of NCEP's Great Lakes wave models in typical wave generation conditions, and their poor skill in predicting more severe sea states.

The development of improved parameterizations of wave growth for numerical wave modeling is the main focus of the ongoing project "Improving wind-wave predictions: Global to regional scales," within the National Oceanographic Partnership Program (NOPP), sponsored by the Office of Naval Research, the Bureau of Ocean Energy Management, USACE, and NOAA (Tolman et al. 2011). The project has allowed the integration of new findings in both theoretical and empirical fields, which have been translated into new source terms that have shown promising results in representing more accurately wave growth and decay. One such parameterization, proposed in Ardhuin et al. (2010, hereafter A10), has been extensively tested at NCEP, and has passed the grade for replacing the TC96 source terms in NCEP's operational wave systems. In fact, the A10 package was implemented in NCEP's global operational wave model system in May 2012.

The source term package proposed by A10 closely follows the work of Banner and Morison (2010). Namely, the wind input source term is a modification of the parameterization proposed in Janssen (1991), with adjustments following Bidlot et al. (2007) and Chen and Belcher (2000), and an ad hoc reduction of the friction velocity u_* that allows balancing input with dissipation rates prescribed by new dissipation source terms accounting for self-breaking waves ("whitecapping"), swell dissipation, interactions of long breakers with short waves, and wave-turbulence interaction.

For self-breaking waves, the A10 package available in WAVEWATCH III offers two different formulations. In the first, which is currently used in NCEP's operational global wave model, wave-breaking dissipation rates are only active for spectral components with saturation values exceeding a threshold, representing a level at which wave breaking is observed. Such a saturation-based framework was initially proposed within a wave modeling context by Alves and Banner (2003), and further developed by Banner and Morison (2010). The second approach, selected at NCEP for the Great Lakes wave models, follows the work of Filipot and Ardhuin (2012): wave-breaking dissipation rates are computed through a parameterization for the probability density of breaking waves. The selection of the latter approach for the Great Lakes was based on a preliminary investigation performed at NCEP, which indicated a significantly better level of performance relative to the original saturation-based dissipation term described by A10.

The parameterization of swell dissipation proposed by A10 is computed through a combination of a linear viscous boundary layer term and a nonlinear turbulent boundary layer expression. Swell dissipation is further tuned via a dependency on wind speed and direction, which makes opposing swells lose more energy than following swells. Short-wave dissipation due to long wave breaking is computed through a formulation that assumes that a larger-scale breaker instantly dissipates all shorter-scale waves, by a factor proportional to the rate at which shorter waves are overtaken by larger breakers.

This section presents results of wave hindcasts generated by NCEP's WAVEWATCH III implementation for the Great Lakes, made with the A10 source terms, and using the GLERL surface wind analyses for 2009 described above. Following Table 1, model hindcasts made with this configuration will be henceforth referred to by the abbreviation GLW-A10-ANL. Figures 15 and 16 illustrate the comparison of GLW-A10-ANL H_s and T_p with measurements made at NDBC buoy 45001. Validation statistics are summarized in Table 3. The average trend of H_s hindcasts was positive, with a 0.06-m mean bias. Mean coefficients of determination indicate that the new physics package captures the observed variance 92% of the time.

In all cases, and for both H_s and T_p, hindcast data from the GLW-A10-ANL runs provided the best bulk statistics in the majority of buoy locations, leading to a significant improvement in the predictions of typical sea states, relative to all other model configurations considered above, including the GLERL wave model. Predictions of larger, storm H_s from NCEP's upgraded Great Lakes wave model were also significantly improved via using the A10 physics package. This is indicated by higher values of normalized standard deviations ranging from [0.90, 0.95], and supported through inspection of the normalized upper percentile ratios, shown in Fig. 14. Figure 14 clearly shows that the GLW-A10-ANL runs generated H_s^{95} and H_s^{99} results that closely tracked the measured values.

The significant improvements brought by the A10 source-term package to the skill of NCEP's Great Lakes wave model system in predicting severe sea states have led to its inclusion as part of a series of upgrades planned for the next operational implementation of the GLW systems at NCEP, scheduled to take place in 2013. Other improvements include a general increase in spatial grid resolutions, with two-way coupling to high-resolution coastal grids, more accurate bathymetric data, and the addition of a hindcast phase to NCEP's GLW-NDFD system, with surface winds generated through the inclusion of an adaptation of the GLERL analysis within NCEP's Real-Time Mesoscale Analysis (RTMA) system.

