THE DEVELOPMENT OF SPECTRAL WAVE MODELS: COASTAL AND COUPLED ASPECTS

Fabrice Ardhuin and Aron Roland

Abstract

The first spectral numerical wave model was developed in the 1950s to deal with dispersive swell propagation arriving in Morocco. These models are still being refined today, reaching typical root mean square errors of 10% on the significant wave height in the middle of oceans, an error level that has dropped 20% over the last 5 years, and 30% for the mean wave period. Errors in coastal areas are now getting close to these levels thanks to the introduction of currents, bottom sediment types, coastal reflection… These latter two aspects are particularly discussed here. Models are also getting more efficient with unstructured grids, allowing unprecedented detailed hindcasts and forecasts, such as provided by the Previmer and IOWAGA projects, and the estimate of new wave-related quantities such as air-sea fluxes, wave breaking statistics, acoustic and seismic noise sources… As these models are being pushed into shallower and shallower waters, the currents and water levels cannot be considered independently of waves. This has spurred an on-going effort on theoretical foundations, numerical techniques and measurement and validation methods for the investigation of coupled wave-current dynamics. We review here some of the important milestones in this effort and point to still open questions. As both authors have been strongly involved in the development of version 4 of the WAVEWATCH III model, soon to be made public, these are part of the ideas that have driven the development of this particular code, but they apply generally to all phase-averaged spectral models.

Key words: waves, spectral models, coupled wave-current modelling, ocean-atmosphere interactions, morphodynamics

1. About spectra and spectral wave models

The basic idea of spectral wave modelling is to represent the random nature of the sea surface elevation by its generalized Fourier spectrum, evolving slowly in space and time. Some available spectral models can carry the phase information that allows to compute wave asymmetry and skewness (Herbers and Burton 1997, a part of the U.S. Nearshore Comunity models). This information is particularly relevant in shallow water, but these models have not been widely adopted by the research or engineering community, probably because of the conceptual difficulty of working with both spectra and bi-spectra. Outside of the surf zone, phase-resolving models have been used very successfully in ocean engineering applications, when the details of the wave shape and flow are required (Dommermuth and Yue, 1987), and also to verify the underlying hypotheses of phase-averaged model and their statistical closure (Tanaka 2001). However, in this region of the ocean, it was found repeatedly that the full statistics of the sea surface are very well described by the quasi-linear random wave model: waves can be represented as a superposition of wave trains that are locally sinusoidal and that propagate in all possible directions with all possible frequencies, with a period T and wavelength L related by the linear dispersion relation for free surface gravity waves (Laplace 1776). As a result, the general three-dimensional wave spectrum collapses to a two-dimensional spectrum. The two spectral dimensions can thus be chosen among the pairs wavenumber and direction (k,θ), frequency and alongshore wavenumber (f,k_y), or more usually frequency and direction (f,θ) as shown in figure 1. For extreme events, including the famous “freak waves”, a second-order correction estimated from the wave spectrum is enough to explain the statistics of extremes, and correct the wave spectrum for the presence of lowest order bound wave components (Tayfun 1980, Janssen 2009). This second order correction includes the partial standing wave term that makes it possible to measure waves without getting wet, using seismic stations on land (Miche 1944, Longuet-Higgins 1950, Herbers et al. 1992, Ardhuin and Herbers 2013).

This second order correction requires the knowledge of the full directional wave spectrum, which is almost never available in enough details, except when using dense arrays or techniques such as stereo-video imagery, as illustrated in figure 1.

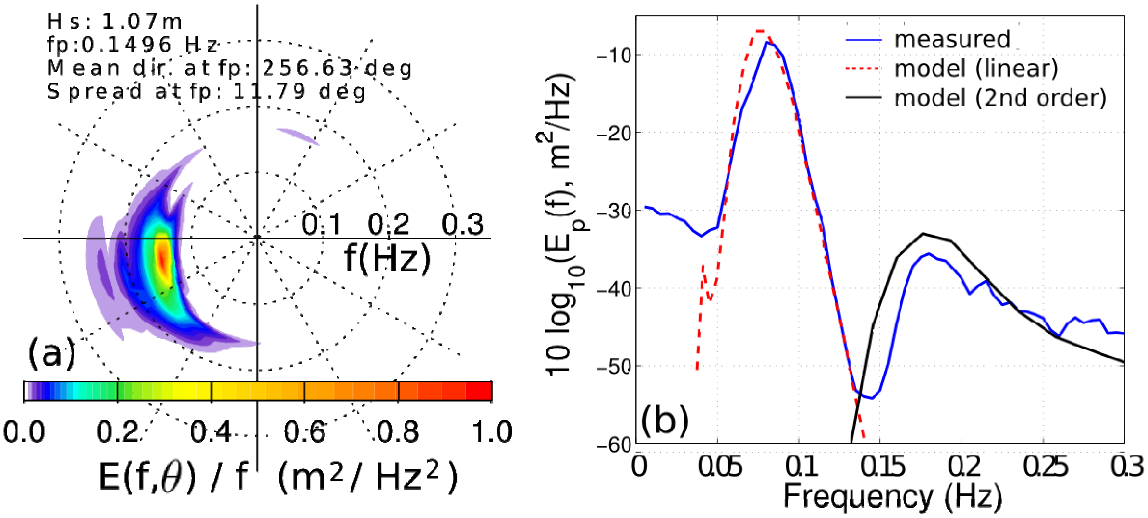

Figure 1. Two examples of wave spectra. (a) Obtained from a stereo-video system measuring maps of sea surface elevation (Benetazzo 2006) deployed on the Katsiveli platform near Sebastopol, Ukraine, (b) Spectrum of bottom pressure from a SBE26 tide gauge deployed in 100 m depth offshore of Brest, compared to its simulation from global wind fields using the WAVEWATCH III code. In this case the measured spectrum is compared to a numerical model result for both the linear part and the second-order correction (Ardhuin et al., in press). This second order contribution, together with measurement noise, is the reason why it is impossible to estimate the spectrum of waves of period 6 s in 100 m depth.

Indeed, wave buoys or combinations of pressure and velocity measurements only provide few parameters for each frequency. The validation of the second order spectrum estimated from a modeled directional spectrum thus provide more information on the width of the peak in the case of sub-harmonics and on the presence of partial standing waves in the case of the super-harmonics, such as induced by partial reflection (e.g. Touboul and Rey 2012). However this second order theory is only valid for a flat bottom breaks down in shallow water, where it fails to represent the net transfer of energy to free components with shorter periods (super-harmonics) or very long periods (sub-harmonics also known as infragravity waves) and which requires the use of a bi-spectrum that carries the relative phase information of the different wave components. Several parameterizations have been proposed for this effect, with some success (Becq 1999, Toledo et al. 2012), avoiding the higher computational cost incurred when computing the bi-spectrum evolution. Although the shape of the wave spectrum will miss the harmonic generation, these triad nonlinear effects may also be ignored, and accurate significant wave heights can still be obtained (e.g. Thornton and Guza 1983, Filipot and Ardhuin 2012). From now on we will focus mostly on the ocean outside of the surf zone.

