CHAPTER 4

Accuracy of Wind and Wave Evaluation in Coastal Regions

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Abstract

We have made a critical analysis of the processes and the parameters that affect the accuracy with which wind and waves can be evaluated close to coast. For each process we quantify the possible error, whenever possible complementing this with numerical tests and practical cases.

1. Introduction

The standard evaluation of the performance of a wave model is usually done off the coast, in the open sea. Typically the analysis fields (wave fields obtained using as input the wind provided by the analysis of 3-D meteorological models) are compared with the measured data available at certain locations. This provides a fair estimate of the overall performance. More detailed analyses, possibly referred to some test cases, can provide information on specific aspects of the model. The forecast fields are compared with the analysis fields to assess the reliability of the results in the forecast mode (in doing so we effectively check the forecast wind fields).

The related statistics are commonly available (see e.g., Günther et al., 1992 and Komen et al., 1994). Particularly during the last three years, with most meteorological centers moved to high resolution meteorological models, the results are quite satisfactory. The average bias for the significant wave height Hs is about 0.10-0.15 m or less, the rms error is limited to a few tens of centimeters.

However, the condition is not similarly satisfactory in coastal areas. Here a number of problems arise. First, the orography of the coast strongly affects the wind field, hence the local evolution of the wave fields. Then, the shallow waters bring to relevance a number of processes, some of them being of difficult evaluation, but

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The practical application of wave modeling in coastal areas requires therefore a careful analysis of the local conditions, to assess, even if only on a qualitative basis, the relevance of each process. This will tell us where to focus our attention, following the principle of "larger corrections first".

We have done an evaluation of the potential relevance of the processes active in coastal areas and of the model parameters that affect the accuracy of the results. Whenever possible, this has been done with numerical tests, supporting the results with wave measurements at suitable locations. In section 2 we discuss the evaluation of the wind field and the related consequences on the evaluation of the wave fields. Then (section 3) we analyze the relevance of the conservative processes arising from the interaction of the waves with the bottom. The dissipative processes are analyzed in section 4. In 5 we turn our attention to the resolution of the grid and of the wave model. Interactions with currents are briefly mentioned in 6. The overall results are summarized and commented in the final section 7.

2. Wind in Coastal Areas

The wind is the source of the whole energy present in the sea in the wind wave frequency range. The sensitivity of waves to even limited variations imply a careful attention to the modifications of the wind fields in coastal areas.

Wind can be modified both at large and local scales. Analyzing a very severe storm in the Mediterranean Sea, Cavaleri et al. (1991) report an increase of the wind speed of about 30% by increasing the resolution from 150 to 70 km. In another case in the same area (Cavaleri et al., 1993), a further increase of resolution to 40 km succeeded in revealing an otherwise unnoticed local turn of the wind, strictly associated to the local orography, that produced a 5 m significant wave height in the Gulf of Genoa, duly found in the measured data. It is not possible to specify the characteristics of a meteorological model that are required for a sufficient accuracy. As a practical rule, we can say that, given a characteristic length D of the local orography (the dimension of a bay, or of an island or a promontory), a good wind requires a resolution of D/5 or better. The same applies if D is the minimal distance from a coast with a complicated orography at which we want to evaluate the fields.

3. Wave Conservative Bottom Processes

We discuss the following processes: refraction, shoaling, bottom scattering. While the first two are a standard part of any shallow water wave model, the third one is rarely considered, but it can become dominant in certain conditions.

Refraction. Well established, both with grid and ray techniques. If no particular complication arises (e.g., caustics), the accuracy for the single spectral component is of the order of a few percents and a few degrees in direction.

