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The NOPP operational wave model improvement project ☆

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ABSTRACT

The National Oceanographic Partnership Program (NOPP) has recently initiated a five-year project entitled "Improving Wind Wave Predictions: Global to Regional Scales". This project focuses on improving operational wind wave modeling, by transitioning new science into such models, and by developing new physics parameterizations for such models. The paper describes the general goals of the project, and the science and operations gaps it attempts to bridge. Further attention is given to data sets and validation techniques for operational models. Finally, an outlook with desired and already achieved outcomes of this project is presented.

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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, and preceding landings in Africa (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)

$$\frac{DF}{Dt} = S_{in} + S_{nl} + S_{ds} + \cdots, \tag{1}$$

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

In the next two decades a large number of wave models were developed. The Sea Waves Modeling Project (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 computationally inexpensive 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).

These modern wave models are generally using an action balance equation (following Bretherthon and Garrett, 1968) accounting for linear wave–current interactions and linear shallow water kinematics, replacing Eq. (1) by

$$\frac{\partial N}{\partial t} + \nabla_x \cdot (\boldsymbol{c}_g + \boldsymbol{U})N + \nabla_s \cdot \boldsymbol{c}_s N = \sigma^{-1}(S_{in} + S_{nl} + S_{ds} + \cdots), \tag{2}$$

where $N \equiv F/\sigma$ is the action density spectrum, σ is the (spectral) intrinsic wave frequency, ∇_x and ∇_s are differential operators in physical and spectral space, respectively, $\boldsymbol{c}_g$ is the wave group velocity, $\boldsymbol{U}$ is the mean ambient current, and $\boldsymbol{c}_s$ represents the characteristic velocity in spectral space. In research studies, the spectral space is often described using the vector wavenumber ($\boldsymbol{k}$), whereas practical (operational) wave models always describe spectral space with the direction θ of the wave component, and either a frequency or the scalar wavenumber, e.g., (σ, θ) or (k, θ). This equation will be discussed in some more detail in Section 2.

☆ MMAB contribution Nr. 300.

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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 the traditional DIA, and many use older source term packages of Snyder et al. (1981), Komen et al. (1984), Janssen (1989), Janssen (1991), and Tolman and Chalikov (1996). This is mostly due to the lack of success in finding efficient yet more accurate replacements of the DIA for nonlinear interactions, and due to our slowly developing understanding of the physics of wave energy dissipation due to wave breaking. 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).

Considering the 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".[1] The project intends 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. WAM, SWAN and STWAVE (Massey et al., 2011) are also used in the project, and can be used as distribution vehicles for new approaches. Due to the modular design of all these models, it will be relatively simple to distribute new approaches to all these models.

Note that this manuscript introduces this NOPP project, while presenting some initial results. We intend to give a full accounting of the results obtained through this NOPP project at the end of its funding cycle.

The outline of the paper is as follows. Section 2 describes the various science and capability gaps that this project attempts to address. Sections 3 and 4 discuss validation data and validation techniques. Finally, an outlook with desired and already achieved outcomes of this projects is presented in Section 5. Additional information on work plans, long term hindcasts, code management, and planned operational implementations can be found in Tolman et al. (2011).

2. State of the science and operational models

Operational forecasting models have progressed but are still hampered by the gap between scientific advance and forecasting efficiency. This gap affects both the applicability of models in various environments (e.g., very shallow water, extreme hurricane conditions) and the accuracy of the models in general. In this section we discuss several possible avenues for improvement.

2.1. Deep water physics and knowledge gaps

The primary aim is to introduce new physics to improve the accuracy of ocean wave forecasts over a wide dynamic range of wind speeds, from the open ocean to the shoreline, in the presence of current systems and ocean swells. These wave systems are driven by complex wind fields which can span from light, variable wind to hurricane strength and which can also turn or suddenly relax. Ideally, the wave modeling system should provide a framework that allows for full coupling to the associated atmospheric and ocean circulation models.