2. Spectral wave models: inherent limitations and recent progress

2.1. *The wave action equation and its numerical solution*

Over the last twenty years, models based on the spectral wave action equation (WAE) such as WAM (WAMDI Group, 1988), TOMAWAC (Benoit et al., 1996), SWAN (Booij et al., 1999), and WAVEWATCH III® (Tolman, 2002, hereinafter WW3) have gained widespread usage, almost pushing out energy-conserving methods based on ray tracing (Dobson 1967, O'Reilly and Guza, 1993) or phase-resolving equations (Berkhoff, 1972; Dalrymple and Kirby, 1988, Kaihatu and Kirby, 1995; Belibassakis, et al. 2001), the latter being now confined to harbor agitation applications. These alternative methods, however, are still very useful for the verification of the models based on the WAE equation. Indeed the WAE-based models are prone to larger errors in their representation of wave propagation as an advection in spatial (x,y) and spectral (f,θ) spaces (Ardhuin and Herbers, 2005). This and other difficulties are reviewed by the WISE Group (2007). More recent developments are discussed below.

The WAE gives the evolution in space and time of the wave spectrum, represented by the advection of spectral densities $A(f,\theta) = E(f,\theta)/\sigma$ where σ is the relative radian frequency, at a velocity given by the group speed vector $\mathbf{C}g(f,\theta)$ plus an advective current velocity $\mathbf{U}_A(f,\theta)$ which is the generalized Lagrangian mean velocity (Andrews and McIntyre, 1978b). So far, the public version of numerical models such as SWAN or WW3 do not bother with this kind of detail, and use instead the same "surface current velocity" **U** for all spectral components instead of more general $\mathbf{U}_A(f,\theta)$. The evolution of the action spectrum is further modified by source terms that represent a wide range of processes: generation by the wind, non-linear evolution of the waves, dissipation by breaking, dissipation by friction at the air-sea interface, bottom friction, scattering by depth or current gradients …
Each of these source terms is computed from theoretical bases and empirical adjustments.

Without these source terms, the conservative WAE could be solved exactly by ray-tracing methods. Introducing source terms in ray tracing makes the solution method difficult (Ardhuin et al., 2001). This is simplified by integrating rays over a single time step, as done in the TOMAWAC model (Benoit et al., 1996), but at the price of some diffusion which may still be much less than the diffusion with a first order finite difference scheme that may be use in other types of models like SWAN or WW3 (Ardhuin and Herbers 2005). Instead, the unsteady 4-dimensional problem can be formulated in an Eulerian sense. The propagation part can than be solved with the aid of common numerical schemes such as FEM, FVM or FDM on either structured or unstructured grids using various time stepping strategies as done in WAM, WW3, SWAN and other models.

With respect to the time stepping strategies these models either use certain flavors of the fractional step method of Yanenko (1974) or solve the problem directly, using implicit time stepping techniques proposed by e.g. Patankar (1980).

The latter methods (Booij et al. 1998) have been advocated to be efficient in the nearshore and implemented into SWAN, because they to not have a strict CFL-like stability criterion, thanks to their implicit formulation. However, in the presence of steep slopes the model suffers from unphysical solutions and certain limiters in spectral space must be applied, as outlined in Dietrich et al. (2012b), where it is mentioned that the turning of the certain wave component must remain in the quadrant of the current sweep. In practice it is finally limited to be not greater than one spectral increment in their solution method, and similar constraints apply to frequency space when waves go over varying currents. As a result, the benefit of implicit methods is questionable since this kind of limiter effectively truncates the solution to something similar to the stable time step of explicit methods.

The great benefit of splitting methods is that it separates the WAE integration into an ordinary differential equation for the source term integration, and a hyperbolic partial differential equation for the propagation part. Once separated, specific numerical schemes and solution procedures can be applied most efficiently for each.
This splitting technique gives excellent results in deep ocean and is used in combination with explicit time integration methods for the propagation part in codes such as WW3 or WAM, which are used by most weather forecasting centers. However, in shallow regions, where strong variations of depth and currents occur, the efficiency of explicit methods is governed by the strict CFL criterion and this may result in a very small stable time step. This drawback can be partly circumvented by splitting not only propagation and source terms, but also spectral and geographical advection, and introducing sub-cycling as done in WWIII. This relaxes the time step constraint on the whole system, especially in the presence of e.g. steep bottom slopes: only refraction computation is limited by a small time step and not the spatial propagation. Due to the sub-cycling, however, splitting errors are introduced into the solution (the solution of the split integration is not exactly equal to the solution of the whole equation), which are growing with the amount sub-cycles. When the near-shore circulation is of concern and the breaking zone needs to be resolved or in

tidal channels the smallest CFL number may become far less than unity and explicit methods become very expensive. Here implicit methods can be applied for geographical space advection to gain some efficiency, which is an option for unstructured grids in version 4 of WW3, but care must be taken because of the splitting done to the equations.

With or without splitting, models have to apply an additional limiter to solve for the right hand part of the equation, which is either linearized following the Patankar rules (Booij et al. 1998) or integrated as an ODE problem within a separate fractional step. This limiter was introduced to circumvent the source term contribution arising from the stiffness of the equation system especially for young waves starting to grow (WAMDI, 1988, Hersbach & Janssen, 1999; Hargreaves & Annan, 2000; Tolman 2002). For the splitting method this limiter is only applied to the source term part when the ODE problem is solved. In SWAN this limiter also has an effect on the propagation part, which may have strong influence on the transient solutions in unsteady environments, such as tidal currents.

Recent numerical developments have largely focused on the improvement of methods on "unstructured grids" made up of triangular meshes (e.g. Roland 2008, Zijlema et al. 2010), or using non-uniformly sized quadrangles (Popinet et al. 2010; Li 2010), or grid nesting (Tolman 2008). The variability of the grid resolution across the domain exacerbates the problems outlined above. In practice, the unstructured version of SWAN that did not include a limiter was often causing the model to blow up (Gonzalez et al. 2011), and the first published results were obtained by setting the refraction term to zero in shallow water (Dietrich et al. 2012a), which is the strongest possible limiter.

The application of spectral advection limiters when unstructured meshes are used becomes problematic since there are generally some poorly resolved regions and some highly resolved regions in the same unstructured mesh, which can have also steep slopes. A limiter acts would typically limit refraction where the slopes are larger than a maximum allowed slope. Ideally some selection procedure would be nice. Selective computations of the various terms and limiters would be a pragmatic solution to reduce the influence of limiters in certain regions and impose them in others where the solution is not of major concern. However, this is difficult under time varying conditions and especially when coupled to circulation models the contribution of the spectral terms depends on the spatial variation of the velocity fields and cannot be neglected easily. Additionally this kind of workaround increases the preprocessing time and gives no guarantees with respect to the stability of the model, let alone its accuracy.

