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THE NOPP OPERATIONAL WAVE MODEL IMPROVEMENT PROJECT [1]

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1 INTRODUCTION

Modeling of wind waves on scales from the ocean to the beach in an operational real-time environment has been the focus of interest for many decades. A key event in this was the attempt to predict waves for the D-day invasion of Normandy, France in 1944 (Sverdrup and Munk, 1946, 1947). Seminal experiments for wave forecasting were the Waves Across the Pacific experiment (Snodgrass et al., 1966), which established the persistence of swells propagating across oceans, and the Joint North Sea Wave Project (JONSWAP, Hasselmann et al., 1973), establishing many current views on the physical processes of wind wave growth and decay.

The first computer-aided wave forecasts were made in the 1950s (see Tolman et al., 2002, for a history of operational wave modeling in the USA). Initial models considered representative wave height(s) and period(s) only. A major breakthrough was achieved with the development of spectral wave models (Gelci et al., 1956, 1957), describing the complex wave field with its energy or variance spectrum, based on work of Rice (1944) on radio waves. Most spectral wave models use a version of the spectral balance equation of Hasselmann (1960)

$$\frac{DF}{Dt} = S_{in} + S_{nl} + S_{ds} + \dots \quad , \qquad (1)$$

where F is the two-dimensional wave energy or variance spectrum, and the terms at the right represent source term for wind input, nonlinear interactions, and dissipation, respectively.

In the next two decades a large number of wave models was developed. The Sea Waves Modeling Project (SWAMP, SWAMP group, 1985), eventually resulted in a convergence of models on so-called third-generation models, where the source terms on the right side of Eq. (1) are all explicitly parameterized, and integrated in time without assumptions on spectral shapes or solutions within the prognostic part of the spectrum. This became possible with the development of a cheap parameterization of the nonlinear interactions S_{nl} known as the Discrete Interaction Approximation (DIA, Hasselmann et al., 1985), and the associated development of the community Wave Model (WAM, WAMDIG, 1988; Komen et al., 1994). Many of the third-generation models based on WAM can now be considered as community models, with the most popular being WAM, SWAN (Booij et al., 1999; Ris et al., 1999) and WAVEWATCH III (Tolman et al., 2002; Tolman, 2008)

Third-generation wave models have the promise of improving wave modeling by direct research into, and parameterization of the physical processes involved. In spite of this most (operational) third-generation wave model still use relatively old parameterizations of the source terms. Virtually every model still uses traditional DIA, and the use of older source term packages of, for instance, Snyder et al. (1981), Komen et al. (1984), Janssen (1989, 1991), and Tolman and Chalikov (1996) is still prevalent. This is mostly due to the lack of success in finding cheap yet more accurate replacements of the DIA for nonlinear interactions, and our slowly developing understanding of the physical of wave energy dissipation due to wave breaking. More recently, however, much progress has been made in our understanding of the physics of wave growth and decay in both deep and shallow water. A review of recent progress is given by the WISE Group (2007).

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Considering the more rapid recent progress in wave science, and the need to transition this to operational wind wave models. the National Oceanographic Partnership Program (NOPP) started a five-year project entitled "Improving Wind Wave Predictions: Global to Regional Scales"[6]. Within NOPP this project is sponsored by the Office of Naval Research (ONR), the US Army Corps of Engineers (USACE), the National Oceanic and Atmospheric Administration (NOAA) and Bureau of Ocean Energy Management (BOEM, formally MMS). The project intended to focus mainly on wave physics for deep and intermediate water depths, with an emphasis on development of methods sufficiently economical to be used in operational wave forecasting. An essential part of the project requirements is that new approaches must be presented to the community at large for general use. Most funded teams have chosen to work with the WAVEWATCH III ® wave modeling framework, and to distribute their new approaches with this model to the public. Nevertheless, it is expected that due to the modular design of the latter model, it will be relatively simple to convert these approaches to other popular third-generation wave models such as WAM, SWAN and STWAVE (Massey et al., 2011). All these wave models are used directly by some of the teams involved.

The outline of the paper is as follows. Section 2 describes the various NOPP science teams, as well as additional 'in kind' contributions of the funding agencies. Sections 3 and 4 discuss validation data and validation techniques. Part of the validation centers around a 30 year hindcast to be performed at NCEP. This hindcast is discussed in Section 5. The collaboration between the teams while working on a single wave modeling framework requires modern code management principles which are discussed in Section 6. Finally, an outlook with desired and already achieved outcomes of this projects is presented in Section 7.

2 NOPP TEAMS

Several teams are funded under this NOPP project. All teams work directly with NOAA or USACE as the receiving agencies for the proposed products. Note that the Naval Research Laboratory (NRL-Stennis) co-develops WAVEWATCH III code by using a joined Subversion (Collins-Sussmann et al., 2004) server at NOAA, and hence is also linked in to all teams. ONR and BOEMRE provide funding and support for logistics etc. NOAA, USACE and NRL-Stennis provide in-kind support, as well as in-kind direct contributions to the project. A large variety of (intermediate) results from this NOPP project are presented in this session of this conference. Below, a brief description of each team (including USACE, NOAA and NRL), their objectives and time lines are given. See the NOPP web site[6] for more details on most of the individual projects and groups.

Three of the teams concentrate on deep water physics. These teams, identified by their lead principal investigators (PIs), are

- The team led by Fabrice Ardhuin (Ifremer, France) is concentrating on wave dissipation parameterizations that combine swell dissipation, wave breaking effects and bottom friction. This work is designed to improve on the parameterizations developed by Ardhuin et al. (2010) by including more physical constraints, in particular the use of dissipation rates and breaking statistics estimated from the stereo-video data system WASS (Gallego et al., 2011). Another part of the team work is the maintenance and improvement of unstructured grid capability in WAVEWATCH III (see Section 7). An update of the dissipation terms is expected by the end of 2012.
- The team led by Alexander Babanin (Swinburne University of Technology, Australia) focuses on observation based input (Donelan et al., 2006; Babanin et al., 2007) and dissipation (Young and Babanin, 2006) functions, and on swell dissipation (Babanin, 2011). It intends to implement new approaches in both WAVEWATCH III and SWAN. Initial implementation of the new approaches in the wave models is expected to be finished in late 2011. The approaches will be refined using extensive hindcasting for the Lake Michigan, Lake George and parts of the Gulf of Mexico, and for hurricanes in the Australian region in 2011-2013. Hindcast validation in the NCEP global operational environment using in-situ and altimeter data will be performed in 2012-2013.
- The aim of the team led by Mike Banner (University of New South Wales, Australia) is to improve the accuracy of ocean wave forecasts over a wide dynamic range of wind speeds out to extreme hurricane conditions. Building upon Banner and Morison (2010), the team will

[6] http://www.nopp.org/funded-projects/fy2009-projects-funded-under-nopp/ topic 1).

contribute refined wind input and dissipation source functions to WAVEWATCH III, adding explicit wave breaking statistics for the wind sea to the forecast products (2012). The team will also decouple swell systems from the wind sea and to provide a framework that allows for full coupling to the associated atmospheric and ocean circulation models (2013). As part of this project the team aims to refine further the parameterization of air-sea and upper ocean fluxes, including sea spray, with a special focus on severe conditions (2013).

Three of the teams concentrate (mostly) on nonlinear interactions. These teams, identified by their lead PIs are

- The team led by Will Perrie (Bedford Institute of Oceanography, Canada) focuses on the Two Scale Approximation (TSA) to the quadruplet interactions, with as the main contribution to provide accurate efficient model code for the nonlinear 4-wave interactions for implementation in operational wave forecast models. The work builds upon Resio and Perrie (2008), Perrie and Resio (2009) and Resio et al. (2010) by adapting the TSA to (i) operational model constraints and (ii) actual evolving ocean wave conditions, The goal is to implement such a TSA in WAVEWATCH III during the project.

- The team led by Tim Janssen (San Francisco State University, USA) will contribute to generalizing the modeling of nonlinear effects in random waves through the development of an efficient quadruplet-triad source term, by combining advances in efficient quadruplet approximations, developments in weakly dispersive wave closures, and recent work on bottom-induced wave dissipation. Furthermore, the team will contribute several relevant field data sets to the project teams for model calibration and validation. In 2012 the team anticipates to finalize several principal parts of the nearshore model developments and continue to work toward the implementation and testing of a generalized nonlinear model.

- The team led by Vladimir Zakharov and Andrei Pushkarev (Waves and Solitons LLC, USA) contributes with development of accurate and fast advanced statistical and dynamical nonlinear models of ocean surface waves, based on first physical principles, which will improve and accelerate both long term ocean surface waves forecasts and prediction of strongly coherent events, such as wave-breaking, freak waves, and tsunami.
  First year expected results include: i) Finding of the new wind input term through experimental, theoretical and numerical approaches ii) Theoretical and numerical proof of nonlinear interaction term domination over wind input and dissipation terms in Hasselmann equation. iii) Detection of swell feedback by sea background through theory and experimental data iv) Design of new method for numerical integration of Hasselmann equation v) Derivation and numerical testing of one-dimensional version of Zakharov equation, especially convenient for theoretical and numerical study of wave-breaking and freak waves Second year expected results include : i) Fine-tuning of new wind input term for specific experimentally detected conditions of fetch-limited growth. ii) Wave dissipation term for Hasselmann equation, development of which will be based on 1D dynamical equation modeling for both cases of individual wave breaking and ensemble wave-breaking. iii) Testing of new method of numerical integration of exact nonlinear source term for Hasselmann equation and its comparison with existing exact methods of its integration.