In deep water, where ambient currents are often ignored, Eq. (2) reduces to a form more similar to Eq. (1)

$$\frac{\partial F}{\partial t} + \boldsymbol{c}_g \nabla_x F = S_{tot}, \tag{3}$$

possibly with an additional term on the left hand side to explicitly describe changes in wave direction while propagating along great circles. The total source term is $S_{tot} = S_{in} + S_{nl} + S_{ds}$, where S_{in} is the atmospheric input spectral source term, S_{nl} is the nonlinear spectral transfer source term representing nonlinear wave–wave interactions and S_{ds} is the spectral dissipation rate, assumed primarily due to wave breaking. These source terms are described in detail in the following sections.

2.1.1. Wind Input S_{in}

There is still no universal consensus for S_{in}, and several proposed forms for this are being evaluated as part of the overall effort. These include the Miles–Janssen form modified for sheltering in the spectral tail region (Banner et al., 2010), and an observation-based form proposed by Donelan et al. (2006) and Babanin et al. (2007). The potentially strong influence of wave steepness in reducing the growth rate (Peirson and Garcia, 2008) presents an additional element that requires investigation. Complex test cases including slanting fetches and relaxing sea states are being used to evaluate these different forms of S_{in}. Note that an important aspect of the input source term is that it is internally constrained, for instance to assure that total input in the wave model is consistent with stress in the atmospheric boundary layer.

An alternate analytical theory of wind-driven sea waves (Zakharov et al., 2012a) proposes that S_{nl} dominates S_{in} and S_{ds} (Zakharov, 2010a,b; Zakharov and Badulin, 2011). According the this theory, it is possible to find self-similar solutions of (3) which accord with experimentally-observed dependence of integral characteristics of wave spectra for duration and fetch (Zakharov, 2005; Badulin et al., 2005, 2007; Zakharov and Badulin, 2011; Zakharov et al., 2012b). This approach offers a new source term for the wind input (Zakharov and Badulin, 2011; Zakharov et al., 2012b).

2.1.2. Nonlinear spectral transfer source term S_{nl}

The full Boltzmann integral description of S_{nl}, for instance, as implemented in the commonly used Web–Resio–Tracy approach (WRT; Webb, 1978; Tracy and Resio, 1982; Resio et al., 1991), typically involves millions of interactions at each time step, and hence is too computationally intensive for operational use. The one-term DIA approximation is arguably oversimplified, and is generally considered as a stumbling block for reproducing detailed spectral balances of source terms. In the NOPP project, the DIA method represents the present operational baseline, whereas the WRT method represents the full description of the nonlinear interactions. Two recently developed new approaches will be used as potentially more accurate yet economical substitutes for the DIA.

One of the new approaches is the "Two Scale Approximation" (TSA) to the quadruplet interactions as introduced by Resio et al. (2008), Perrie et al. (2009), and Resio et al. (2011) to provide accurate and efficient model code for the nonlinear four-wave interactions for implementation into operational forecast models. The NOPP effort builds on the above work by adapting the TSA to (i) operational model constraints and (ii) actual evolving ocean wave conditions.

The other approach is the Generalized Multiple DIA (GMD, Tolman, 2010a; Tolman, submitted for publication; Tolman and Grumbine, submitted for publication). This approach provides a cascade of interaction approximations with increasing accuracy and cost, specifically optimized for selected input and dissipation

[1] http://www.nopp.org/funded-projects/fy2009-projects-funded-under-nopp/topic1.

source terms, and has been shown to be able to closely reproduce WRT results at modest increase of computational costs of operational wave models. Development of a GMD for new source term packages is automated (Tolman, 2010b), and generally consists of three steps. (i) Develop S_{in} and S_{ds} using WRT for idealized conditions. (ii) Replace the WRT with an optimized GMD. (iii) Apply to realistic conditions to fine tune S_{in} and S_{ds}.

2.1.3. Spectral dissipation rate S_{ds}

Recent progress towards understanding and parameterizing the least-understood source term S_{ds} has had a significant impact on reducing the errors in wave forecast modeling over a broad range of conditions (e.g., Banner et al., 2010; Ardhuin et al., 2010; Young and Babanin, 2006; Babanin, 2011). These various dissipation rate parameterizations are being evaluated and extended in NOPP to embrace directional wave breaking effects and swell dissipation. For overall bias reduction in global wave models, swell decay rates are critical (Tolman et al., 2002). Previously, swell decay has been modeled as "negative wind input" (Tolman and Chalikov, 1996). Recent detailed observation of swell decay (Ardhuin et al., 2009a) has provided (nonlinear) dissipation source terms for swell which are expected to significantly improve operational wave model accuracy.