6. Concluding remarks

The development of a Great Lakes operational wave forecasting system at NCEP is described. The system has two major components, based on implementations of the third-generation wave model WAVEWATCH III. Although identical in most aspects, NCEP's two-wave model systems use atmospheric forcing data from different sources: NCEP's regional atmospheric model (NAM) and the National Digital Forecast Database (NDFD).

A brief literature review is made of previous Great Lakes wave modeling efforts, including sections on past and present forecasting systems, and hindcast databases developed for several scientific and engineering applications. A history and the motivations behind the development of NCEP's Great Lakes wave forecasting system are also provided, followed by a more detailed description of the current operational systems in terms of spatial grids, spectral resolutions, forcing fields, and forecasting schedules. Emphasis is given to the differences between NAM- and NDFD-driven wave model systems at NCEP.

A performance assessment is made of modeled wind speeds, wave heights and peak periods, based on several bulk validation statistics, relative to NDBC buoy data in the Great Lakes. Results indicate that NAM and NDFD wind data overestimate the observed wind speeds. NAM winds outperform the NDFD data in terms of bulk validation statistics, particularly in its better performance in simulating higher wind speeds, although the latter may also be an artifact of NAM currently making winds available at a higher temporal resolution (1 h) than that of NDFD (3 h). Nevertheless, it is reasonable to state that both the NAM and NDFD models have very similar skill levels in forecasting surface wind speeds in the 24–48-h ranges. Consequently, in terms of wave heights, both NAM- and NDFD-driven wave model systems at NCEP (GLW-TC96-NAM and GLW-TC96-NDFD, respectively) provide very similar trend and random error scores. GLW-TC96-NAM, however, outperforms GLW-TC96-NDFD in representing