The final three teams concentrate on shallow water physics (including the above interactions). These teams, identified by their lead PIs, are

- The team led by James Kaihatu (Texas A&M University) and Alexandru Sheremet (University of Florida) focuses on near-coastal processes of waves over cohesive sediments (mud) and vegetation. In addition to straightforward extension of wave-mud models, a set of coupled Boussinesq equations for two layer flow are derived, and the nature of possible (resonant and near-resonant) nonlinear interactions between the surface and interface waves are determined. The lower fluid layer is also made viscous to simulate the effect of mud on these interactions (Tahvildari and Kaihatu, 2011)
  Much work has also been performed concerning analysis of the data taken during recent ONR-supported field campaigns over the Atchafalaya shelf off the Louisiana (USA) coast, showing a clear time-dependence of interactions during and after the passing of wave events (Safak et al., 2010; Sahin et al., 2011). Knowledge of the mud evolution will help adjust modeling ef-

fort to allow for a more dynamic interaction between surface waves and mud.

- The team led by Gerbrant van Vledder (Delft University of Technology, with contributions from Shell) focuses on shallow water physics through modeling and observations. Traditional bottom friction terms (e.g., JONSWAP) are revisited, and a new depth-limited wave breaking source term is developed, accounting for local water depth, local bottom slope and directional spreading. In addition a memory function is built in to better reproduce dissipation rates in strongly varying condition. The parameterizations are tested in SWAN, and will be available at the end of 2011. Triad wave-wave interactions have been formulated in analogy with the formulation of quadruplet wave-wave interactions with the scaling provided by an extended Boussinesq model (Booij et al., 2009). Calibration and verification under both laboratory and field conditions are planned for 2011 and 2012.
  In addition, shallow water wave measurements using AWACs (Pedersen et al., 2007) at the Field Research Facility (FRF) in Duck, North Carolina, will be analyzed, focusing on probability distributions, on the evolution of the frequency-direction spectrum in space and time, and on infra-gravity wave energy. The latter observations will be compared to the Ideal Surf Beat (IDSB) numerical wave model.

- The team led by Jeff Hanson (US Army Corps of Engineers at Duck, NC) focuses on two issues. First, the team is involved with the continuous data gathering at the FRF. For the NOPP project, relevant data sets are processed and made available to the NOPP data base. Such data sets include meteorological forcing, waves (spectra and time series), current profiles, tides, and sea surface temperature. Furthermore, supporting bathymetry survey data and Argus imagery are available for download from the FRF web site[7]. Second, this team is working with WAVEWATCH III and SWAN developers at NOAA NCEP to implement (1) a wave partitioning capability in SWAN similar to what we previously provided for WAVEWATCH III, and (2) a spatial tracking capability that can be used in both models to track the space-time evolution of coherent wave systems in the model output (initial codes have been delivered).

[7] http://frf.usace.army.mil

USACE supports this project through the Engineer Research and Development Center (ERDC), Coastal Hydraulic Laboratory (ERDC/CHL), with Don Resio and Jane McKee Smith as lead PIs. The STWAVE model is the workhorse (coastal) spectral wind wave model of the USACE, whereas WAM and SWAN are also regularly used. USACE uses this NOPP project to improve these models. Furthermore, USACE supports this project by:

- Providing data from the Field Research Facility (FRF) in Duck, North Caroline, including observations from Currituck Sound [7] (processed by the Hanson team above).
- A first version of a new set of base source terms were developed and tested, but not yet implemented in a full model.
- Development of additional metrics for model validation (spectral peakedness, spectral shape (equilibrium range), ratio of duration and time growths, behavior of spectra in turning winds).
- Further development of the the Interactive Model Evaluation and Diagnostics System (IMEDS, e.g. Hanson et al., 2009), making this system available to all NOPP teams.
- Assessment of impact of nonlinear interactions on directional wave spectra (Resio et al., 2010).
- Coupling of WAM/STWAVE and ADCIRC for wave-surge modeling for hurricanes (Dietrich et al., 2011).
- Some of the wave system tracking capabilities mentioned above are also provided as an in-kind contribution (see Hanson team above).

NOAA supports this project through the Environmental Modeling Center (EMC) of the National Centers of Environmental Prediction (NCEP), with Hendrik Tolman as lead PI. EMC is responsible for the operational wind wave models of the National Weather Service (NWS). All operational NOAA models are implementations of the WAVEWATCH III wave modeling framework. EMC uses this NOPP project to guide upgrades of the operational wave models as will be outlined in Section 7. Furthermore, EMC supports this project by

- Providing improved nonlinear interaction approximations (Tolman, 2010a) and conservative nonlinear spectral filtering (Tolman, 2011).
- Providing quasi-stationary model options (Van der Westhuysen, 2011).

- Providing a code management environment for joint development of the WAVEWATCH III code using the NCEP Subversion (svn, Collins-Sussmann et al., 2004) server (see Section 6). The wave model is furthermore providing a venue to distribute new parameterizations to the general public.
- Maintaining a data server for sharing model forcing, model results and validation data among NOPP team members.
- Providing pre-operational testing capabilities for new source terms parameterizations at EMC as part of the continuous upgrade cycle for operational wave models.
- Leveraging a 30 year wave hindcast project using NCEP's CFSRR wind and ice forcing (Saha et al., 2010), see Sections 3 and 5.
- Leveraging joint development work with USACE (wave partitioning, to be ported from WAVEWATCH III to SWAN) and NRL (new grid approaches, coupling using ESMF).

NRL-Stennis provides in-kind development effort of WAVEWATCH III that is leveraged for the present NOPP project, with Erick Rogers and Tim Campbell as lead PIs. Present development efforts include

- Addition of curvilinear grid options.
- Integration of new grid options into the mosaic approach.
- Development of an ESMF wrapper for the wave model to enable model coupling.
- Development of an automated regression testing capability for the model.
- Advice on use of version control software to enable team development of the wave model.

3 VALIDATION DATA

As a forced and damped problem, wind wave prediction can be performed without the use of any wave observations and data assimilation. Observations, however, are critical for developing, validating and monitoring operational wave models. As part of the NOPP project, a comprehensive set of validation data are gathered and archived at NCEP. Such validation data are only usable if corresponding model setups are available, including bathymetry (possibly with obstruction information for unresolved coastlines) and model forcing (wind, ice, mean water motion, etc.).

For each observation data set in the archive at NCEP, a WAVEWATCH III model setup (including forcing) will be generated and added to the archive to facilitate wide use of the data sets. The philosophy of the archive is to take data 'as is', with the originator providing tools to read an process data. We will not attempt to homogenize the data sets, only to facilitate easy and automated access.

For operational wave modeling, two types of testing and validation are relevant. First, operational models need to work properly all the time for all conditions encountered. This corresponding behavior can be assessed only by using long term model analysis using a large volume of routinely made wave observations (typically buoy and altimeter data). Second, operational models can be improved systematically only when individual physical processes are properly understood and modeled; a model that gives good results without proper parameterizations of physical processes cannot be expected to be accurate in uncommon conditions, and is less suitable for systematic physical improvements of a model. Understanding and modeling of physical processes requires targeted observations and experiments, which are generally of shorter duration, and involve much less data than the bulk validations mentioned earlier.

Considering the above, it is prudent to identify specific physical behavior to be tested, and then find appropriate data sets for these conditions. Since this NOPP project focuses on modeling, we can only use existing data sets. In the following five subsections, specific model behavior and/or physical processes to be considered in this project are identified and discussed, together with suitable data sets to test these. Note that the list in essence is a living document. A full table with actual data sets will be presented at a later stage, when the project reaches maturity.

3.a LONG TERM VALIDATION

Long term wave model validation on global to coastal scales requires high-quality high-resolution global wind fields. Recently, a 30 year reanalysis wind data set with a spatial resolution of $0.5 \times 0.5°$ and a temporal resolution of 1 h has become available (Climate Forecast System Reanalysis, CFSR, Saha et al., 2010). Wind and sea ice data from the CFSR are archived in WAVEWATCH III input format at the NCEP NOPP data server, and this data set allows for the production of a 30 year wave hindcast (see Section 5) as part of the NOPP study, although shorter sections of this period will generally be used for model development. Initial assessment of the quality of these wind fields indicates that they are equivalent to present operational wind analysis at NCEP (Spindler et al., 2011).

Wave data to be used in combination with global model runs forced by the CFSR winds consist mainly of long-term sustained observations systems. These typically consist of in-situ buoy observations (e.g., Bidlot et al., 2002) and altimeter data sets (e.g., Queffeulou, 2004). Such data sets from various source have been included in the NCEP validation data set.

An interesting observation has already been made from the long-term validation of the operational wave model at NCEP, and from the CFSR wind data set; wave model biases in particular in the southern oceans are sensitive to the most extreme wind speeds (Chawla et al., 2009). Without notable changes in mean wind speeds, biases can become significantly larger if 95 percentile wind speeds increase. In this context, the CFSR wind are insufficiently homogeneous with respect to high-percentile southern ocean winds (Spindler et al., 2011), and will require some statistical correction if the data are used to assess long term trends in wave conditions.

3.b WIND SEA AND SWELL

In a wave model, wind sea and swell behave very differently. To assess the separate physical processes of both, selected data sets and analysis techniques can be used.

Wind seas can be addressed in ideal offshore wind conditions such as considered in the JONSWAP project. However, conditions with dominant wind seas also naturally occur in enclosed and semi-enclosed basins. For this reason, wave conditions on the Great Lakes will be considered using analyzed wind from the Great Lakes Environmental Research Laboratory (GLERL, Schwab and Morton, 1984), together with routine buoy observations. Furthermore, results from selected measurement campaigns will be considered, such as the Lake George data (Young et al., 2005). The latter data are particularly interesting as they considers wave growth (wind seas) in shallow water.