As well as improving spectral wave forecast accuracy, efforts are underway to add reliable routine breaking wave forecasts to sea state forecasts, as this is a significant safety of life at sea issue that is presently not addressed by operational wave models. Validations are proposed in the NOPP project, including the use of dissipation rates and breaking statistics estimated from the stereo-video data system WASS (Gallego et al., 2011; Benetazzo et al., 2012).

Within the alternate analytical theory of wind-driven sea waves (Zakharov et al., 2012a), it is also possible to offer a new source term for the whitecap dissipation that complements their new wind input source term (Zakharov and Badulin, 2011; Zakharov et al., 2012b). This alternative approach is being evaluated critically within NOPP.

2.2. Shallow water physics and knowledge gaps

In shallow water, the bathymetry exerts a profound effect on processes governing the evolution of the wave spectrum, and all terms in Eq. (2) are important. The conservation of action rather than energy implies an energy exchange between waves and currents in spatially varying current fields $\boldsymbol{U}$. The spatial variation of $\boldsymbol{c}_g$ due to the bathymetry results in changes of wave energy associated with wave shoaling. A similar effect is associated directly with spatial variations of the current $\boldsymbol{U}$. In addition, the gradient operator in spectral space also includes variations in spectral energy with respect to direction (due to depth and current induced refraction) and with respect to frequency (due to wave–current interaction) and wavenumber (due to depth variations, i.e., shoaling).

The right hand side S_{tot} still retains the same general form as in the deep water Eq. (3), but with the addition of triad interactions and depth-limited breaking. Furthermore, bottom friction, previously unaddressed, becomes more important as the waves enter shallow water; consequently, the need for addressing bottom type also becomes paramount, particularly if the bottom is comprised of cohesive material. Finally, in very shallow areas such as estuaries, the presence of vegetation also affects the wave propagation, and there is a need for inclusion of the appropriate damping mechanisms.

2.2.1. Effect of cohesive bottom material and vegetation on shallow water waves

There is substantial evidence, from both model results (Sheremet et al., 2005; Kaihatu et al., 2007) and measurements (Elgar and Raubenheimer, 2008; Sheremet et al., 2011), that the presence of cohesive sediments under waves affects not only the linear transformation of the wave spectrum (in terms of energy damping) but also the nonlinear energy transfer. Sheremet and Stone, 2003 first noticed the damping of both low and high frequency waves due to a mud suspension event on the Atchafalaya Shelf in Louisiana, USA. It was later hypothesized (Sheremet et al., 2005; Kaihatu et al., 2007) that the high frequency damping seen was due to subharmonic interactions exacerbated by the damping of low frequencies due to the mud. The effect of a coflowing current on this interaction was investigated by Kaihatu and Tahvildari (2012).

In addition to these modeling efforts, measurements of wave–mud interaction have been performed on the Atchafalaya shelf (Safak et al., 2010; Sheremet et al., 2011; Sahin et al., submitted for publication). It was evident from the measurements that the damping characteristics of the mud were not static but had a clear time dependence during and after passage of wave events. In concert with the modeling effort, these data will allow for incorporation of dynamic mud behavior into operational models. There is some precedence to this (Winterwerp et al., 2007) but more work is needed. One possible mechanism for accounting for dynamic behavior of the mud is by inclusion of the effect of lutocline – free surface interactions (Tahvildari and Kaihatu, 2011).

The presence of vegetation on the coastal plain has been a recent interest since the recent active hurricane seasons (Irish et al., 2008), but incorporation of this effect into models is still largely unexplored. One exception is Augustin et al. (2009), where the effect of vegetation has been included into a nonlinear wave model, but further work on the effect of vegetation-induced dissipation over the wave spectrum is needed.

2.2.2. Deep water–shallow water transitions

As waves approach shallow water, there is a transition from slow, resonant four wave interactions to near-resonant three wave interactions. The prevailing theories for deep and shallow water nonlinearity, however, have no overlap in intermediate water depth, and thus there is still no systematic crossover mechanism between four wave and three wave interactions. Janssen et al. (2006) retain both triad and quadruplet terms in their model, but require a way to switch between the two terms. One possible way forward would be in the investigation of the statistical signature of higher order wave phase correlations – bispectra and related quantities – which would help demarcate the transition. In addition, appropriate quadruplet approximations and weakly-dispersive wave closures are required to enable this transition. Moreover, triad formulations require a reliable formulation in the phase-averaged format of operational wave models; Booij et al. (2009) have investigated this with an extended Boussinesq model.