The application of limiters for the spectral part, and the presence of splitting errors renders the solution of the WAE in inhomogeneous environments and rapidly varying currents and depths a complex and complicated task with many open challenges from the physical and numerical points of view. The application of such heuristic methods in the solution procedure renders the final numerical schemes inconsistent and can lead to convergence problems (e.g. Zijlema and van der Westhuysen, 2005). Dedicated numerical schemes needs to be investigated that circumvent these shortcomings and allow for and efficient and accurate integration of wave evolution, and its coupling to ocean circulation models (e.g. Dietrich et al. 2012a, Roland et al. 2012).

2.2. ***Global and regional wave modelling***

In general the accuracy of wave model results in terms of significant wave height is governed, in decreasing order of importance by

- the accuracy of forcing fields: first the wind (and/or the offshore boundary in cases of nested grids), then the currents, and finally the water levels.
- the accuracy of source term parameterizations
- the effect numerical schemes.

This order is generally verified for large scales, and the developers of numerical wave models have, for a very long time, found an easy culprit for the poor wave model performance in the poor quality of atmospheric models, especially in coastal areas (e.g. Cavaleri and Bertotti 1997). Yet, the performance of operational atmospheric models is improving at a dramatic pace, with errors on wind speed reduced by more than 20% between 1992 and 2006 (Janssen 2008). In these conditions it has become increasingly clear that wave model parameterizations could be upgraded. Figure 2 shows the reduction in wave model errors on the significant wave height when changing the wave generation and dissipation terms from the WAMDI Group formulation (1988) to the Tolman and Chalikov settings (1996), the formulation of Bidlot et al. (2005) and, possibly the most accurate formulation to date, the one by Ardhuin et al. (2010) with a recent update by Rascle and Ardhuin (2013). Further progress is certainly on the way with ongoing important research projects that are addressing this question of parameterizations (the U.S. NOPP wave modelling project, the E.U. MyWave project …).

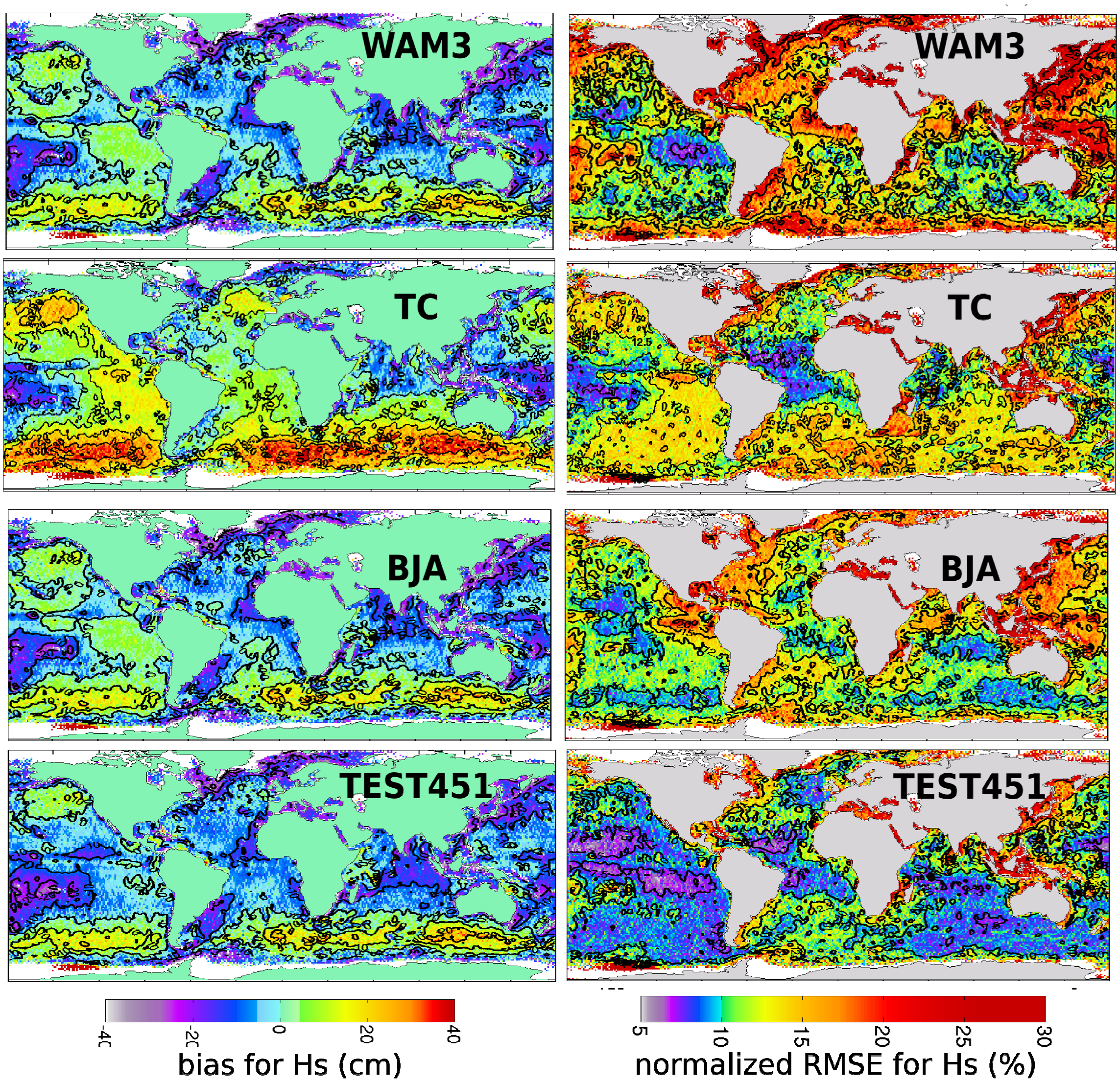

Figure 2. Bias and normalized RMS error against altimeter data for the year 2007, using the same forcings but 4 different parameterizations of the wind input and dissipation: WAM Cycle 3 (WAMDI 1988), TC (Tolman and Chalikov 1996), BJA (Bidlot et al. 2005) and TEST451 (Rascle and Ardhuin 2013). Solid lines in the right column correspond to contours at the 7.5, 10, 12.5, 15 and 20% levels.

These improvements have further revealed flaws in the model forcing. In particular the bands of low and high bias along the equatorial Pacific are clearly associated with ocean currents (Rascle et al., 2008), while icebergs in the southern ocean have been found to be a major source of error if not taken into account (Ardhuin et al. 2011). Here icebergs are represented by the surface currents are still neglected due to large errors in global ocean circulation models.

The little impact of advanced numerical schemes on the model results in terms of significant wave height may be rather discouraging but it comes from the smoothing effect of low order schemes. Indeed, while ECMWF and Meteo-France still use the first order upwind scheme of the original WAve Model (WAMDI Group 1988), the third order scheme used by NCEP and the Prévimer project (http://www.previmer.org) for their regular grids with the WW3 code only show their benefits when the wave field is partitioned into swells and wind seas (Wingeart, 2001).