Swells can be tracked over long distance in the ocean using traditional in-situ spectral observation, and was demonstrated by Snodgrass et al. (1966). More recently it has been shown that Synthetic Aperture Radar (SAR) is sufficiently accurate to not only track swell, but also estimate swell decay rates (Ardhuin et al., 2009a). Thus, swell behavior will be addressed by using in-situ spectral wave data as well as SAR data.

Spectral partitioning in wave model results and full spectral observations (Gerling, 1992; Hanson and Phillips, 1999) makes it possible to separate wind seas and swell in almost arbitrary wave conditions. This technique will be important to use the above SAR data, and will make it possible to address individual wind sea and swell behavior in mixed seas. using tools that will be described below.

Finally, wave growth in the presence of significant swells and the corresponding swell decay represent conditions that have traditionally been avoided in wave growth studies. Recent observations targeting wave growth in the presence of swell (e.g., Violante-Carvalho et al., 2004; Ocampo-Torres et al., 2010; Romero and Melville, 2010) therefore augment traditional observations, and are intended to be included in the NOPP data base. The Duck dataset also includes such conditions (e.g., Ardhuin et al., 2007).

3.c NON-ALIGNED WINDS

Traditionally, wave growth experiments have focused on simple conditions including waves aligned with winds, not including responses to changes in wind direction, or misaligned winds. Recent studies have shown that there are major differences in model behavior in such conditions related to model physics, and hence explicitly including such conditions in the model development and validation is essential. Two situations lead to misalignment, and will be considered in model testing and validation.

Slanting fetch
Slanting fetch conditions occur when offshore winds are not perpendicular to a mostly straight coastline. Details of the source term balance determine the accuracy of in particular predicted wave directions in such conditions (e.g. Ardhuin et al., 2007). Such conditions regularly occur in the FRF in Duck NC, and the corresponding data set will be mined for such conditions. Corresponding wind conditions can be taken from the CFSR winds, if necessary augmented with local wind observations.

Tropical cyclones
Wind waves misaligned with winds also systematically occur in Tropical Cyclones (TCs). Recent stud-

ies have shown that model accuracy in such conditions is sensitive to the nonlinear interaction approximation (Tolman, 2010a). Routine observations can be used to address accuracy of wave models in TC conditions, but such data are generally too sparse to provide conclusive test results (e.g., Chao and Tolman, 2010). A unique opportunity to address the quality of wave model in TC conditions comes from the Surface Radar Altimeter (SRA), and its successor, the Wide Swath Radar Altimeter (WSRA, ProSensing, 2008). This instrument provides targeted spectral wave observations throughout TCs (e.g. Moon et al., 2003). The entire SRA/WSRA data set will be used in the NOPP project, tentatively using hurricane wind analysis from Powell et al. (1998), merged with CFSR large-scale wind fields.

3.d EXTREME CONDITIONS

When wind wave modeling is considered as a safety of life at sea issue, modeling extreme conditions accurately is of paramount importance. One case of extreme conditions are TCs, mentioned in the previous section. Furthermore, the 30 year hindcasts allows for mining for the most extreme observed conditions. The key to make this successful is not in selecting individual cases, but in analysis of the long term record. In the long term record (buoy and altimeter), individual extreme events need to be isolated. Since these events are effectively all wind seas, a correlation between local wind and wave errors can be used to provide an in-depth analysis of wave model behavior.

Extreme wave conditions do not only imply extreme wave heights, but can also imply extreme wave steepness and/or breaking intensity. The latter two conditions are also associated with marine safety. As one of the potential improvements of operational models is to explicitly predict wave breaking, data sets with explicit breaking observations (Holthuijsen and Herbers, 1986; Banner et al., 2000; Babanin et al., 2001; Banner et al., 2002) will be of high value to this NOPP project.

3.e DIMINISHING WINDS

Wave model development has historically focused on modeling wave growth, and this has led to fairly similar model behavior in idealized wave growth conditions for most established models, even for previous second generation model (see SWAMP group, 1985). More recently, an additional focus has been on swell attenuation. The transition from wind sea to swell, however, has not been getting much attention. In such conditions, established physics packages like the WAM4 package used at ECMWF and the default WAVEWATCH III package used at NCEP behave radically different, as has been know for well over a decade (Tolman, personal communication). It is therefore important to address the transition of wind sea to swell in a comprehensive test and validation approach of wave models.

Initial attempts have been made in the NOPP study to address such transition conditions by using ONR FAIRS experiment (Gemmrich and Farmer, 2004), as reported elsewhere in this conference. It is not clear if there are other suitable datasets to address this issue, but tentatively, long term hindcasts studies using routine observations can be mined for such conditions.

As a special case of such conditions we will consider fully or over-developed wind seas as occur in trade wind and monsoon conditions. Such conditions represent the asymptotic conditions of wave growth, with systematically different spectral energy balances than occur in wave growth conditions (e.g., Glazman, 1994). Wave observations in the Arabian Sea from the Indian National Center for Ocean Information Services (INCOIS) and from buoys south of Hawaii (particularly National Data Buoy Center (NDBC) buoy 51004) can tentatively be used for evaluating wave behavior in such conditions.

3.f SHALLOW WATER

The present NOPP study includes depth-limited conditions. In such conditions, a variety of processes can dissipate wave energy, such as bottom friction, bottom motion and percolation. An early review of such processes can be found in Shemdin et al. (1978). Even if only bottom friction is considered, there are a large number of approaches available to model this, as reviewed in, e.g., Tolman (1994). Recently, it has been shown that wave-mud interactions (e.g., Jiang and Mehta, 1996; Sheremet and Stone, 2003; Elgar and Raubenheimer, 2008; Rogers and Holland, 2009; Sheremet et al., 2011) and wave-reef interactions (Lowe et al., 2005, or PILOT project web site[8]) represent different, locally dominant, wave attenuation processes. Note that the data sets for sandy and muddy bottoms used here will also be used to address behavior of breaking and nonlinear interac-

[8] http://www.frf.usace.army.mil/pilot/pilot.shtml

tions in extremely shallow water (e.g., triad interactions) as addressed by several teams (see Section 2).

In operational wave models wave-bottom interaction approaches are typically selected in an ad-hoc manner, after which parameters are optimized for local conditions. True progress can only be made by using physics-based approaches, tested and validated with the appropriate observations. This NOPP study will mostly focus on sandy and muddy bottoms, using data sets from the FRF in Duck, and form the Mississippi delta (Atchafalaya delta). Additional data may be considered, such as data from the Great Australian Bight (Young and Gorman, 1995) as well as older swell propagation data sets.

Parameterizations for depth-induced breaking triad wave-wave interactions will be verified with laboratory observations from Delft Hydraulics, Imperial College, HR Wallingford, Aalborg University, Delft University and US Army Engineer Research and Development Center in Vicksburg and with field observations from the southern North Sea, Guam and the Black Sea.

4 VALIDATION TECHNIQUES

Traditionally, operational wave model validations focus on errors in the overall wave height only (e.g., Bidlot et al., 2002), typically showing scatter or probability density plots, and bulk error measures such as biases, root-mean-square errors (rms), standard deviations (std), and scatter indices (SI, normalized rms or std error), using either in-situ observations or altimeter data. In some cases, quantile-quantile plots are considered to address the representation of the (extreme) wave climate in models. As wave models have become proficient in reproducing such observations, it becomes more important to address errors in more detail. Particularly when wave models are used in coupled modeling, or for newer applications such as correcting satellite observations, a more in-depth analysis of model performance is needed. Several examples of more in-depth analysis can be found in literature, and will be considered in this NOPP project.

- For many applications parameters describing wave events rather than bulk measures for a time series are important. For instance, for hurricanes maximum wave heights and their timing are important features to be addressed individually (e.g. Chao et al., 2005; Chao and Tolman, 2010).
- A step beyond assessing quality of overall wave parameters of the spectrum is to address such parameters for individual wave fields, as is done with the IMEDS software package (e.g., Hanson et al., 2009).
- Alternatively, spectral data can be addressed in more detail, for instance by addressing the evolution of the one-dimensional wave spectrum in time (e.g. Wingeart et al., 2001; Alves et al., 2005). This allows for tracing individual swell systems.
- The latter two papers also allow for assessing how many observed wave systems are represented in the model. For wave forecasting such "hit and miss" statistics, including false alarm rates, represent a highly relevant metric that is usually ignored in scientific papers. Hit and miss statistics for warning levels of wave heights are similarly of importance for practical wave forecasting.
- Finally additional parameters such as mean-square-slope, and any parameter relevant for model coupling are important if a wave model is to be used beyond its traditional "safety of life at sea" applications (e.g., Ardhuin et al., 2009b)

Apart from adding new parameters to the validation, presentation of validation results is also important.

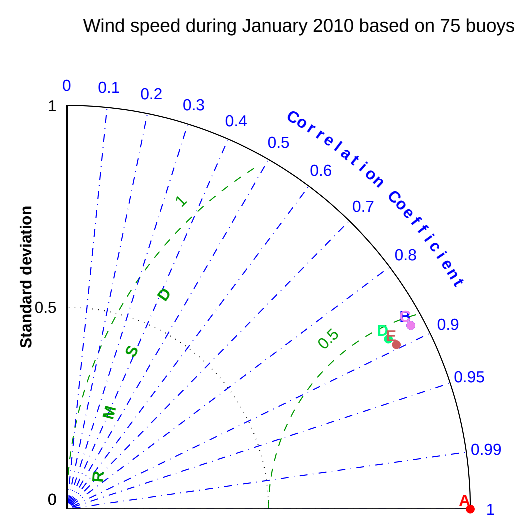

Fig. 1: Taylor diagram for various global wind field errors for January 2010 based on wind speed observations at 75 buoys. A represents the observations, B-E represent various wind field sources.