More care is required when dealing with a full 2-D spectrum, from which we extract the mean direction (we anticipate here a result connected to the subject of section 5). Hubbert and Wolf (1991) have considered a narrow swell approaching at

60° with respect to the isobaths a one-dimensional 1:10^4 sloping coast. Figure 1 shows the resulting turning of the swell mean direction while approaching the beach, as a function of the directional resolution used in the model. While all the results are good, and excellent for a resolution of 15° or better, we need to go down at 5° before being able to reproduce the result obtained with Snel's law (note: Komen et al., 1994, p. 345, point out that, contrarily to the common use, the correct spelling of this Dutch mathematician requires a single "l").

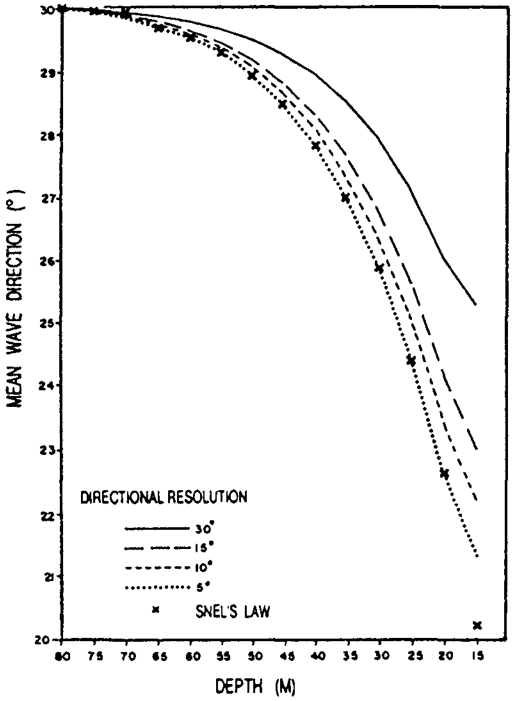

Figure 1. Refraction on a sloping bottom as a function of directional resolution (after Hubbert and Wolf, 1991).

Shoaling. When shoaling a wave spectrum towards the coast, two basic approaches are possible: to use linear theory for each component separately, or to summarize the spectrum into a representative wave of given height and period, and to use one of the several nonlinear theories available. To our knowledge no general method to deal with nonlinear shoaling of the whole 2-D spectrum has been published. We expect some substantial improvement not far in the future. For the time being we call the attention to one result of strong interest for the coastal engineer. Starting from recorded data and by numerical integration of the KdV equation, Osborne (1993) has analyzed the shoaling of a heavy swell case in the Northern Adriatic Sea, shows the same system of waves at 6 meters of depth. The relevant point is the development by nonlinear interactions of long period components, formally appearing as a train of solitons. These long components are important for beach shaping and harbor management. They appear for large Ursell numbers in the field. In this case the results of standard theories should be taken with care.

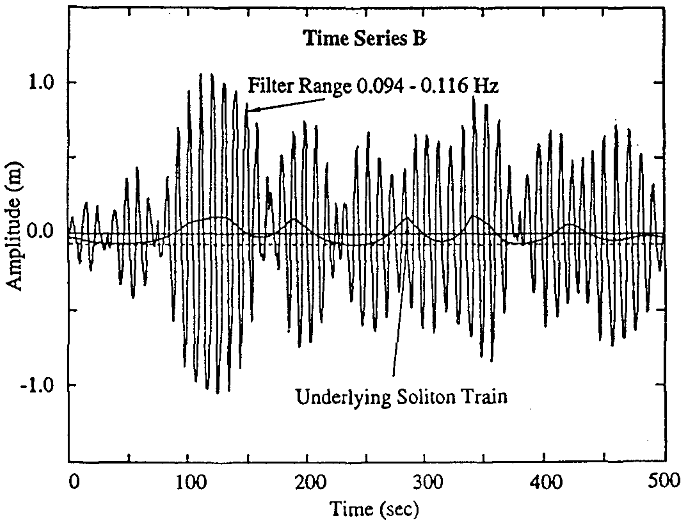

Figure 2. Non linear shoaling of a heavy swell case in the Northern Adriatic Sea. Surface profile evaluated at 6 m of depth. Note the development of long period wave components.