2.3. ***Coastal seas***

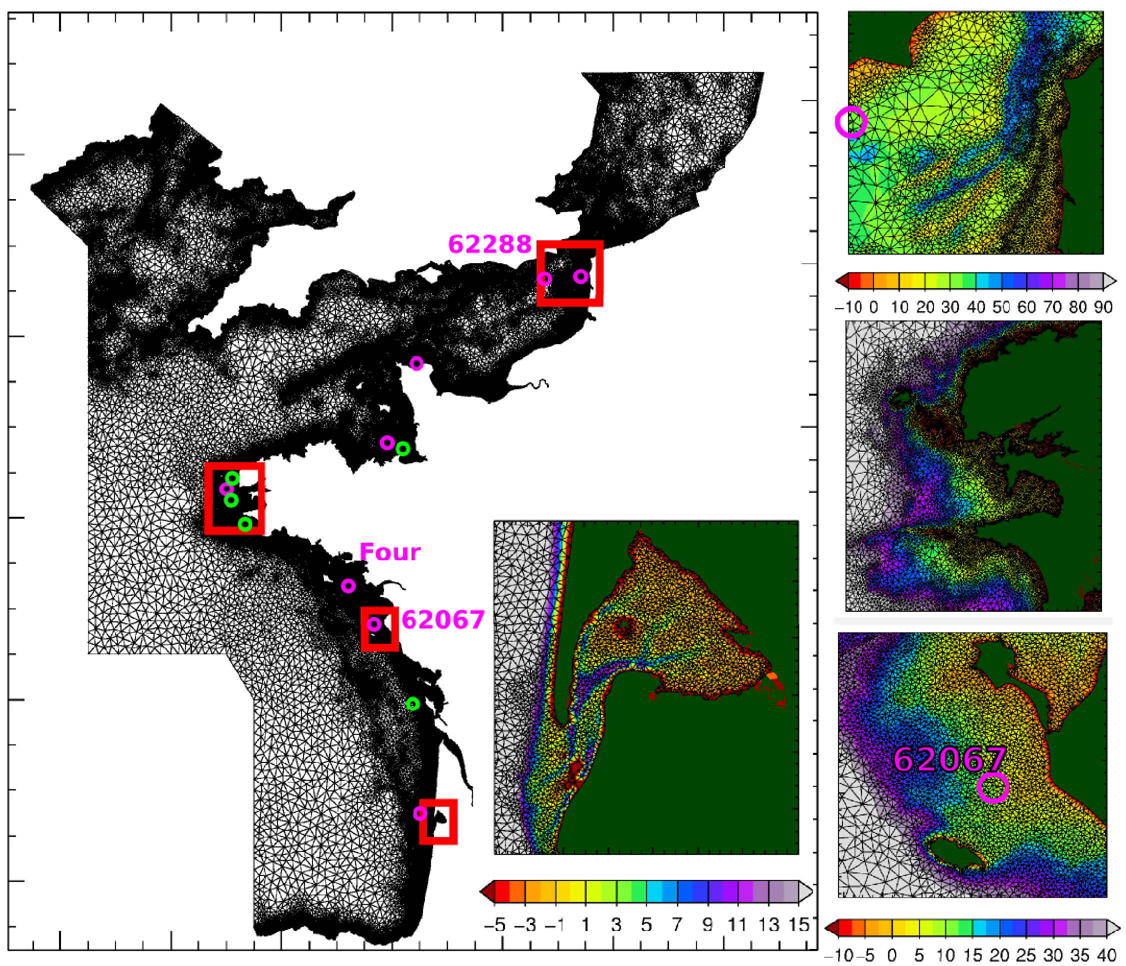

Figure 3. Map showing the “NORGASUG” mesh used for hindcasts and forecasts as part of the IOWAGA, HOMERE and Prévimer projects. Magenta and green circles show location of permanent and temporary buoys used for calibration in addition to satellite altimeter data. Inset are zooms of four grid areas, showing typical alongshore resolutions. The full mesh contains 110,000 wet nodes.

When moving towards the coastal ocean, many effects can come into play. For open coasts, the quality of lateral boundary conditions from a global or regional wave model is obviously important because the waves mostly come from the open ocean. Coastal areas are often influenced by strong currents, driven by either tides on density gradients. Recent works have shown that wave model results can be strongly improved by taking into account currents, and their effects on wave refraction, enhanced wave breaking and change in relative wind speeds (van der Westhuysen et al. 2012; Ardhuin et al. 2012).

Another important effect, when the water depth is less than half the dominant wavelength, is bottom friction. Although it has been known for decades that bottom friction may lead to strong wave energy dissipation, reducing the wave height by as much as a factor 3 in some conditions (Ardhuin et al., 2003), a physically-based parameterization of this effect has not been introduced into mainstream spectral wave models until very recently. Here we particularly discuss the implementation in WW3 of the "SHOWEX" movable-bed bottom friction as proposed by Tolman (1994) and adjusted by Ardhuin et al. (2003). The model was verified to reproduce the ray-tracing results obtained by Ardhuin et al. (2003) for the North Carolina shelf. A particular attention was given to the treatment of heterogeneous sediment types, including rocky bottoms. This was performed on the English Channel and French Atlantic coasts.

2.4. ***The IOWAGA hindcast and Prévimer system***

In this context we have used a 110,000 node unstructured mesh with an along-shore resolution of 300 to 500 m, shown in figure 3. The model configuration uses 32 frequencies from 0.037 to 0.72 Hz and 24 directions. It is nested in a multi-grid WAVEWATCH III model that combines 0.5 and 0.15° resolution grids for our region of interest (Rascle and Ardhuin 2013).

The model is forced by operational ECMWF wind analysis at a resolution of 0.25° or better, with a time step of 6 hours (3 hours since January 2013, thanks to the combination of forecasts and analyses). Currents and water levels on a series of grid with resolution around 200 m is provided by the Prévimer system based on the MARS2D model. A map of median grain size has been established from the French Hydrographic Service (SHOM) database, used to produce the bottom types maps that are commercially available (Garlan 1995, 2009, 2012).

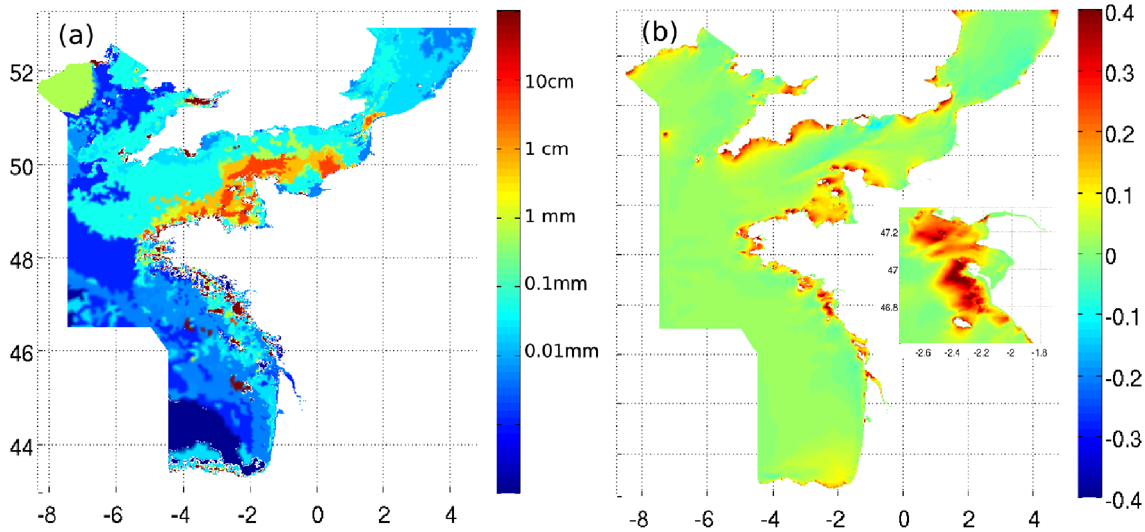

Figure 4. (a) Map of sediment median diameter and (b) mean difference in significant wave height (in meters) over the month of February 2010 between a model run using the "JONSWAP" bottom friction parameterization and another using the "SHOWEX" parameterization that included a constant Nikuradse roughness length of 12 cm for rocks. Inset is a zoom on the region around Yeu and Noirmoutier islands where the impact of this friction is very clear, as also shown in figure 5a.