Note that for (combined four- and) three-wave interactions, no baseline solution like WRT is available. For further development of operational wave models, such a model would be of high value. Hence, the NOPP project focuses on such an approach, although it is not expected to yield direct improvements for operational models.

2.2.3. Wave dissipation and low-frequency energy

To improve accuracy of operational models in shallow water, wave dissipation mechanisms appropriate to operational model formats need to be included. The appropriateness of typical shelf-scale bottom friction mechanisms such as the JONSWAP formulation needs to be investigated and altered, if necessary. Depth-induced wave breaking in the nearshore waters, formulations for which have been limited to unidirectional waves over mild sloping bathymetry, is now affected by the water depth, bottom slope, and directional characteristics of the wave field. In addition, wave breaking "memory" affects how the wave breaks over steep bathymetry. Many of these effects have been investigated and included in SWAN by Salmon and Holthuijsen (submitted for publication). The resultant spectral characteristics can be verified with observations made from sophisticated instruments such as acoustic wave and current profilers (Pedersen et al., 2007).

The nearshore dissipation and transformation process can lead to the generation of low frequency surf beat, which can be detected by nearshore instruments. Mechanisms for accounting for their generation and transformation need to be included in operational wave models.

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 and 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), as is done in the ongoing JCOMM[2] operational model intercomparison project (Bidlot et al., 2002). 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 behaviors to be tested, and then find appropriate data sets for these conditions. Since this NOPP project focuses on modeling, we can mainly use existing data sets (with exceptions as identified in the previous section). 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.

3.1. 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 $0.5 \times 0.5^{\circ}$ 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 (Chawla et al., 2011, 2013). 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 sources 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 (see also Young et al., 2011). In this context, the CFSR wind are not sufficiently 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, particularly in the Southern Hemisphere.

3.2. 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 occur naturally 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 consider wave growth (wind seas) in shallow water.

Swells can be tracked over long distance in the ocean using traditional in situ spectral observations, 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). Furthermore, SAR data can infer directional wave energy distributions for originating winds seas from directional dispersion patterns of swell. Therefore, 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, 2001) makes it possible to separate wind seas and swell in almost arbitrary wave conditions. This technique will be important to use with 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 et al., 2010) therefore augment traditional observations, and are

[2] WMO–IOC Joint technical Committee on Oceanography and Marine Meteorology, UNESCO.

intended to be included in the NOPP data base. The Duck[3] data-set also includes such conditions (e.g., Ardhuin et al., 2007).

3.3. 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. Particularly, parameterizations of nonlinear interactions appear to have a significant impact on turning wind behavior, and will be investigated in particular with exact interactions, the TSA and GMD parameterizations. Two situations lead to misalignment (see sections below), and will be considered in model testing and validation.

3.3.1. 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, particularly of 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.

3.3.2. Tropical cyclones

Wind waves misaligned with winds also systematically occur in Tropical Cyclones (TCs) (e.g., Young, 2006). Recent studies have shown that model accuracy in such conditions is sensitive to the nonlinear interaction approximation (Tolman, 2010a, submitted for publication). 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 models 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, possibly using hurricane wind analysis from Powell et al. (1998), merged with CFSR large-scale wind fields.

3.4. 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 hindcast 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; Babanin et al., 2001; Banner et al., 2000, 2002 will be of high value to this NOPP project.

3.5. 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 models (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 known for well over a decade (NCEP oral presentations at various conferences). 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 in an oral presentation at the 2011 Wave Forecasting and Hindcasting Workshop in Kona, Hawaii.[4] It is not clear if there are other suitable datasets to address this issue, but tentatively, virtually every data set already mentioned here 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), from buoys south of Hawaii (particularly National Data Buoy Center (NDBC) buoy 51004, as used in the Glazman study), and East of the Windward Islands (buoys 41101 and others) can tentatively be used for evaluating wave behavior in such conditions.