Bottom-scattering. We refer here to the interaction of a surface wave spectrum with the oscillations of the bottom. The theory is well established (see Long, 1973), but it has rarely been applied for the practical difficulty to have the necessary data available (the 2-D spectrum of the depth variations is required) and because of the very large computer power requirements. However, some laboratory experiments have clearly confirmed the theory and provided spectacular results. Davies and Heathershaw (1983) have shown that four oscillations of the bottom (wavelength half of that of the surface wave) are sufficient to reflect in the opposite direction 80% of the incoming wave height. Ten oscillations reflect 90%.

The wavelength is critical, which makes the application problematic. However, because of its potential dominant role, this process should be kept in mind whenever a series of transversal parallel bars or reefs is present in front of a coast.

4. Dissipative Bottom Processes

We discuss bottom friction, percolation, breaking and bottom elasticity.

Bottom friction. It can be evaluated with both linear and nonlinear (fully spectral) approaches. The non linearity leads to more correct evaluations, but this is paid with two orders of magnitude in computer power. A rather comprehensive treatment of the subject is given by Weber (1991). The linear approach suffices till water particles velocity at the bottom of about 0.15 m/s, above which it underestimates the energy loss at an increasing rate. A first hand estimate of the expected wave conditions at a given location and of the associated orbital velocity will tell the user which approach is to be followed.

A good example of the possible difference between the two approaches is given in figure 3, showing a 1-D spectrum at an oceanographic tower located on 16 m of depth at the far north of the Adriatic Sea, in front of Venice (Cavaleri et al., 1989). The tower is at the upper end of a long, slowly sloping continental platform, and the swell represented in the figure has been propagating in shallow water for many tens of kilometers. Clearly, the linear approach (WAM in the figure) fails to dissipate the low frequency energy at a sufficiently high rate.

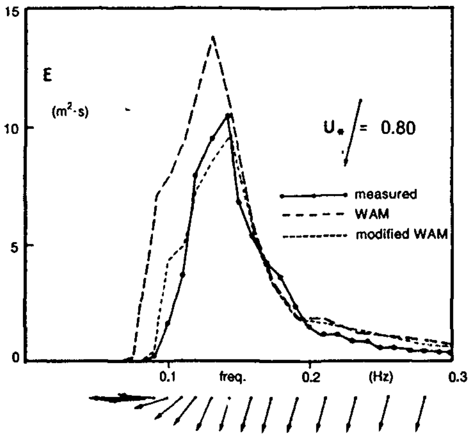

Figure 3. Comparison between measured and evaluated 1-D spectra in the Northern Adriatic Sea. WAM, evaluated with linear theory for bottom friction; modified WAM, with non linear theory (after Cavaleri et al., 1989).

Percolation. Of little importance offshore, it becomes important when the bottom is composed of shingles or very coarse sand, which are usually found close to the beach. Its role is never dominant. If to be considered, its proper evaluation requires laboratory tests to measure the transmission coefficient necessary for the estimate of the related energy budget (see, e.g., Shemdin et al., 1978).

Breaking. It is the most dominant factor for wave height in shallow water. Its consideration is essential whenever Hs>0.4 depth.

The breaking is not fully understood. Notwithstanding this, well-devised approaches provide very good results (see Battjes and Beji, 1993, for a clear example). In general, also simple methods provide acceptable results, simply because all of them essentially follow the basic principle of limiting the wave height to a certain percentage of depth. Larger differences, in percent terms, are found very close to shore.

Bottom elasticity. This phenomenon is rarely considered because in the very large majority of cases the energy involved is negligible. Besides, the bottom material (e.g., sand) is practically elastic, with a negligible absorption of energy. In a few special cases (the Mississippi Delta and the Bay of Bengal are the best known examples), the bottom is locally composed of viscoelastic mud. In this case tremendous absorptions of energy can be experienced in heavy storm. Figure 4 shows the evolution of a shoaling wave spectrum during hurricane Federic (Forristall et al., 1990). In 30 km the wave height passed from 8.6 m (in deep water) to 2.4 m (in 19 m of depth), a loss of energy of more than 90%. It is obvious then, whenever present, this process must be considered and it is going to be the dominant one.