Model results can be viewed on the wave modelling page of www.previmer.org, with numerical results available at http://tinyurl.com/iowagaftp , including full spectra for over 4000 grid points, and the full frequency spectrum over the entire grid. At this high resolution the refraction over shoals and tidal currents, and the sheltering by islands and headlands is well modeled (Ardhuin et al. 2013). However, a few coastal locations, not well sampled by satellite altimeters, reveal a very strong impact of bottom friction when the presence of rocky platforms is taken into account. This is particularly the case of the Yeu buoy (number 62067). However, this modified bottom friction has very limited impact at other locations (figure 5), in particular in the Eastern Channel, at buoy 62288 (Hastings) where the waves are too short to be significantly modified by bottom friction. At that site, however, we have found a very beneficial impact of adding reflection off the shoreline with a bias reduced from -11.5% to -2% as the shoreface slope is increased from 0.1 to 0.15, using the parameterization by Ardhuin and Roland (2012). Error statistics for a few buoys are summarized in table 1.

Table 1. Statistics of errors against buoy data for the “NORGASUG” model grid for the month of February 2010.

Buoy	“JONSWAP” bottom friction		“SHOWEX” bottom friction	
	S.I.	bias	S.I.	bias
62288	17.7	-1.8	17.0	-5.0
Four	13.9	8.15	13.3	7.15
62067	14.3	17.7	11.3	1.5
62060	10.4	8.8	10.7	5.2

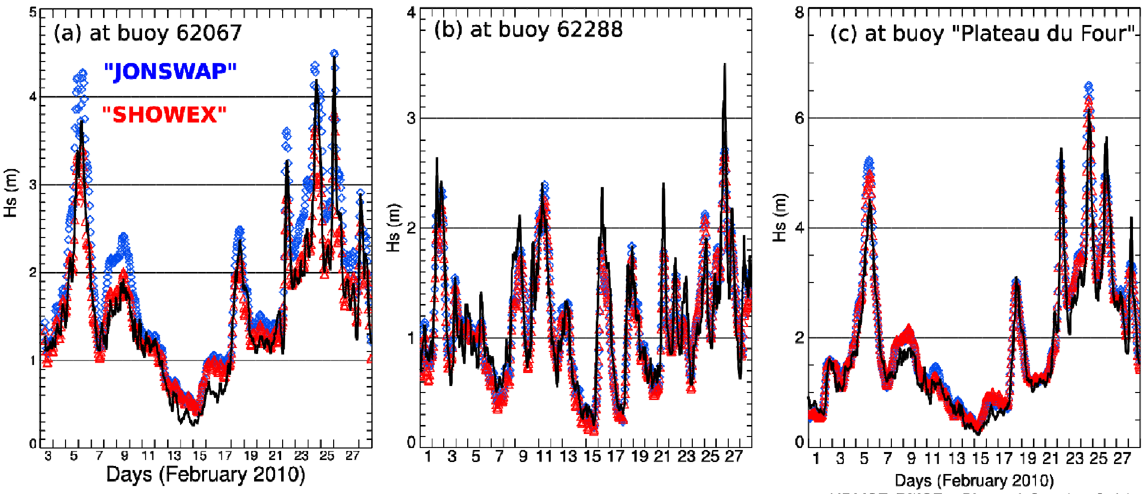

Figure 5. (a) Time series of observed and modeled significant wave height at several buoys using the JONSWAP or SHOWEX parameterizations for bottom friction.

3. **Wave models in coupled systems**

In the applications described above the waves was forced by winds, currents and water levels, meaning that the feedback of waves on the atmosphere and ocean circulation was not taken into account. There are however, a number of circumstances where this feedback must be taken into account to arrive at accurate results. In the case of winds, the effect of waves on the ocean roughness is a well know aspect (Mastenbroek et al. 1993, Bertin et al. 2010) although the details and magnitude of that effect is still debated (Drennan et al. 2005). The interaction with the ocean currents has been the topic of a flurry of research, with new theory, observations, and practical models. These are only briefly summarized here.

3.1. ***Theoretical foundations***

3.2. The wave-current interaction processes can be roughly divided into 4 parts:

- the modification of air-sea fluxes of momentum and energy due to the presence of waves (Miles 1957, Reul et al. 2008).
- the conservative (adiabatic) exchange of momentum and energy (Longuet-Higgins and Stewart 1960, Garrett 1976, Andrews and McIntyre 1978a, Smith 2006, McWilliams et al. 2004, Ardhuin et al. 2008a, Aiki and Greatbatch 2012).
- the flow acceleration and mixing induced by waves (Longuet-Higgins 1953, Bowen 1969, Agrawal et al. 1992), responsible for phenomena like longshore currents and boundary layer streaming.
- the distortion of turbulence by waves, which may inhibit or modify mixing (Miles 1996, Groeneweg and Klopman 1998).

In these four domains, that can be closely linked, the first three have been given a lot of attention. It is thus our duty here to highlight the step-child of these efforts, the question of wave-turbulence interactions. The work of Miles (1996) deals with turbulence in the air, while Groeneweg's thesis work focused on turbulence in the water, but these two are clearly connected and show how a turbulence closure scheme applied to the phase-averaged flow can be a very bad approximation of turbulence effects in the presence of waves.

We probably have to write a few words on the adiabatic wave-current interaction, because this is probably the topic that the organizers wanted us to cover. Let's try to find something useful that has not been written before and that may help guide the reader to the jungle of conflicting publications. Some good introductory texts to the general theory are the papers by Lane et al. (2008) and Bennis et al. (2011).

Basically, we have an exact theory for the formulation of wave-induced forces on the mean flow in three dimensions, given by Andrews and McIntyre (1978a). This theory is given in two forms, one for the total momentum (which include the Stokes drift, this is the “alternative” and it was used by Groeneweg and Klopman 1998), The other form is formulated for the quasi-Eulerian velocity (without the Stokes drift). The latter turns out to be more practical because it does not involve vertical fluxes of wave momentum which cannot be derived from usual depth-integrated wave models (Ardhuin et al. 2008b). The equations of Ardhuin et al. (2008a) are just a practical approximation of the exact equations, in which the wave action has been approximated to second order in the wave steepness and to first order in the vertical current shear.