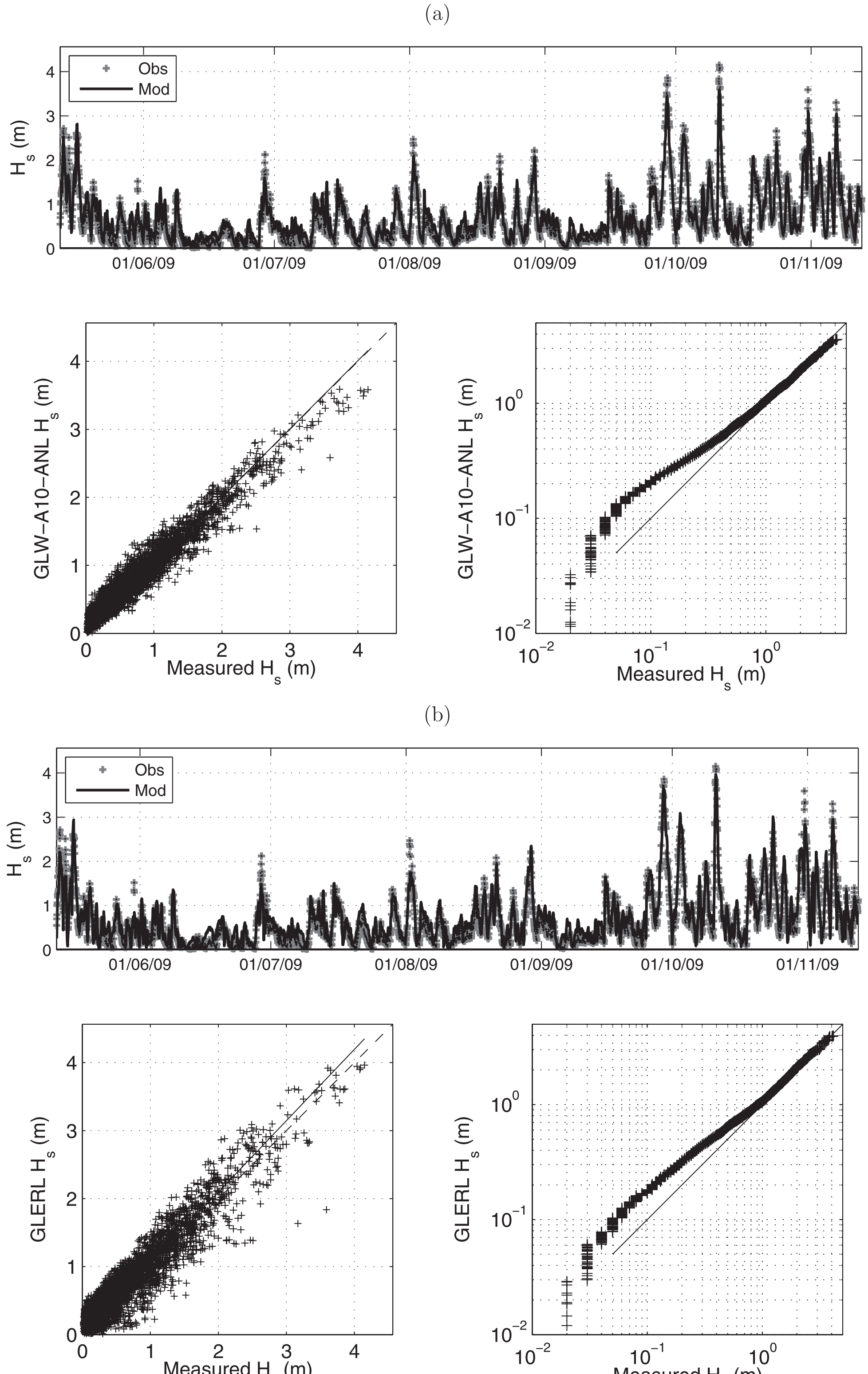


FIG. 15. Validation statistics of wave heights H_s from (a) GLW-NAM and (b) GLERL hindcasts during 2009, at the location of NDBC buoy 45001 (Lake Superior). Panel groups show (top) time series, (bottom left) scatterplots, and (bottom right) quantile–quantile plots.