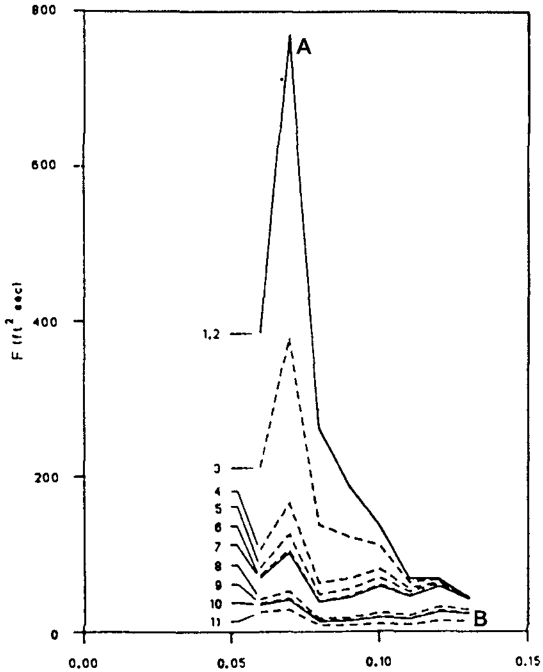

Figure 4. Attenuation of the wave spectrum during hurricane Frederic in the Gulf of Mexico. A and B locations are only 30 km apart (after Forristall et al., 1990).

5. Grid and Model Resolution

Grid resolution. It is essential in establishing the scale at which we want to analyze the phenomenon. The resolution affects the results of a wave model, particularly when strong gradients are present in the field. In this case a doubling of the resolution (say from 40 to 20 km) can increase the estimate of the peak wave height by 10-20%.

The grid resolution establishes also the accuracy with which we describe the coast. An uncertainty of half the grid step size on the actual position of the coast must be considered. This becomes critical in slanting fetch conditions or, e.g., with waves coming towards the coast after going around a promontory enclosing a gulf. To avoid errors larger than 10%, the point of interest should be at a distance from the coast at least five times the uncertainly in its exact location.

The overall effect of the grid resolution is exemplified in Figure 5. A very severe storm in the Mediterranean Sea (Hs>11 m between Tunisia, Sardinia and Sicily, 8 m in the Sicily Channel) has been hindcast using the same input wind, but two different resolutions, namely 0.5° and 0.25° (see Cavaleri et al., 1991). The figure shows the differences (with 0.5 m isolines) between the two fields, at the peak of the storm. They are partly due to a better description of the wave generation, and partly to coastal effects.

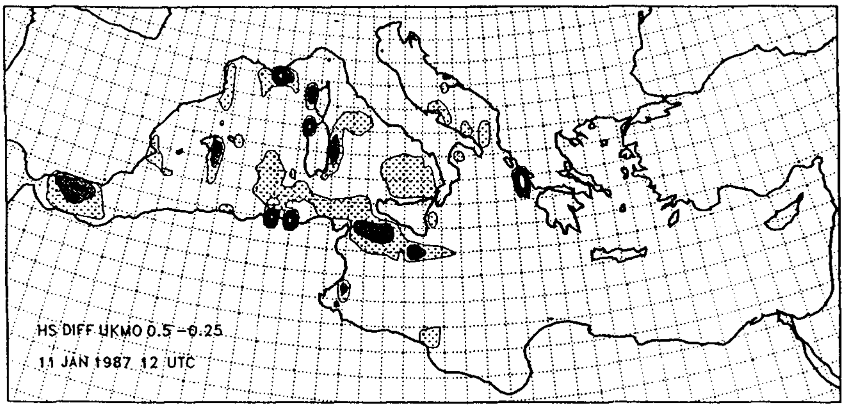

Figure 5. Wave height comparison between the hindcasts of a severe storm in the Mediterranean Sea done with different grid resolution. The differences are indicated as isolines at 0.5 m interval (after Cavaleri et al., 1991).