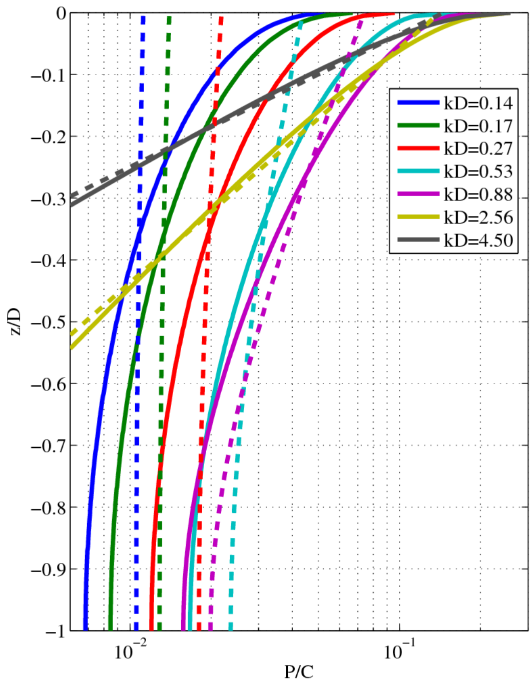

Figure 6. Profiles of Stokes drift for nearly breaking waves according to stream-function theory (solid lines) and linear theory (dashed lines) for non-dimensional water depths from kD = 0.14 to kD = 4.5. The elevation z is normalized by the water depth D, and the Stokes drift P is normalized by the phase speed C.

The resulting equation is fully consistent with that of McWilliams et al. (2004), which means that their mean velocity can be understood as a quasi-Eulerian velocity, i.e. the Lagrangian mean minus the Stokes drift. Aiki and Greatbatch (2012) have also arrived at the same equations using a different averaging operator. I will not discuss further here the many other theories that have been proposed and that have some inconsistencies at their lowest order, leading to unphysical solutions in some very simple cases (see Bennis et al. 2011).

The great advantage of the quasi-Eulerian equation as an approximation to the full equation of Andrews and McIntyre is that we can go back to the approximations and see what is their influence. Figure 6 shows one example, for the Stokes drift (or, more precisely the wave pseudo-momentum). For nonlinear periodic nearly breaking waves on a flat bottom we can use the exact numerical solution given by Dalrymple (1974) to compute the true Stokes drift and compare it to its 2nd order approximation given by linear wave theory (yes, linear waves do have a Stokes drift). It is very interesting to note that even in the shallow water limit the Stokes drift is strongly sheared, a fact already noted by Miche (1944), and that cannot be reproduced by cnoïdal wave theory. That feature may be very important for the transport of tracers in or near the surf zone. There is thus a lot more research to be done on this adiabatic wave-current interaction, and certainly even more on the delicate problem of wave-turbulence interactions.

3.3. ***Practical applications***

With all their limitations, coupled wave-current models in three dimensions have provided very interesting results for conditions with large vertical current shears or some density stratification. The first application was performed by Newberger and Allen (2007), using an approximation for shallow water waves. Their simulations particularly focused on the instabilities of the longshore current, offering an alternative to previous numerical solutions based on the Boussinesq equations, that missed the possible strong vertical shear of the velocity profiles. A further investigation was performed by Uchiyama et al. (2009) using more general equations, and found that the current effect on the waves could stabilize the longshore current instabilites while at the same time making eddies more energetic once the instability is present. In both works it is not clear that the use of a full 3D model brings a qualitative change to the previous 2D simulations (Ozkhan-Haller and Li 2003).

More interestingly, the possibility of using waves and 3D flows coupled together now makes it possible to study a wide range of situations, in particular the transition between the surf zone and the inner shelf (Rascle 2007), which is highly important for the cross-shore transport of pollutants and other material. The first study of that kind was performed by Kumar et al. (2012), giving a reasonable agreement with the wave-driven flows on the inner shelf, as observed by Lentz et al. (2008). Further recent works has documented the possible influence of waves on the inner shelf circulation on open coasts (Michaud et al. 2012) or on semi-enclosed bays with freshwater runoff (Delpey 2012). In the latter case the model predicts a large influence of waves on freshwater exchanges between the bay and the open ocean. These results are very important for water quality applications and will need to be verified by further observations.

4. **Summary and perspectives**

Numerical wave models have involved dramatically over the last two decades. First of all they are get more accurate thanks to improvements in forcing fields and parameterizations, but also more capable of handling complex coastal topographies with efficient numerical schemes on small computer cluster or massively parallel machines.

A landmark in this progress will certainly be the release of version 4 of the WAVEWATCH III code: “alpha” releases are already available from NCEP, and the developments will be frozen in the fall of 2013 with a “beta” release that will allow some bug fixes and, an official release before January 16, 2014.
This wave modeling framework has been augmented with many features, including improved

parameterizations of wave generation and dissipation, bottom friction. The new code handles curvilinear and unstructured grids (Roland, 2008; Ardhuin et al., 2009; Ardhuin and Roland 2012; Ardhuin et al. 2012), which have been thoroughly tested with 20-year hindcasts and routine forecasts as part of the Prévimer project, and these different grid types can be two-way nested is a single multi-grid run. The code also allows coupling or off-line forcing with all necessary 2D or 3D fields computed and, if necessary, output as NetCDF files.

Beyond the wave model itself, we also have the basic numerical tools now to investigate complex wave-current interaction problems (e.g. Roland et al. 2012). The first benefit of the efforts will certainly be a improved wind and current forcing for the wave models, and these open many exciting perspectives. From air-sea fluxes to sediment transport and the interpretation of remote sensing data, we have exciting years coming up.

Acknowledgements

This was was made possible by the help and dedication of many, including Jérémy Lepesqueur who generated the bottom type files and performed the initial simulations with variable roughness. We thank CETMEF and SHOM for providing the data, and the organizers of *Coastal Dynamics 2013* for soliciting this contribution. F.A. is funded by ERC grant #240009 ``IOWAGA" with additional support from the U.S. National Ocean Partnership Program, under grant N00014-10-1-0383.

References

Agrawal, Y. C., Terray, E. A., Donelan, M. A., Hwang, P. A., Williams, A. J., Drennan, W., Kahma, K., and Kitaigorodskii, S., 1992. Enhanced dissipation of kinetic energy beneath breaking waves, *Nature*, 359, 219–220.

Aiki, H. and Greatbatch, R. J., 2012. *J. Phys. Oceanogr.*, Thickness–Weighted Mean Theory for the Effect of Surface Gravity Waves on Mean Flows, 42, 725–747.

Andrews, D. G. and McIntyre, M. E., 1978a. An exact theory of nonlinear waves on a Lagrangian-mean flow, *J. Fluid Mech.*, 89, 609–646.

Andrews, D. G., and McIntyre, M. E., 1978b. On wave action and its relatives, *J. Fluid Mech.*, 89, 647–664. Corrigendum: vol. 95, p. 796.