Taylor and target diagrams (Taylor, 2001; Jolliff et al., 2009) allow for a simultaneous representation of various model characteristics. Figure 1 shows an illustration of a Taylor diagram for various wind fields used for wave modeling at NCEP. As this figure is intended to illustrate the use of Taylor diagrams, details on the wind fields (B-E) are irrelevant. Point A represents the perfect model without error.

The lower left corner of the diagram can be considered as its origin. The distance from the origin represents the (in this case normalized) variability (standard deviation) of the wind speed. The perfect model A by definition has a variability of 1. Wind fields B and C approach the ideal normalized variance of 1, whereas fields D and E underestimate the variance more (i.e., are too smooth). The radial lines represent a constant correlation coefficient, with the scale displayed at the outer circle. The diagram shows that model E combines an underestimation of the variance of the winds with a slightly better correlation than all other wind models. The distance from point A (concentric green circles) represent the rms error of the models against the data. Point A represents the perfect model with no error. As with the correlation coefficient, model E outperforms the other three models with respect to the rms error.

The ideal model will approach point A. In a conventional analysis of error measures individually, the representation of the model variance of the parameter is generally not considered. In such an analysis, model E would be identified as the best model, based on the smallest error and largest correlation coefficient. The Taylor diagram, however, suggests that the slightly higher error and lower correlation coefficients of models B and C are associated with a clearly more realistic description of the observed variance of the winds, and might therefore be considered superior.

Similarly, target diagrams simultaneously represent model bias (not represented in Taylor diagrams), rms error and variance representation (figures not presented here). Taylor and target diagrams will be considered as part of the standard model assessment tools for this project.

5 30 YEAR WAVE HINDCAST

As already mentioned in previous sections, a 30 year hindcast is performed is conjunction with the NOPP project. The hindcast is separately funded by NCEP, NRL and DOE, with in-kind support from USACE. The hindcast is performed using the CFSR wind and ice forcing. No data assimilation is used, since there is insufficient wave data to produce a data-dominated analysis. The hindcast is scheduled to be performed in three phases:

I Generate a baseline hindcast using the present default WAVEWATCH III model as run at NCEP and the CFSR winds as is.

II Generate a second hindcast using the first NOPP based physical upgrade for operational wave models at NCEP (see Section 7). Apply wind corrections as needed to provide a best possible ‘climate record’ for this period (see Spindler et al., 2011). Expand the model domain further into the Arctic Ocean using curvilinear or unstructured grids, ideally covering the entire domain.

III Using the best possible physics from the NOPP project (including shallow water physics) and unstructured grids approaches at the coast to provide a NOPP based consensus optimal 30 year hindcast,

The hindcast initially will use the operational NCEP global wave model grids (58 km resolution), including the corresponding higher resolution offshore grids (18 km resolution) and coastal grids (7.5 km resolution). These grids have been regenerated using the most recent bathymetric data, and have been augmented with high-resolution grids for Australia, Iceland, Northern Europe, the Mediterranean, and the Horn of Africa (see Chawla et al., 2011). The latter grids have been added to spatially resolve the location of available in-situ observations, and to satisfy requirements of the sponsors of this project.

The computations for the first stage of this project are scheduled to be finished in October 2011, and initial results will be presented elsewhere in this conference.

6 CODE MANAGEMENT

Traditionally the WAVEWATCH III model code has been distributed as a set of ‘tar’ files and an installation script, only when a public release was made (model version 1.18, 2.22 and 3.14, respectively). The limited contributions of outside collaborators were provided back to NOAA in a similar fashion, with NOAA integrating external contributions manually back into the NOAA model versions. Such an approach was feasible with only a small number of developers working on the code.

In the NOPP project, various research teams, several of the projects sponsor agencies, and some collaborators outside the NOPP project, are all working simultaneously on a single WAVEWATCH III code. In such a case, modern version control principles need to be used. Over the last few years, NOAA/NCEP/EMC has been transitioning the development and maintenance of all its operational models to a Subversion version control system (svn, Collins-Sussmann et al., 2004). The same has been done for the community WAVEWATCH III code.

With this version control capability, the extended NOPP team is now considered the development team of the WAVEWATCH III code. At least one code manager of each of the teams has access to the EMC svn server, as do code managers of collaborators outside the NOPP project (NRL Stennis, the Met Office, the Bureau of Meteorology and several universities). All these code managers have direct access to the most recent developmental model versions, and provide contributions of their teams back to NOAA through the svn server (as an update to the most recent research version of the model). Overall code management and integration of contributions from outside NOAA is performed by the NOAA code management team, presently consisting of Jose-Henrique Alves and Arun Chawla, with support of André van der Westhuysen and Hendrik Tolman.

Whereas svn enables joint model development, it is not a magic bullet to solve all problems. The NOAA team plans the model updates including upgrades from collaborators external to NOAA. This process requires sufficient communication between teams. As part of the process a best practices guide has been developed (Tolman, 2010b). In this NOAA and the NOPP team were fortunate to be able to leverage previous experience of in particular other teams in EMC (particularly Paul van Delst), and of NRL Stennis (particularly Tim Campbell). The best practices guide is a living document, which NOAA expects to update regularly, and is considered to be a deliverable product of the NOPP project.

7 OUTLOOK

As outlined in the Introduction, the main expectation of this NOPP project is to provide a significant improvement to operational wind wave modeling, particularly at sponsoring agencies (NOAA, USACE and the US Navy). Whereas none of these agencies has as of yet implemented results from this NOPP project in operations, many upgrades are already available in various research version of WAVEWATCH III at the EMC svn server, for instance:

- Curvilinear (Rogers and Campbell, 2009) and unstructured grid (Roland, 2009) approaches are available in the base research version of the model, and are being integrated in the full two-way nested mosaic approach of Tolman (2008).
- A quasi-stationary approach has been implemented in the model for individual grids, and will be adopted to the mosaic approach (Van der Westhuysen, 2011).
- Various new source functions are available on the server, including new base source functions from the Ifremer group (Ardhuin et al., 2010), a new nonlinear filter (Tolman, 2011), a Generalized Multiple DIA (GMD) (Tolman, 2010a), and movable bed bottom friction terms (Tolman, 1994; Ardhuin et al., 2003).
- A massively expanded number of output parameters, including many parameters relevant for model coupling.
- Various new tools including NetCDF post-processing programs, a utility for merging gridded output, and a genetic optimization package for the GMD.
- Interfaces to couple the wave model to other environmental models using ESMF (Collins et al., 2005) or PALM (Buis et al., 2006) are available or nearing completion.

Even in the early stages of this project, it is clear that significant improvements in operational wave modeling will be achieved. The effort on improving the basic (deep water) wave growth dynamics are already resulting in potential upgrades of operational wave models as will be discussed below. At the end of the project, it is expected that all three main source terms will have been upgraded in some operational wave models. Particularly exciting is the prospect that for the first time since the development of the WAM model, the parameterization of the nonlinear interactions will be upgraded substantially, and that much of the recent research on breaking waves is finding its way into operational wave models.

In (intermediately) shallow water significant improvements are also expected. Whereas physics-based bottom friction terms have been available for many years, many operational models still use an empirical linear bottom friction term. Some of this is due to the complexity of the physics involved, inclu-

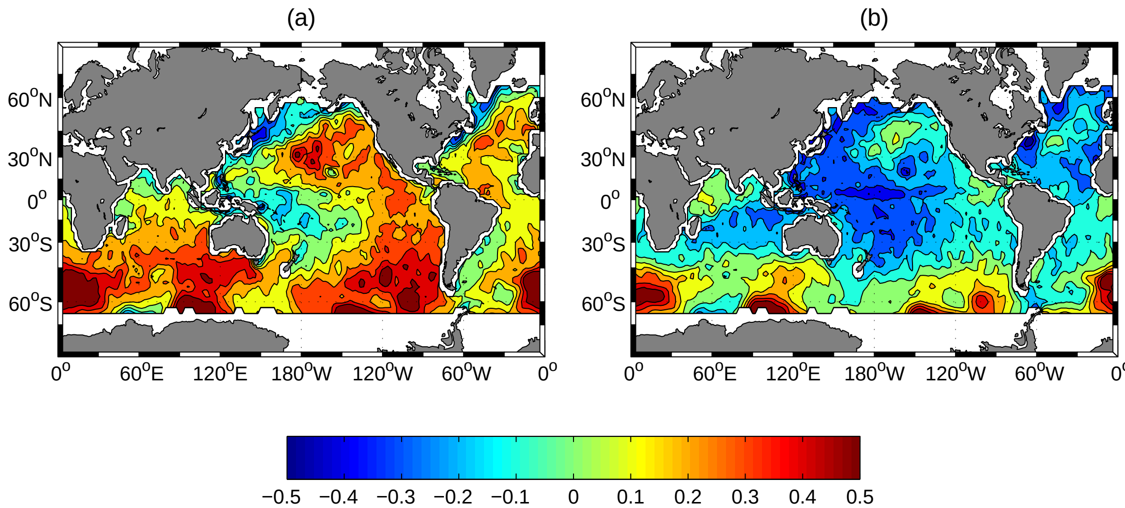

Fig. 2: Global model biases against Jason-1 altimeter data data for the December 2009 - February 2010. (a) Present operational NCEP global model. (b) Proposed NOPP based model upgrade .

ding (i) nonlinear features of the bottom boundary layer, and (ii) a possibly strong interactions between wave motion and sediment resulting in massive spatial and temporal variability of the physical roughness of the bottom. Through a combination of implementing existing formulations, and rigorous validation in coastal test sites, we expect significant improvements of shelf-scale behavior of wave models. Added to this is the evolving capability of modeling wave-mud interactions, which appear to be a dominant wave attenuation process in muddy coasts and deltas. Note that several of the groups also address nonlinear interactions in shallow water, including the expansion of traditional quadruplet interactions from deep water to limiter water depths (e.g., Janssen and Onorato, 2007).