3.6. 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 et al., 2009; Sheremet et al., 2011) and wave-reef interactions (Lowe et al., 2005 or PILOT project web site[5]) 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 interactions 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 from the Mississippi (Atchafalaya delta). Additional data may be considered,

[3] US Army Corps of Engineers Field Research Facility at Duck, NC.

[4] Wind wave model performance in relaxing wind seas, R.P. Morison, M.L. Banner, J.H. Alves and P. Sullivan, Paper I16.

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

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 and 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).
- A key element of IMEDS is spectral partitioning (Gerling, 1992; Hanson and Phillips, 2001), allowing for validation of each individual wave field within the spectrum. This partitioning is routinely available in WAVEWATCH III, and is transitioned to SWAN. The partitioning allows for space–time tracking of coherent wave systems (Devaliere et al., 2009; Van der Westhuysen et al., in preparation), which opens new venues for validating swell dispersion and decay.
- 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 also allows for tracing individual swell systems.
- The latter two papers 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. Taylor and target diagrams (Taylor, 2001; Jolliff et al., 2009) allow for a simultaneous representation of various model characteristics. Fig. 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.

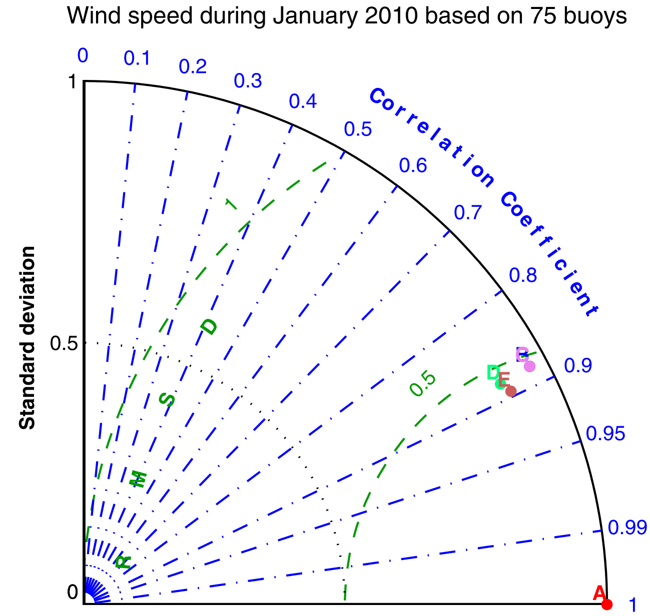

Fig. 1. Taylor diagram for various global wind field errors for January 2010 based on wind speed observations at 75 buoys. A represents the observations, B–E represent various wind field sources. Note that point C is covered by point B in the graph.

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. Examples of Taylor diagrams, or alternate representations as suggested by Boer and Lambert (2001), can be found in Figs. 6 and 7 of Tolman et al. (2011).

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. 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). Even in the early stages of this project, it is clear that significant improvements in operational wave modeling will be achieved. The efforts on improving the basic (deep water) wave growth dynamics are being implemented at NCEP (see Tolman et al., 2011, Section 7). 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, including (i) nonlinear features of the bottom boundary layer, and (ii) a possibly strong interaction 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 limited 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 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.

Ideally, the NOPP project would result in a consensus set of best physics parameterizations for operational wind wave models. However, it is also likely that several competing parameterization sets will be developed with similar performances against detailed objective validation. Whereas a single set of parameterizations needs to be chosen for a deterministic wave model, this is not necessarily the case for probabilistic (ensemble) wave model approaches. Recent progress in general atmospheric ensemble approaches (e.g., Zhu, 2005), and in hurricane forecasting (e.g., Kumar et al., 2003; Krishnamurti et al., 2010) have indicated the potential of ensembles with a variety of physics approaches (Multi Model Ensemble or MME). The potential of such an approach for wind wave modeling has been shown by Durrant et al. (2009). A set of optimized physics parameterizations for wind waves from this NOPP project would present a unique starting point for a MME stochastic forecast approach for wind waves.

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 (Tolman et al., 2011, Section 6), which has already led to an acceleration of development of capabilities for this model (e.g., Tolman et al., 2011 page 10). Central to this effort are the EMC Subversion (svn, Collins-Sussmann et al., 2004) 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.[6]

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