Ardhuin, F., and Herbers, T. H. C., 2005. Numerical and physical diffusion: Can wave prediction models resolve directional spread?, *J. Atmos. Ocean Technol.*, 22(7), 886–895.

Ardhuin, F., Rascle, N., and Belibassakis, K. A., 2008. Explicit wave-averaged primitive equations using a generalized Lagrangian mean, *Ocean Modelling*, 20, 35–60.

Ardhuin, F., Marié, L., Rascle, N., Forget, P., and Roland, A., 2009. Observation and estimation of Lagrangian, Stokes and Eulerian currents induced by wind and waves at the sea surface, 2009. *J. Phys. Oceanogr.*, 39, 11, 2820–2838.

Ardhuin, F., Jenkins, A. D., and Belibassakis, K., 2008. Comments on 'the three-dimensional current and surface wave equations' by George Mellor, *J. Phys. Oceanogr.*, 38, 1340–1349.

Ardhuin, F., and Herbers, T. H. C., 2013. Double-frequency noise generation by surface gravity waves in finite depth: gravity, acoustic and seismic modes, *J. Fluid Mech.*, 716, 316–348.

Ardhuin, F., Lavanant, T., Obrebski, M., Marié, L., Royer, J.-Y., d'Eu, J.-F., Howe, B. M., Lukas, R., and Aucan, J., 2013. A numerical model for ocean ultra low frequency noise: wave-generated acoustic-gravity and Rayleigh modes, *J. Acoust. Soc. Amer.*, in press.

Ardhuin, F., et al., 2010. Semi-empirical dissipation source functions for wind-wave models: part I, definition, calibration and validation, *J. Phys. Oceanogr.*, vol. 40(9), 1917–1941.

Ardhuin, F., Dumas, F., Bennis, A.-C., Roland, A., Sentchev, A., Forget, P., Wolf, J., Girard, F., Osuna, P., and Benoit, M., 2012. Numerical wave modeling in conditions with strong currents: dissipation, refraction and relative wind, *J. Phys. Oceanogr.*, 42, 2101–2120.

Becq-Girard, F., Forget, P., and Benoit, M., 1999. Non-linear propagation of unidirectional wave fields over varying topography, *Coastal Eng.*, 38, 91–113.

Belibassakis, K. A., Athanassoulis, G. A., and T. P. Gerostathis, 2001. A coupled-mode model for the refraction-diffraction of linear waves over steep three-dimensional bathymetry, *Appl. Ocean Res.*, 23, 319–336, 2001.

Benetazzo, A., 2006. Measurements of short water waves using stereo matched image sequences, *Coastal Eng.*, 53, 1013–1032.

Bennis, A.-C. and Ardhuin, F., 2011. Comments on "the depth-dependent current and wave interaction equations: A revision", *J. Phys. Oceanogr.*, 41, 2008–2012.

Benoit, M., Marcos, F., and Becq, F., 1996. Development of a third generation shallow-water wave model with unstructured spatial meshing, *Proceedings of the 25th International Conference on Coastal Engineering, Orlando*, 465–478, ASCE.

Berkhoff, J. C. W., 1972. Computation of combined refraction-diffraction, *Proceedings of the 13th International Conference on Coastal Engineering, Vancouver*, 796–814, ASCE, New York, N. Y.

Bertin, X., Bruneau, N., Breilh, J.-F., Fortunato, A. B., and Karpytchev, 2012. M., Importance of wave age and resonance in storm surges: The case Xynthia, Bay of Biscay, *Ocean Modelling*, 42, 16–30.

Booij, N., Ris, R. C., and Holthuijsen, L. H., 1999. A third-generation wave model for coastal regions. 1. model description and validation, *J. Geophys. Res.*, 104(C4), 7,649–7,666.

Bowen, A. J., 1969 . The generation of longshore currents on a plane beach, *J. Mar. Res.*, 27, 206–215.

Cavaleri, L., and Bertotti, L., 1997. In search of the correct wind and wave fields in a minor basin, *Mon. Weather Rev.*, 125(8), 1964–1975.

Dalrymple, R. A., 1974. A finite amplitude wave on a linear shear current, *J. Geophys. Res.*, 79, 4498–4504.

Dalrymple, R. A., and Kirby, J. T., 1988. Models for very wide-angle water waves and wave diffraction, *J. Fluid Mech.*, 192, 33–50.

Delpey, M., 2012. Etude de la dispersion horizontale en zone littorale sous l'effet de la circulation tridimensionnelle force par les vagues. *PhD thesis, Université Europénne de Bretagne, Ecole doctorale des Sciences de la Mer, Brest, France*.

Dietrich, J. C., et al., 2011. Hurricane gustav (2008) waves and storm surge: Hindcast, synoptic analysis, and validation in southern Louisiana, *Mon. Weather Rev.*, 139, 2488–2522.

Dietrich, J. C., et al., 2012a "Performance of the Unstructured-Mesh, SWAN+ADCIRC Model in Computing Hurricane Waves and Surge." Journal of Scientific Computing, 52(2), 468-497, DOI:10.1007/s10915-011-9555-6.

Dietrich, J. C., et al. 2012b. "Limiters for Spectral Propagation Velocities in SWAN." Ocean Modelling, in press, DOI: 10.1016/j.ocemod.2012.11.005.

Drennan, W. M., Taylor, P. K., and Yelland, M. J., 2005. Parameterizing the sea surface roughness, *J. Phys. Oceanogr.*, 35, 835–848, 2005.

Filipot, J.-F., and Ardhuin, F., 2012. A unified spectral parameterization for wave breaking: from the deep ocean to the surf zone, *J. Geophys. Res.*, 117, C00J08.

Garlan T., 1995. La cartographie des sédiments du littoral français. Résultats et objectifs. *J. Rech. Océanogr.* 20, 50-54.

Garlan T., 2009. De la classification des sédiments à la cartographie de la nature des fonds marins. *Annales Hydrographiques*, N° 774.

Garlan. T., 2012. Deux siècles de cartographie des sédiments marins. *CFC, Cartes et Géomatique*, 211:115-139

Garrett, C., 1976. Generation of Langmuir circulations by surface waves - a feedback mechanism. *J. Mar. Res.*, 34, 117–130.

Gonzalez-Lopez, J. O., Westerink, J., Mercado, A., Capella, J., Morell, J., and Canals, M., 2011. Effect of a steep and complex-featured shelf on computed wave spectra, *Proceedings, 12th Int. Workshop of Wave Hindcasting and Forecasting, Hawaii*.

Groeneweg, J. and Klopman, G., 1998. Changes in the mean velocity profiles in the combined wave-current motion described in GLM formulation, *J. Fluid Mech.*, 370, 271–296.

Herbers, T. H. C., and Burton, M. C., 1997. Nonlinear shoaling of directionally spread waves on a beach, *J. Geophys. Res.*, 102(C9), 21,101–21,114.

Herbers, T. H. C., Lowe, R. L., and Guza, R. T., 1992. Field observations of orbital velocities and pressure in weakly nonlinear surface gravity waves, *J. Fluid Mech.*, 245, 413–435.

Janssen, P. A. E. M., 2008. Progress in ocean wave forecasting, *J. Comp. Phys.*, 227, 3572–3594.