On the edge of the scope of this project is the treatment of nonlinear (triad) interactions in (extremely) shallow water. Unlike for general quadruplet interactions, no baseline 'exact' interactions approach exists for triads. Whereas such an approach is expected to be far too expensive for operational models, it should be feasible for use in research models. An exact triad interaction is essential to be used as a baseline for developing accurate yet economical parameterizations, and is therefore deemed essential in a research-to-operations wave modeling framework. It is expected that this project will yield such a baseline exact interaction approach for arbitrary water depths, integrating quadruplet and triad features.

As mentioned above, NOAA is planning its upgrades of operational wave models based on results of this NOPP project. In early 2012, NOAA hopes to replace the traditional physics package of Tolman and Chalikov (1996) with a package from the Ifremer group (Ardhuin et al., 2010), based on established accuracy for the global wave models as well as for Great Lakes applications. The upgrade is not yet approved, as it requires some additional computational resources for the global models, whereas it has proven to be cheaper to run for the Great Lakes. An example of some of the improvements of these operational model achieved through this NOPP project are presented in the following figures. A full report on the underlying studies will be presented elsewhere.

Figures 2 and 3 present results for the global wave model. Figure 2 presents global wave model biases in m against Jason-1 altimeter data for Dec. 2009 through Feb. 2010. The old operational model (left panel) shows a systematic overestimation of wave heights at higher latitudes (positive biases). Note that the biases in the southern Pacific Ocean have occurred only recently, due to changes in NCEP weather model characteristics in southern latitudes (Chawla et al., 2009; Spindler et al., 2011). In the new model (right panel), these biases are greatly reduced.

Figure 3 present global monthly mean model errors against ENVISAT, Jason-1 and Jason-2 altimeter

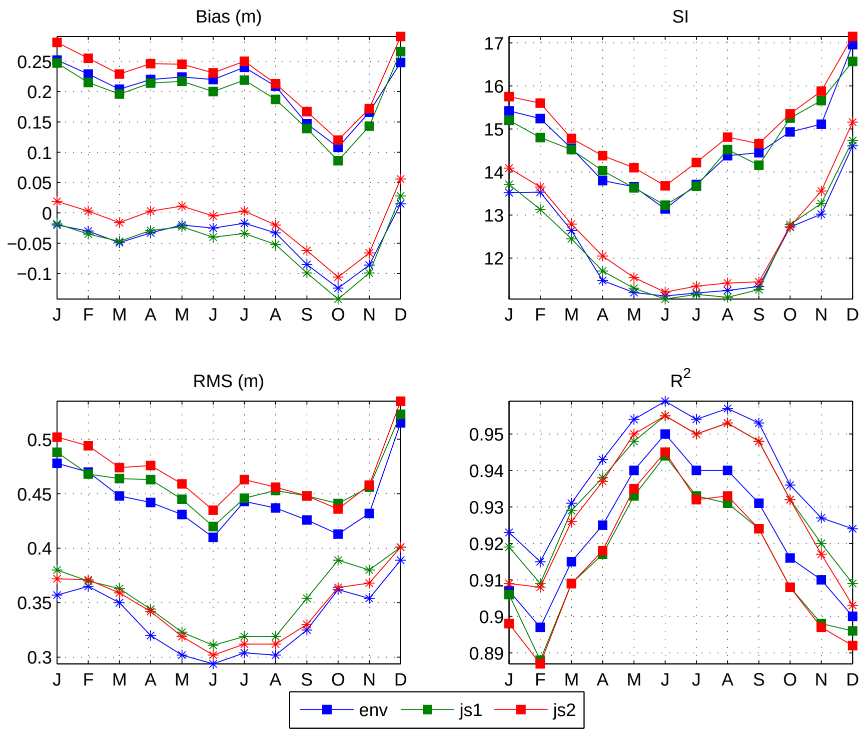

Fig. 3: Global monthly model error statistics against the ENVISAT (env), Jason-1 (js1) and Jason-2 (js2) altimeter for 2009. Bias (m), Scatter Index (%), rms error (m) and R^2 (-). Solid squares for old model (as in Fig. 2a), asterisk for new model (as in Fig. 2b).

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data. the old model (solid squares) shows systematic positive biases throughout the year, which are mostly removed in the new model (asterisk). Scatter indices in the new model are systematically 2-3% smaller than in the old model, and correspondingly rms errors are smaller by generally more than 0.1 m. Finally, correlation coefficients are also systematically improved in the new model.

Figures 4 through 7 present results for the Great Lakes wave model, driven by analyzed wind fields of Schwab and Morton (1984). Figure 4 shows traditional validation results for the present operational Great Lakes wave model configuration for 2009 at buoy 45007 in Lake Michigan. The upper panel shows the time series of wave heights H_s for the year (note that the buoy is removed for the winter months). The present operational model closely follows observations for lower wave heights, but systematically underestimates peak events. This is also obvious in the lower left panel of the figure, representing a traditions scatter plot with regression line, and the lower right panel, presenting a quantile-quantile (qq) plot, comparing probability density functions of the model and the observations.

Figure 5 shows the corresponding results obtained with the new physics package of Ardhuin et al. (2010), using parameter settings optimum for the Great Lakes. The time series, scatter plots and qq plots all show a dramatic improvements of the model behavior for the highest waves, without degeneration of model behavior for lower waves.

Figure 6 shows a Taylor diagram representation of model errors for individual buoys and various models. The buoys are identified by individual symbols, the models are identified by color. Added to this figure are results for the GLERL-Donelan model (Schwab et al., 1984), representing an operational second-generation model used for the Great Lakes. The model represent the previous operational model, and is still used interactively at Weather Forecast Offices (WFOs) in the Great Lakes region.

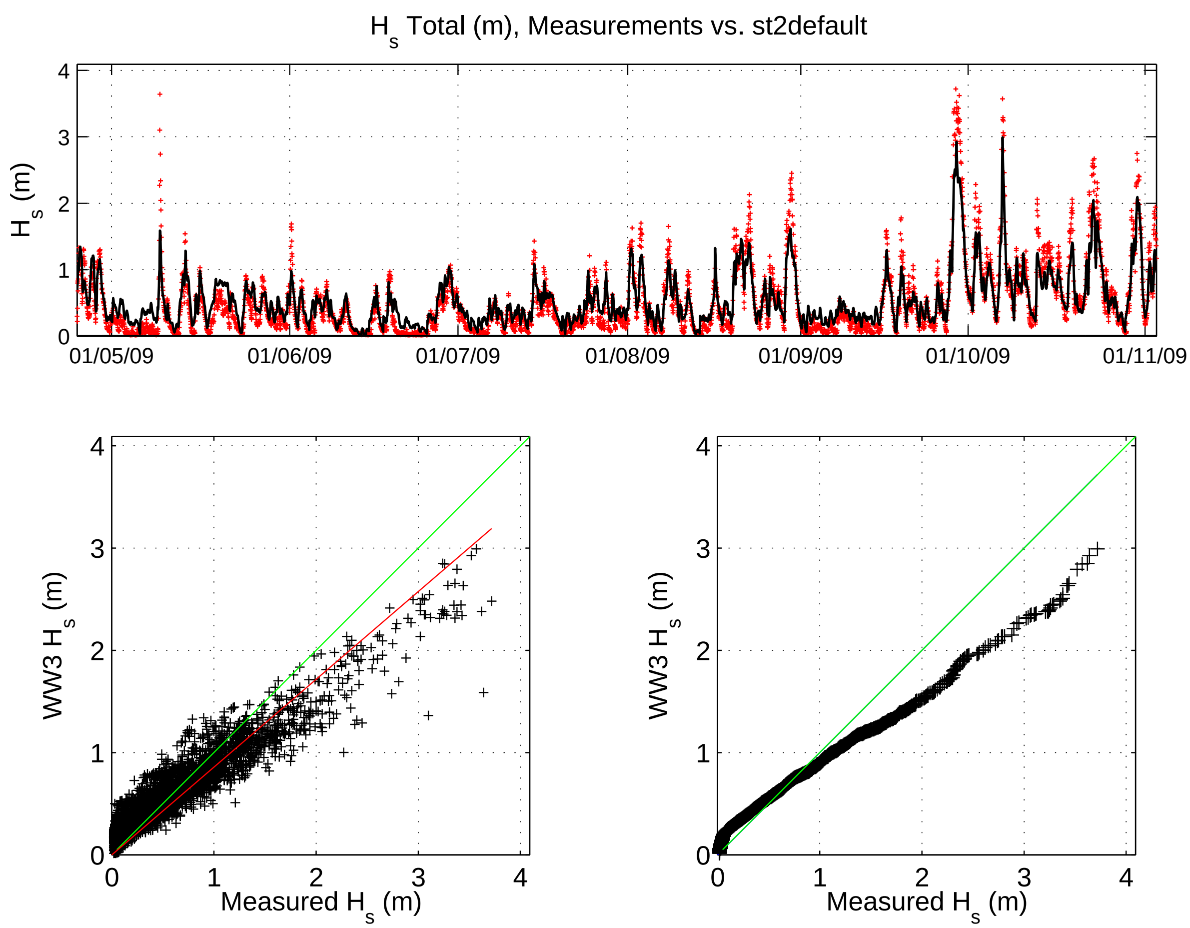

Fig. 4: Wave height validation for Great Lakes buoy 45007 for 2009. Upper panel is time series, with mode as black line and observations as red symbols. Lower left panel is scatter plot, with linear regression line in green. Lower right plot is quantile-quantile (qq) plot comparing pdfs of model and observations. Present operational model based on Tolman and Chalikov (1996) physics.