Model resolution. The integration time step ΔT is connected to the grid step size and to the time scale of the phenomenon we want to describe. Therefore ΔT must be equal or smaller than the time required by the minimal change we want to detect in the evolution of the storm. If larger, the phenomenon will be smoothed, and we must expect a likely underestimate of the peak conditions.

The resolution in frequency is usually not a problem. We have formerly discussed in section 3 the implications for refraction. Some particular cases, e.g., the proper evaluation of swell on the Pacific Ocean, can require an extension towards the low frequency range. De La Heras (1990) gives a nice example of this.

A more critical aspect for coastal engineers is the resolution in direction. The usual 24 or 30 degree resolution suffices for most of the cases. However, when approaching a complicated shallow water topography or a winding coastal shape, an increased resolution will provide a substantially better description of the wave distribution. Errors of 15-20% on Hs can easily be found at some location, if a coarse resolution in direction is used.

6. Interactions with Current

The wave-current interactions are usually neglected by the wave modeller for two reasons. First, in the large majority of cases the currents are not strong enough to affect a developed wave field in an appreciable way. Second, very rarely a detailed distribution of the current field is available. In any case many wave models (see Tolman, 1991 and Komen et al., 1994) are built to face the problem.

In practical terms, till when the current speed is below a few tens of centimeters per second, there is no strict need of taking it into consideration. Rather the problem for the coastal engineer is the eventual, if necessary, availability of a detailed description of the current field. Particularly in coastal areas, with a strong spatial variability, this can be a serious problem that deserves a particular attention. Besides, to properly evaluate the interactions, the grid resolution of the wave model must be better than that required for a proper description of the current field.

7. Summary

In the previous sections we have highlighted the possible relevance of each single process and model parameter in the modeling of wind waves in coastal areas. The difficulty in so doing is that the influence of the single factor can span a wide range of values, depending on the conditions in the area of interest.

Some processes, like bottom scattering and bottom elasticity, require special conditions for their appearance. They are usually not considered. However, when the conditions are present, their role becomes dominant.

Even if only on a qualitative basis, we have summarized in figure 6, the relevance of the single physical processes. The figure provides an "expected" level of influence at 20 m of depth, at 5 m of depth, and the maximum possible relevance of each process in the local energy budget.

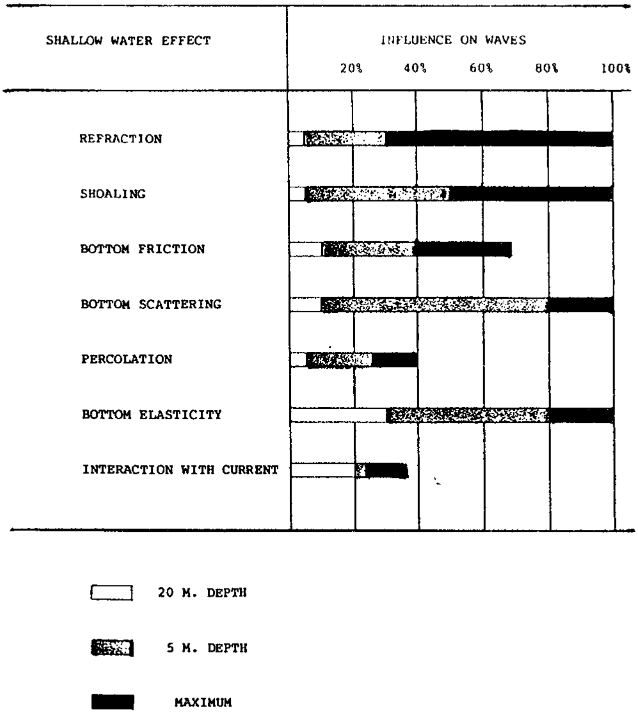

Figure 6. Possible influence of the single physical processes affecting waves in shallow water.