Janssen, P. A. E. M., 2009. On some consequences of the canonical transformation in the Hamiltonian theory of water waves, *J. Fluid Mech.*, 637, 1–44.

Kumar, N., Voulgaris, G., Warner, J. C., and Olabarrieta, M., 2012. Implementation of the vortex force formalism in the coupled ocean-atmosphere-wave-sediment transport (COAWST) modeling system for inner shelf and surf zone applications, *Ocean Modelling*, 35, 65–95.

Lentz, S. J., Howd, M. F. P., Fredericks, J., and Hathaway, K., 2008. Observations and a model of undertow over the inner continental shelf, 2008. *J. Phys. Oceanogr.*, 38, 2341–2357.

Longuet-Higgins, M. S., 1953. Mass transport under water waves, *Phil. Trans. Roy. Soc. London A*, 245, 535–581.

Mastenbroek, C., Burgers, G., and Janssen, P. A. E. M., 1993. The dynamical coupling of a wave model and a storm surge model through the atmospheric boundary layer, *J. Phys. Oceanogr.*, 23, 1856–1867.

McWilliams, J. C., Restrepo, J. M., and Lane, E. M., 2004. An asymptotic theory for the interaction of waves and currents in coastal waters, *J. Fluid Mech.*, 511, 135–178.

Miche, A., 1944. Mouvements ondulatoires de la mer en profondeur croissante ou décroissante. Première partie. Mouvements ondulatoires périodiques et cylindriques en profondeur constante, *Annales des Ponts et Chaussées*, 114, 42–78.

Miles, J. W., 1957. On the generation of surface waves by shear flows, *J. Fluid Mech.*, 3, 185–204.

Miles, J., 1996. Surface wave generation: a viscoelastic model, *J. Fluid Mech.*, 322, 131–145.

O'Reilly, W. C., and Guza, R. T., 1993. A comparison of two spectral wave models in the Southern California Bight, *Coastal Eng.*, 19, 263–282.

Lane, E. M., Restrepo, J. M., and McWilliams, J. C., 2007. Wave-current interaction: A comparison of radiation-stress and vortex-force representations, *J. Phys. Oceanogr.*, 37, 1122–1141.

Li, J.-G., 2010. Global transport on a spherical multiple-cell grid, *Mon. Weather Rev.*, 139, 1536–1555.

Longuet-Higgins, M. S., 1950. A theory of the origin of microseisms, *Phil. Trans. Roy. Soc. London A*, 243, 1–35.

Michaud, H., Marsaleix, P., Leredde, Y., Estournel, C., Bourrin, F., Lyard, F., Mayet, C., and Ardhuin, F., 2012. Three-dimensional modelling of wave-induced current from the surf zone to the inner shelf, *Ocean Sci.*, 8, 657–681.

Newberger, P. A. and Allen, J. S., 2007. Forcing a three-dimensional, hydrostatic, primitive-equation model for application in the surf zone:2. application to DUCK94," *J. Geophys. Res.*, 112, p. C08019, 2007.

Ozkan-Haller, U. T. and Li, Y., 2003. Effects of wave-current interaction on shear instabilities of longshore currents," *J. Geophys. Res.*, 108, C5, p. 3139.

Patankar, S.V., 1980. Numerical heat transfer and fluid flow: Computational methods in mechanics and thermal science. Washington, DC, Hemisphere Publishing Corp., 210 p.

Popinet, S., Gorman, R. M., Rickard, G. J., and Tolman, H. L., 2010. A quadtree-adaptive spectral wave model," *Ocean Modelling*, 34, 36–49.

Rascle, N., 2007. Impact of waves on the ocean circulation. PhD thesis, Université de Bretagne Occidentale. http://tel.archives-ouvertes.fr/tel-00182250/.

Rascle, N., and Ardhuin, F., 2013. A global wave parameter database for geophysical applications. part 2: model validation with improved source term parameterization, *Ocean Modelling*, in press.

Reul, N., Branger, H., and Giovanangeli, J.-P., 2008. Air flow structure over short-gravity breaking water waves, *Boundary-Layer Meteorol.*, 126, 477–705.

Roland, A., 2008. Development of WWM II: Spectral wave modelling on unstructured meshes. PhD thesis, Technische Universität Darmstadt, Institute of Hydraulic and Water Resources Engineering.

Roland, A., Y. J. Zhang, H. V. Wang, Y. Meng, Y.-C. Teng, V. Maderich, I. Brovchenko, M. Dutour-Sikiric, and U. Zanke (2012), A fully coupled 3D wave-current interaction model on unstructured grids, *J. Geophys. Res.*, 117, C00J33, doi:10.1029/2012JC007952.

Smith, J. A., 2006. Wave-current interactions in finite-depth, *J. Phys. Oceanogr.*, 36, 1403–1419.

Tanaka, M., 2001. Verification of Hasselmann's energy transfer among surface gravity waves by direct numerical simulations of primitive equations, *J. Fluid Mech.*, 444, 199–221.

Tayfun, A., Narrow-band nonlinear sea waves, 1980. *J. Geophys. Res.*, 85(C3), 1543–1552.

Thornton, E. B., and Guza, R. T., 1983. Transformation of wave height distribution, *J. Geophys. Res.*, 88(C10), 5,925–5,938.

Toledo, Y., Hsu, T.-W., and Roland, A., 2006. Extended time-dependent mild-slope and wave-action equations for wave-bottom and wave-current interactions, *Proc. Roy. Soc. London A,* 468, 184–205.

Tolman, H. L., 2002. Limiters in third-generation wind wave models, Global Atmos. Ocean Syst., 8, 67–83.

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

Touboul, J., and Rey, V., 2012. Bottom pressure distribution due to wave scattering near a submerged obstacle, *J. Fluid Mech.*, 702, 444–459.

van der Westhuysen, A. J., van Dongeren, A. R., Groeneweg, J., van Vledder, G. P., Peters, H., Gautier, C., and van Nieuwkoop, J. C. C., 2012. Improvement in spectral wave modelling in tidal inlets seas, *J. Geophys. Res.*, 117, C00J28.

Wingeart, K. M., "Validation of operational global wave prediction models with spectral buoy data," in Proceedings of the 4th International Symposium Ocean Wave Measurement and Analysis, San Francisco, September 2001, 590–599, ASCE, 2001.

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

Yanenko, N. N., 1971. The method of fractional steps. Springer-Verlag.

Yue, D. K. P., and Dommermuth, D.G., 1987, A high-order spectral method for the study of nonlinear gravity waves, *J. Fluid Mech.*, 184, 267–288.

Zijlema, M., van der Westhuysen, A.J., 2005, On convergence behaviour and numerical accuracy in stationary SWAN simulations of nearshore wind wave spectra, Coastal Engineering, Volume 52, Issue 3, March 2005, Pages 237-256, ISSN 0378-3839, 10.1016/j.coastaleng.2004.12.006.

Zijlema, M., 2010. Computation of wind-wave spectra in coastal waters with SWAN on unstructured grids. *Coastal Engng*, 57, 267–277.