Note that wave models are fairly accurate, with correlation coefficients of typically 0.9. This implies that in the traditional Taylor diagram, differences in model behavior may not be easily observed, as all models occupy only a small subset of the diagram space (see Fig. 6). This can be alleviated by using an alternate presentation of Boer and Lambert (2001), as is presented in Fig. 7. Note that the information presented in this last two figures is identical.

The present operational model (blue symbols in figures) replaced the GLERL-Donelan model (black symbols in the figures). The present model has clearly better correlation with the observations, and a similar or slightly higher rms model error. However, the present model does not properly describe the range of wave conditions, as it typically represent less than 75% of the observed wave height variability. Conversely, the GLERL-Donelan model closely reproduces the observed wave variability. The new model setup (red symbols in figures) shows a correlation with the observations that is as good as or better than the correlation of the present model (blue symbols), combined with a realistic description of the wave height as in the GLERL-Donelan model (black symbols), while having significantly smaller rms errors than both previous models.

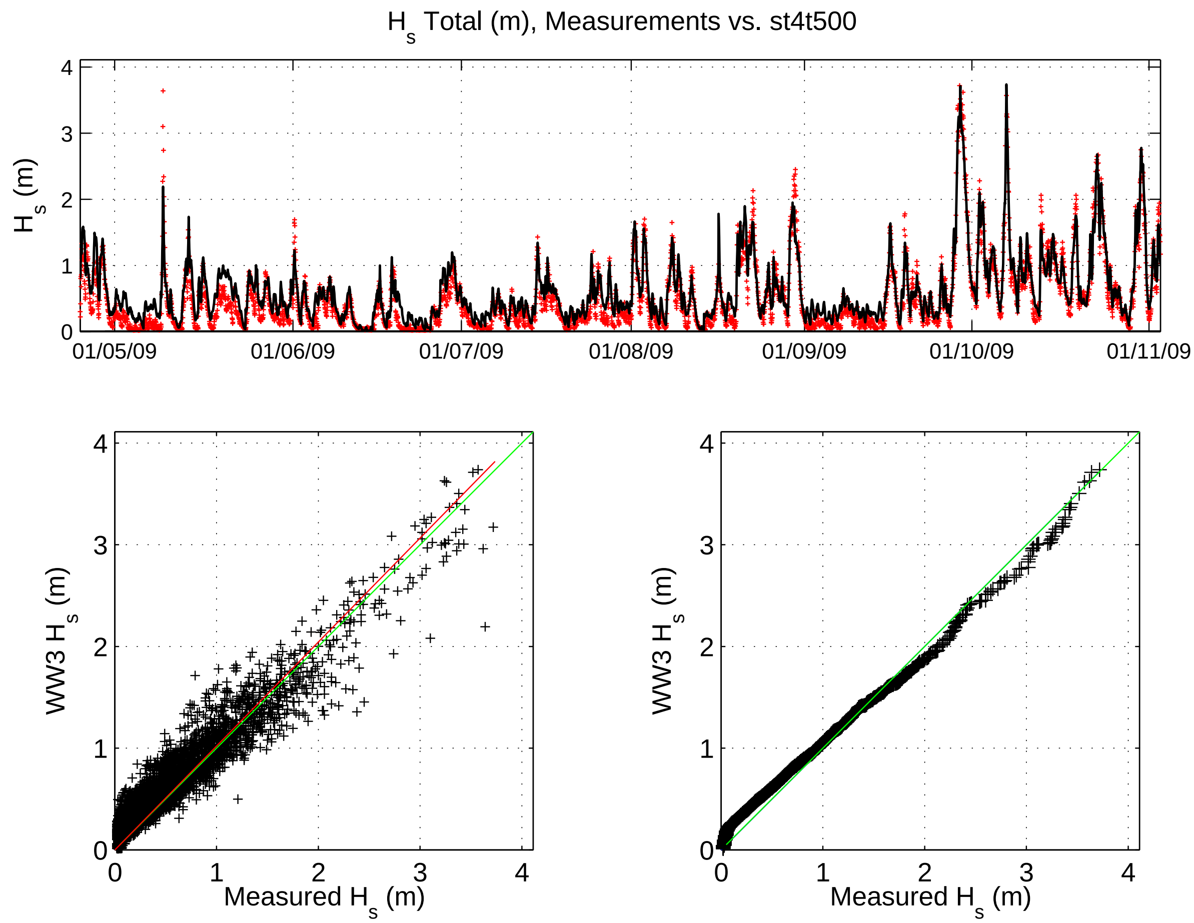

Fig. 5: Like Fig. 4 for (Ardhuin et al., 2010) physics package with optimum parameter settings for Great Lakes.

The second NOPP upgrade of NOAA operational wave models is expected to require a significant increase of computational effort, and is therefore tentatively scheduled for the after next NOAA computer upgrade in 2014/15. This upgrade is likely to include the first serious upgrade on the nonlinear interactions since the introduction of the DIA, and is expected to include upgrades of virtually all source terms in the wave model. Equally important will be the tentative addition of explicit prediction of wave breaking intensity. This has a direct impact for safety of life at sea, as well as on many marine engineering issues, and opens the possibility of generating highly relevant new operational wave model products. Additional new capabilities are the tracking of wave partitions in space and time, and the inclusion of sea spray in the computation of fluxes (particularly important in coupled models).

Two other developments at NOAA tie into this NOPP project. First, the validation data sets including the 30 year hindcasts (forcing and model results) are intended to become a sustained resource to the wave modeling community at large. Second, NOAA is using this NOPP project as a prototype for community modeling and model development using the WAVEWATCH III wave modeling framework. Central to this effort are the EMC svn server, and the development of best practices for code development by a group of developers. NOAA intends to support this svn server and active code management of WAVEWATCH III well beyond the time frame of this NOPP project.

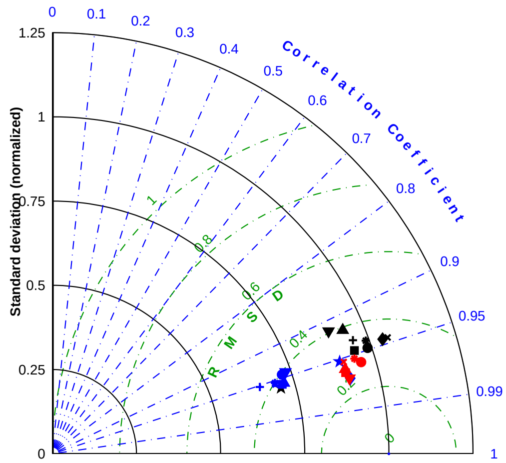

Fig. 6: Taylor diagram for wave heights for deep water buoys in the Great Lakes for 2009 using analysis wind fields of Schwab and Morton (1984). Symbols identify individual buoys. Colors identify model. Blue: Tolman and Chalikov (1996) physics. Red: Ardhuin et al. (2010) physics. Black: second generation GLERL-Donelan model (Schwab et al., 1984).

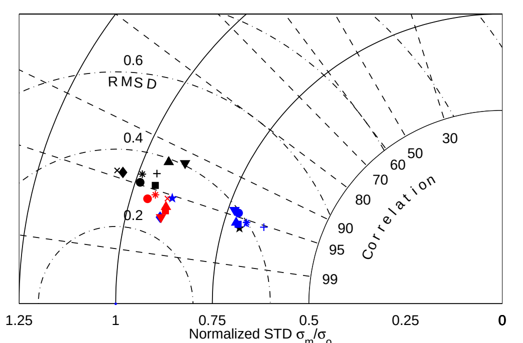

Fig. 7: Like Fig. 6 using alternate presentation of Boer and Lambert (2001).

References

Alves, J.-H. G. M., Y. Y. Chao and H. L. Tolman, 2005: The operational North Atlantic hurricane wind-wave forecasting sytem at NOAA/NCEP. Tech. Note 244, NOAA/NWS/NCEP/MMAB, 59 pp.

Ardhuin, F., B. Chapron and F. Collard, 2009a: Ocean swell evolution from distant storms. *Geophys. Res. Lett.*, **36**, L06607.

Ardhuin, F., T. H. C. Herbers, K. P. Watts, G. Ph. van Vledder, R. Jensen and H. Graber, 2007: Swell and slanting fetch effects on wind wave growth. *J. Phys. Oceanogr.*, **37**, 908–931.

Ardhuin, F., L. Marié, N. Rascle, P. Forget and A. Roland, 2009b: Observation and estimation of Lagrangian, Stokes and Eulerian currents induced by wind and waves at the sea surface. *J. Phys. Oceanogr.*, **39**(11), 2,820–2,838.

Ardhuin, F., W. C. O'Reilly, T. H. C. Herbers and P. F. Jessen, 2003: Swell transformation across the continental shelf. Part I: Attenuation and directional broadening. *J. Phys. Oceanogr.*, **33**, 1921–1939.

Ardhuin, F., W. E. Rogers, A. V. Babanin, J. Filipot, R. Magne, A. Roland, A. van der Westhuysen, P. Queffeulou, J. Lefevre, L. Aouf and F. Collard, 2010: Semiempirical dissipation source functions for ocean waves. Part I: Definition, calibration, and validation. *J. Phys. Oceanogr.*, **40**, 1,917–1,941.

Babanin, A. V., , I. R. Young and M. L. Banner, 2001: Breaking probabilities for dominant surface waves on water of finite constant depth. *J. Geophys. Res.*, **106**, 11,659–11,676.