Acknowledgments

This research has been partially funded by the *Progetto Salvaguardia Laguna Venezia*.

References

Battjes J.A. and S. Beji, 1993. Breaking waves propagation over a shoal, ICCE 1992, **3**, 42-51.

Cavaleri, L., L. Bertotti and P. Lionello, 1989. Shallow water application of the third generation WAM wave model, *J. Geophys. Res.*, **C94**, 8111-8124.

Cavaleri, L., L. Bertotti and P. Lionello, 1991. Wind wave-cast in the Mediterranean Sea, *J. Geophys. Res.*, **C96**,10739-10764.

Cavaleri, L., L. Bertotti, C. Koutitas, S. Christopoulos, G. Komen, G. Burgers, K. Mastenbroek, J.M. Lefevre, A. Guillaume, J.C. Carretero, A. Guerra, L. Iovenitti and P. Cherubini, 1993. MAST Contract 0042, Final Report, 211 pp.

Davies, A.G. and A.D. Heathershaw, 1983. Surface wave propagation over sinusoidally varying topography: Theory and observation, I.O.S. Report no. 159, Part 1, Wormley (UK), 88 pp.

Forristall, G.Z., E.H. Doyle, W. Silva and M. Yoshi, 1990. Verification of a soil interaction model (SWIM), p. 41-68, In: *Modeling Marine Systems*, **II**, A.M. Davies (ed), CRC Press, Boca Raton, Florida (USA).

Günther, H., P. Lionello, P.A.E.M. Janssen, L. Bertotti, C. Brüning, J.C. Carretero, L. Cavaleri, A. Guillaume, B. Hanssen, S. Hasselmann, K. Hasselmann, M. de las Heras, A. Hollingworth, M. Holt, J.M. Lefevre and R. Portz, 1992. Implementation of a third generation ocean wave model at the European Centre for Medium-Range Weather Forecasts, Final Report for EC Contract SC1-0013-C(GDF), ECMWF, Reading (UK).

Heras, M. de las, 1990. WAM hindcast of long period swell, KNMI Afeling Oceanografisch Onderzoek Memo, OO-90-09, De Bilt (NL), 10 pp.

Hubbert, K.P. and J. Wolf, 1991. Numerical investigation of depth and current refraction of waves, *J. Geophys. Res.*, **C96**(C2), 2737-2748.

Komen, G.J., L. Cavaleri, M. Donelan, K. Hasselmann, S. Hasselmann and P.A.E.M. Janssen, 1994. *Dynamics and Modelling of Ocean Waves*, Cambridge University Press, 532 pp.

Long, R.B., 1973. Scattering of surface waves by an irregular bottom. *J. Geophys. Res.*, **78**, 7861-7870.

Osborne, A.R., 1993. Behavior of solitons in random-function solutions of the periodic Korteweg-de Vries equation, *Physical Review Letters*, **71** (19), 3115-3118.

Shemdin, P., K. Hasselmann, S.V. Hsiao and K. Herterich, 1978. Non-linear and linear bottom interaction effects in shallow water, p. 347-372, In: *Turbulent*

Fluxes Through the Sea Surface, Wave Dynamics and Prediction, A. Favre and K. Hasselmann (eds.), Plenum Press, New York, 677 pp.

Tolman, H.L., 1991. A third-generation model for wind on slowly varying, unsteady and inhomogeneous depths and currents, *J. Phys. Oceanogr.*, **21**, 782-797.

Weber, S.L., 1991. Eddy-viscosity and drag-law models for random ocean wave dissipation, *J. Fluid Mech.*, **232**, 73-98.