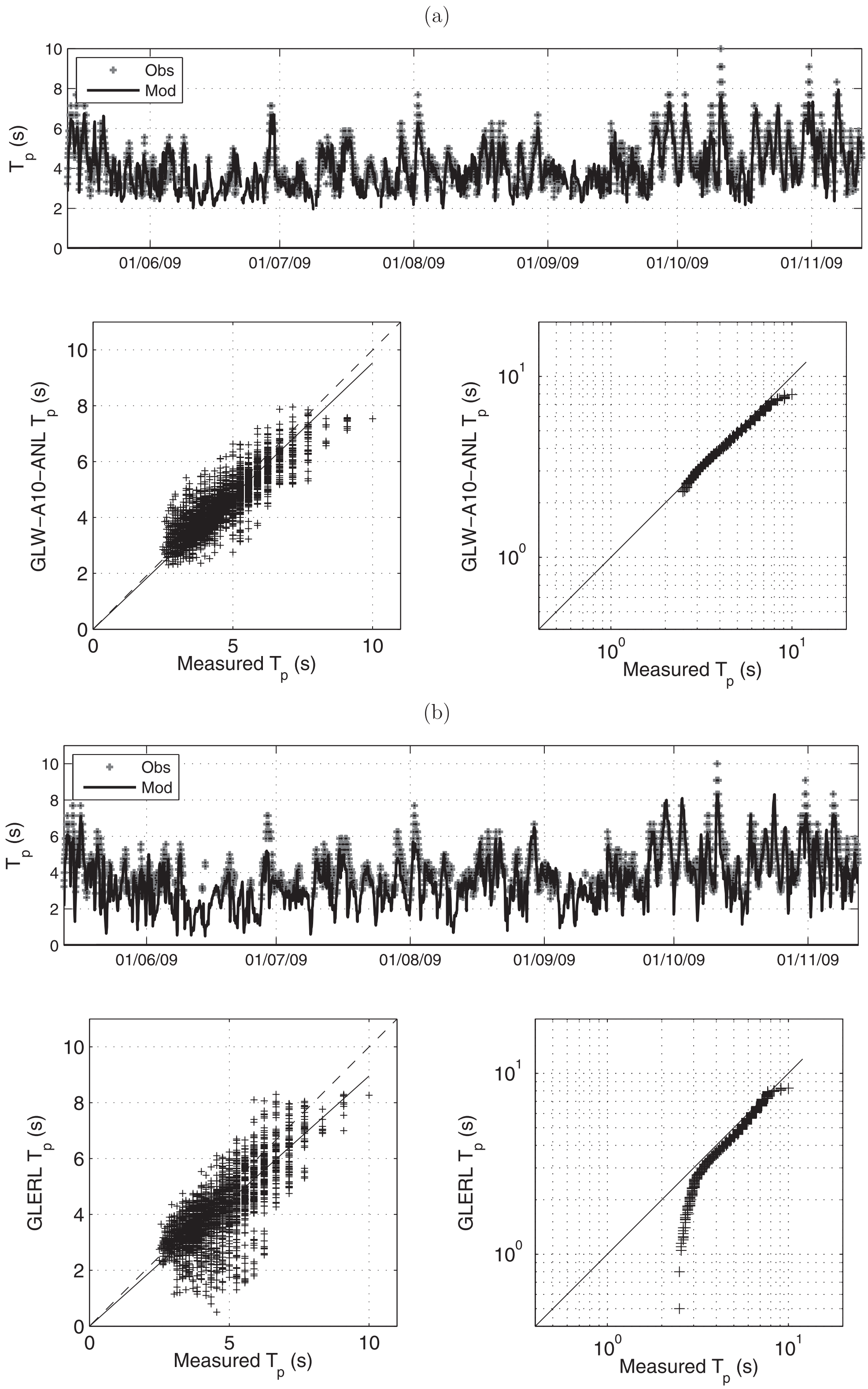


FIG. 16. As in Fig. 15, but for T_p.

measured wave-height patterns and total variance. Although both models show a trend toward underestimating measured peak periods, the NAM-driven model has a significantly better level of performance than GLW-TC96-NDFD.

A comparative performance analysis between the two operational wave model systems at NCEP and the semioperational GLERL wave model reveals that NCEP's GLW-TC96-NAM has more skill in predicting H_s, in terms of most bulk validation statistics, which makes it a more appropriate source for wave guidance than the GLW-TC96-NDFD and GLERL systems, in typical Great Lakes wave conditions. Standard deviations and upper percentiles of H_s relative to measured data indicate that both NCEP wave models consistently underestimate larger-wave measurements, and that the GLERL model provides a better match to the observations of storm waves. This has supported the use of the GLERL wave model as a more reliable source of wave guidance in forecasts of severe sea states.

A closer evaluation of wave model skill is made via comparing hindcast waves generated by the NCEP and GLERL wave model systems, both using identical high quality surface wind analyses made available by GLERL. Our results confirm that the skill of the WAVEWATCH III implementations used in the current operational Great Lakes wave model systems at NCEP outperforms that of the GLERL wave model, in terms of predictions of both H_s and T_p during typical wave conditions observed in the Great Lakes. On the other hand, our results also confirm that NCEP's GLW systems have deliver performance in predicting the highest measured H_s (95th and 99th percentiles), while GLERL hindcasts provide a more accurate representation of the highest measured waves.

A discussion is provided of upgrades to NCEP's Great Lakes wave models, scheduled to become operational in 2013 that shows clear improvements of their skill in predicting severe sea states. Such improvements are obtained through the use of a recent parameterization for wave growth and decay proposed by Ardhuin et al. (2010) and Filipot and Ardhuin (2012), included as source terms in the WAVEWATCH III model. The new source-term package has allowed NCEP's Great Lakes model systems to bridge their performance gap between good estimates of typical open-water wave conditions, and poor prediction of rapid wave growth in storms that develop under the more constrained Great Lakes environments. Results discussed show that NCEP's Great Lakes wave model system, fitted with WAVEWATCH III's new source-term package, produces bulk validation statistics that outperform all wave model configurations currently used at NCEP and GLERL. More importantly, WAVEWATCH III's new physics package led to significant improvements in the skill of NCEP's GLW model predictions of severe sea states.

The present study described how NCEP's Great Lakes wave prediction systems have been gradually developed over the years, to a quality level that make them a reliable source of wave guidance to marine forecasters, in all ranges of sea state conditions observed in the Great Lakes, including severe storms. Outcomes of NCEP's efforts in the Great Lakes region will assist in minimizing risks during severe weather, maximizing the safe usage of the Great Lakes during commercial operations and by the general public.

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