Babanin, A. V., 2011: *Breaking and dissipation of ocean surface waves*. Cambridge University Press, 480 pp.

Babanin, A. V., M. L. Banner, I. R. Young and M. A. Donelan, 2007: Wave follower measurements of the wind input spectral function. Part 3. Parameterization of the wind input enhancement due to wave breaking. *J. Phys. Oceanogr.*, **37**, 2,764–2,775.

Banner, M. L., A. V. Babanin and I. R. Young, 2000: Breaking probability for dominant waves on the sea surface. *J. Phys. Oceanogr.*, **30**, 3,145–3.160.

Banner, M. L., J. R. Gemmrich and D. M. Farmer, 2002: Multiscale measurement of ocean wave breaking probability. *J. Phys. Oceanogr.*, **32**, 3364–3374.

Banner, M. L. and R. P. Morison, 2010: Refined source terms in wind wave models with explicit wave breaking prediction. Part I: Model framework and validation against field data. *Ocean Mod.*, **33**, 177–189.

Bidlot, J.-R., D. J. Holmes, P. A. Wittmann, R. Lalbeharry and H. S. Chen, 2002: Intercomparison of the performance of operational ocean wave forecasting systems with buoy data. *Wea. Forecasting*, **17**, 287–309.

Boer, G. J. and S. J. Lambert, 2001: Second-order space-time climate difference statistics. *Climate Dynamics*, **17**, 213–218.

Booij, N., L. H. Holthuijsen and M. P. Benit, 2009:

A distributed collinear triad approximation in SWAN. in *Coastal Dynamics 2009*. Paper 3, 9 pp.

Booij, N., R. C. Ris and L. H. Holthuijsen, 1999: A third-generation wave model for coastal regions, Part I, model description and validation. *J. Geophys. Res.*, **104**, 7,649–7,666.

Buis, S., A. Piacentini and D. Déclat, 2006: PALM: A computational framework for assembling high performance computing applications. *Concurrency Computat.: Pract. Exper.*, **18**, 247–262.

Chao, Y. Y., J. H. G. M. Alves and H. L. Tolman, 2005: An operational system for predicting hurricane-generated wind waves in the North Atlentic Ocean. *Wea. Forecasting*, **20**, 652–671.

Chao, Y. Y. and H. L. Tolman, 2010: Performance of NCEP regional wave models in predicting peak sea states duting the 2005 North Atlantic hurricane season. *Wea. Forecasting*, **25**, 1543–1567.

Chawla, A., D. M. Spindler and H. L. Tolman, 2011: WAVEWATCH III® Hindcasts with Re-analysis winds. an initial look at model setup. Tech. Note 291, NOAA/NWS/NCEP/MMAB, 35 pp. + Appendices.

Chawla, A., H. L. Tolman, J. L. Hanson, E.-M. Devaliere and V. M. Gerald, 2009: Validation of a multi-grid WAVEWATCH III ™ modeling system. in *11th international workshop on wave hindcasting and forecasting & coastal hazards symposium, JCOMM Tech. Rep. 52, WMO/TD-No. 1533*. Paper K2.

Collins, N., G. Theurich, C. DeLuca, M. Suarez, A. Trayanov, V. Balaji, P. Li, W. Yang, C. Hill and A. da Silva, 2005: Design and implementation of components in the earth system modeling framework. *International Journal of High Performance Computing Applications.*, **19**, 341–350.

Collins-Sussmann, B., B. W. Fitzpatrick and C. M. Pilato, 2004: *Version control with subversion*. O'Reilly, 320 pp.[9]

Dietrich, J. C., M. Zijlema, J. J. Westerink, L. H. Holthuijsen, C. Dawson, R. A. Luettich, R. Jensen, J. M. Smith, G. S. Stelling and G. W. Stone, 2011: Modeling hurricane waves and storm surge using integrally-coupled, scalable computations. *Coastal Eng.*, **58**, 45–65.

Donelan, M. A., A. V. Babanin, I. R. Young and M. L. Banner, 2006: Wave follower measurements of the wind input spectral function. Part 2. Parameterization of the wind input. *J. Phys. Oceanogr.*, **36**, 1,672–1,688.

Elgar, S. and B. Raubenheimer, 2008: Wave dissipation by muddy seafloors. *Geophys. Res. Lett.*, **35**, L07611, doi:10.1029/2008GL033245.

Gallego, G., A. Yezzi, F. Fedele and A. Benetazzo, 2011: A variational stereo method for the three-dimensional reconstruction of ocean waves. *IEEE Trans.*, doi:10.1109/TGRS.2011.2150230.

Gelci, R., H. Cazalé and J. Vassal, 1956: Ulitization des diagrammes de propagation à la prévision énergétique de la houle. *Bulletin d'information du commité central d'océanographie et d'études des côtes*, **8**, 169–197.

Gelci, R., H. Cazalé and J. Vassal, 1957: Prévision de la haule. La méthode des densités spectroangulaires. *Bulletin d'information du commité central d'océanographie et d'études des côtes*, **9**, 416–435.

Gemmrich, J. R. and D. M. Farmer, 2004: Near-surface turbulence in the presence of breaking waves. *J. Phys. Oceanogr.*, **34**, 1,067–1,086.

Gerling, T. W., 1992: Partitioning sequences and arrays of directional ocean wave spectra into component wave systems. *J. Atmos. Oceanic Techn.*, **9**, 444–458.

Glazman, R. E., 1994: Surface gravity waves at equilibrium with a steady wind. *J. Geophys. Res.*, **99**, 5,249–5,262.

Hanson, J. L. and O. M. Phillips, 1999: Windsea growth and dissipation in the open ocean. *J. Phys. Oceanogr.*, **29**, 1633–1648.

Hanson, J. L., B. A. Tracy, H. L. Tolman and R. D. Scott, 2009: Pacific hindcast performance of three numerical wave models. *J. Atmos. Oceanic Techn.*, **26**, 1614–1633.

Hasselmann, K., 1960: Grundgleichungen der seegangsvoraussage. *Schiffstechnik*, **7**, 191–195.

Hasselmann, K., T. P. Barnett, E. Bouws, H. Carlson, D. E. Cartwright, K. Enke, J. A. Ewing, H. Gienapp, D. E. Hasselmann, P. Kruseman, A. Meerburg, P. Müller, D. J. Olbers, K. Richter, W. Sell and H. Walden, 1973: Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP). *Ergänzungsheft zur Deutschen Hydrographischen Zeitschrift, Reihe A(8)*, **12**, 95 pp.

Hasselmann, S., K. Hasselmann, J. H. Allender and T. P. Barnett, 1985: Computations and parameterizations of the nonlinear energy transfer in a gravity-wave spectrum, Part II: parameterizations of the nonlinear energy transfer for application in wave models. *J. Phys. Oceanogr.*, **15**, 1,378–1,391.

Holthuijsen, L. H. and T. H. C. Herbers, 1986: Statistics of breaking waves observed as whitecaps in the open sea. *J. Phys. Oceanogr.*, **16**, 290–297.

Janssen, P. A. E. M., 1989: Wind-induced stress and the drag of air-flow over sea waves. *J. Phys.*

[9] Updated versions available online at http://subversion.tigris.org/.

Oceanogr., **19**, 745–754.

Janssen, P. A. E. M., 1991: Quasi-linear theory of of wind wave generation applied to wave forecasting. *J. Phys. Oceanogr.*, **21**, 1631–1,642.

Janssen, P. A. E. M. and M. Onorato, 2007: The intermediate depth limit of the Zakharov equations and consequences for wave prediction. *J. Phys. Oceanogr.*, **37**, 2,389–2,400.

Jiang, F. and A. Mehta, 1996: Mudbanks of the southwest coast of india V: Wave attenuation. *J. Coastal Res.*, **12**, 890–897.

Jolliff, J. K., J. C. Kindle, I. Shulman, B. Penta, M. A. M. Friedrichs, R. Helber and R. A. Arnone, 2009: Summary diagrams for coupled hydrodynamic-ecosystem model skill assessment. *J. Mar. Sys.*, **76**, 64–82.

Komen, G. J., L. Cavaleri, M. Donelan, K. Hasselmann, S. Hasselmann and P. A. E. M. Janssen, 1994: *Dynamics and modelling of ocean waves.* Cambridge University Press, 532 pp.

Komen, G. J., S. Hasselmann and K. Hasselmann, 1984: On the existence of a fully developed wind-sea spectrum. *J. Phys. Oceanogr.*, **14**, 1,271–1,285.

Lowe, R. J., J. L. Falter, M. D. Bandet, G. Ph.wlak, M. J. Atkinson, S. G. Monismith and J. R. Koseff, 2005: Spectral wave dissipation over a barrier reef. *J. Geophys. Res.*, **110**, doi:10.1029/2004JC002711.

Massey, T. C., M. E. Anderson, R. Jones, J. Gomez and J. McKee Smith, 2011: STWAVE: Steady-state spectral wave model user's manual for STWAVE, version 6.0. Tech. Rep. SR-11-1, ERDC/CHL.

Moon, I. J., I. Ginnis, T. Hara, H. L. Tolman, C. W. Wright and E. J. Walsh, 2003: Numerical modeling of sea surface directional wave spectra under hurricane wind forcing. *J. Phys. Oceanogr.*, **33**, 1680–1706.

Ocampo-Torres, F. J., H. García-Nava, R. Durazo, P. Osuna, G. M. Díaz Ménendez and H. C. Graber, 2010: The INTOA experiment: A study of ocean-atmosphere interactions under moderate to strong offshore winds and opposing swell conditions in the Gulf of Tehuantepec, Mexico. *Bound. Layer Meteor.*, **doi:10.1007/s10546-010-9561-5**.

Pedersen, T., E. Siegel and J. Wood, 2007: Directional wave measurements from a subsurface buoy with an acoustic wave and current profiler (AWAC). in *Proceedings Oceans 2007, Vancouver, Canada.*

Perrie, W. and D. T. Resio, 2009: A two-scale approximation for efficient representation of nonlinear energy transfer in a wind wave spectrum. Part II: Application to observed wave spectra. *J. Phys. Oceanogr.*, **39**, 2,451–2,476.

Powell, M. D., S. H. Houston, L. R. Amat and N. Morisseau-Leroy, 1998: The HRD real-time hurricane wind analysis system. *J. Wind Engineer. and Indust. Aerodyn.*, **77–78**, 53–64.

ProSensing, 2008: Operational Wide Swatch Radar Altimeter final report. SIBR report, US DOC/NOAA, 21 pp.

Queffeulou, P., 2004: Long term validation of wave height measurement from altimeters. *Mar. Geod.*, **27**, 495–510.

Resio, D. T., C. E. Long and W. Perrie, 2010: The role of nonlinear momentum fluxes on the evolution of directional wind-wave spectra. *J. Phys. Oceanogr.*, **41**, 781–801.

Resio, D. T. and W. Perrie, 2008: A two-scale approximation for efficient representation of nonlinear energy transfer in a wind wave spectrum. Part I: Theoretical development. *J. Phys. Oceanogr.*, **38**, 2,801–2,816.

Rice, S. O., 1944: Mathematical analysis of random noise. *Bell System Techn. J.*, **23**, 282–332.

Ris, R. C., L. H. Holthuijsen and N. Booij, 1999: A third-generation wave model for coastal regions, Part II: verification. *J. Geophys. Res.*, **104**, 7,667–7,681.

Rogers, W. E. and T. J. Campbell, 2009: Implementation of curvilinear coordinate system in the WAVEWATCH III model. report NRL/MR/7320–09-9193, Naval Research Laboratory Stennis.

Rogers, W. E. and K. Holland, 2009: A study of dissipation of wind-waves by viscous mud at Cassino Beach, Brazil: prediction and inversion. *Cont. Shelf Res.*, **29**, 676–690.

Roland, A., 2009: *Development of WWM II: Spectral wave modelling on unstructured meshes.* Ph.D. thesis, Technische Universität Darmstadt, Institute of Hydraulic and Water Resources Engineering.

Romero, L. and W. K. Melville, 2010: Airborne observations of fetch-limited waves in the Gulf of Tehuantepec. *J. Phys. Oceanogr.*, **40**, 441–465.

Safak, I., A. Sheremet, M. Allison and T. Hsu, 2010: Bottom turbulence on the muddy Atchafalaya Shelf, Louisiana, USA. *J. Geophys. Res.*, **115**, C12019, doi:10.1029/2010JC006157.

Saha, S., S. Moorthi, H. Pan, X. Wu, J. Wang, S. Nadiga, P. Tripp, R. Kistler, J. Woollen, D. Behringer, H. Liu, D. Stokes, R. Grumbine, G. Gayno, J. Wang, Y. Hou, H. Chuang, H. Juang, J. Sela, M. Iredell, R. Treadon, D. Kleist, P. V. Delst, D. Keyser, J. Derber, M. Ek, J. Meng,

H. Wei, R. Yang, S. Lord, H. van den Dool, A. Kumar, W. Wang, C. Long, M. Chelliah, Y. Xue, B. Huang, J. Schemm, W. Ebisuzaki, R. Lin, P. Xie, M. Chen, S. Zhou, W. Higgins, C. Zou, Q. Liu, Y. Chen, Y. Han, L. Cucurull, R. Reynolds, G. Rutledge and M. Goldberg, 2010: The NCEP climate forecast system reanalysis. *Bull. Am. Meteor. Soc.*, **91**, 1,015–1,057.

Sahin, C., I. Safak, T.-J. Hsu and A. Sheremet, 2011: Observations of sediment stratification on the muddy Atchafalaya Shelf, Louisiana, USA. *J. Geophys. Res.*, Submitted.

Schwab, D. J., J. R. Bennett, P. C. Liu and M. A. Donelan, 1984: Application of a simple numerical wave prediction model to Lake Erie,. *J. Geophys. Res.*, **89**, 3,586–3,592.

Schwab, D. J. and J. A. Morton, 1984: Estimation of overlake wind speed from overland wind speed: A comparison of three methods. *J. Great Lakes Res.*, **10**, 68–72.

Shemdin, O., K. Hasselmann, S. V. Hsiao and K. Heterich, 1978: Nonlinear and linear bottom interaction effects in shallow water. in *Turbulent fluxes through the sea surface, wave dynamics and prediction*, pp. 347–365. NATO Conf. Ser. V, Vol 1.

Sheremet, A., S. Jaramillo, S.-F. Su, M. A. Allison and K. T. Holland, 2011: Wavemud interaction over the muddy Atchafalaya subaqueous clinoform, Louisiana, United States: Wave processes. *J. Geophys. Res.*, **116**, C06005, doi:10.1029/2010JC006644.

Sheremet, A. and G. W. Stone, 2003: Observations of nearshore wave dissipation over muddy sea beds. *J. Geophys. Res.*, **108**, 3357, doi:10.1029/2003JC001885.

Snodgrass, F. E., G. W. Groves, K. F. Hasselmann, G. R. Miller, W. H. Munk and W. H. Powers, 1966: Propagation of swell across the pacific. *Trans. Roy. Soc. London*, **A 259**, 431–497.

Snyder, R. L., F. W. Dobson, J. A. Elliott and R. B. Long, 1981: Array measurements of atmospheric pressure fluctuations above surface gravity waves. *J. Fluid Mech.*, **102**, 1–59.

Spindler, D. M., A. Chawla and H. L. Tolman, 2011: An initial look at the CFSR Reanalysis winds for wave modeling. Tech. Note 290, NOAA/NWS/NCEP/MMAB, 23 pp.

Sverdrup, H. U. and W. H. Munk, 1946: Empirical and theoretical relations between wind, sea and swell,. *Trans. Amer. Geophys. Union*, **27**, 823–827.

Sverdrup, H. U. and W. H. Munk, 1947: Wind, sea and swell: Theory and relations for forecasting. Tech. Rep. H. O. Pub. No. 601, United States Navy Department, Hydrographic Office.

SWAMP group, 1985: *Ocean wave modelling*. Plenum Press, 256 pp.

Tahvildari, N. and J. M. Kaihatu, 2011: Weakly nonlinear resonant interactions among long surface and interfacial waves. *J. Fluid Mech.*, Submitted.

Taylor, K. E., 2001: Sumarizing multiple aspects of model performance in a single diagram. *J. Geophys. Res.*, **106**(D7), 7,183–7,192.

Tolman, H. L., 1994: Wind-waves and moveable-bed bottom-friction. *J. Phys. Oceanogr.*, **24**, 994–1009.

Tolman, H. L., 2008: A mosaic approach to wind wave modeling. *Ocean Mod.*, **25**, 35–47.

Tolman, H. L., 2010a: Optimum Discrete Interaction Approximations for wind waves. Part 4: Parameter optimization. Tech. Note 288, NOAA/NWS/NCEP/MMAB, 175 pp.

Tolman, H. L., 2010b: WAVEWATCH III ® development best practices. Tech. Note 286, Ver. 0.1, NOAA/NWS/NCEP/MMAB, 19 pp.

Tolman, H. L., 2011: A conservative nonlinear filter for the high-frequency range of wind wave spectra. *Ocean Mod.*, **39**, 291–300.

Tolman, H. L., B. Balasubramaniyan, L. D. Burroughs, D. V. Chalikov, Y. Y. Chao, H. S. Chen and V. M. Gerald, 2002: Development and implementation of wind generated ocean surface wave models at NCEP. *Wea. Forecasting*, **17**, 311–333.

Tolman, H. L. and D. V. Chalikov, 1996: Source terms in a third-generation wind-wave model. *J. Phys. Oceanogr.*, **26**, 2497–2518.

Van der Westhuysen, A. J., 2011: Development of a quasi-stationary version of WAVEWATCH III®. Tech. note, NOAA/NWS/NCEP/MMAB, in preparation.

Violante-Carvalho, N., F. J. Ocampo-Torres and I. S. Robinson, 2004: Buoy observations of the influence of swell on wind waves in the open ocean. *Appl. Ocean Res.*, **26**, 49–60.

WAMDIG, 1988: The WAM model – a third generation ocean wave prediction model. *J. Phys. Oceanogr.*, **18**, 1,775–1,810.

Wingeart, K. M., W. C. O'Reilly, T. H. C. Herbers, P. A. Wittmann, R. E. Jenssen and H. L. Tolman, 2001: Validation of operational global wave prediction models with spectral buoy data. in B. L. Edge and J. M. Hemsley, editors, *4th International Symposium on Ocean Wave Measurement and Analysis*, pp. 590–599. ASCE.

WISE Group, 2007: Wave modelling - the state of the art. *Progress in Oceanography*, **75**, 603–674.

Young, I. R. and A. V. Babanin, 2006: Spectral distribution of energy dissipation of wind-generated waves due to dominant wave breaking. *J. Phys. Oceanogr.*, **36**, 376–394.

Young, I. R., M. L. Banner, M. A. Donelan, A. Babanin, W. K. Melville, F. Veron and C. McCormick, 2005: An integrated system for the study of wind wave source terms in finite depth water. *J. Atmos. Oceanic Techn.*, **22**, 814–828.

Young, I. R. and R. M. Gorman, 1995: Measurements of the evolution of ocean wave spectra due to bottom friction. *J. Geophys. Res.*, **100**, 10,987–11,004.