MAUSAM, 48, 4 (October 1997), 629-644

551.466.32 : 551.46.072

Wave modelling in the oceans and in the regional seas : A critical look and perspective

LUIGI CAVALERI

Instituto Studio Dinamica Grandi Masse-CNR
San Polo 1364, 30125 Venice, Italy

सार — क्षेत्रीय समुद्रों में लहरों की मॉडलिंग के दौरान उत्पन्न होने वाली समस्याओं को विशेष रूप से ध्यान में रखते हुए लहरों के मॉडलिंग कार्य की स्थिति की समीक्षा की गई है । स्पैक्ट्रल तरंग निदर्श के संक्षिप्त विवरण सहित व्यवहारिक समस्याओं का मुख्य रूप से उल्लेख करते हुए इसके अनुप्रयोग के विभिन्न स्केलों के संबंध में चर्चा की गई है । निदर्श के भौतिक और संख्यात्मक भागों के समीक्षात्मक विश्लेषण के साथ बहुतायत से उपयोग में आने वाले प्रयोगों की चर्चा की गई है । तत्पश्चात् निवेशी पवन क्षेत्रों की परिशुद्धता की सार्थकता पर प्राप्त हुए लहरों के परिणामों की परिशुद्धता के संबंध में इसके महत्व पर बल देते हुए विचार किया गया है । लहरों के पूर्वानुमान से जुड़ी समस्याओं पर भी विचार किया गया है । निष्कर्षों के आधार पर निकट भविष्य में इस क्षेत्र में प्रगति की आशा की जा सकती है ।

ABSTRACT. The state-of-the-art in wave modelling is reviewed, with particular attention on the problems arising by its application in the regional seas. After giving a compact description of a spectral wave model, the different scales of application are discussed, highlighting the practical implications. The most relevant uses are described, with a critical analysis of the physical and numerical parts of a model. Then the relevance of the accuracy of the input wind fields is considered, stressing its importance for the accuracy of the derived wave results. The problems connected to wave forecasting are considered. The conclusions indicate expectations for further developments in the near future.

Key words — Wind waves, Wave modelling, Regional seas, Wave forecast, Sea storms.

1. Introduction

Wave modelling is the art of deriving the wave conditions at a given time and location, starting from the essential information of the wind and the geometry of the basin. Old as the history of man and sea, wave modelling (henceforth indicated as WM) has evolved paralleling the increase of knowledge and experience about the sea. The old sailors of the previous centuries were capable of remarkably good estimates of the wave conditions. However, their capability was drastically hampered by two basic limitations. First the information available to them was essentially local, without any knowledge of what was going on "beyond the horizon". Then, their estimates were based on their previous experience; hence they were hopeless when facing a new phenomenology. Basically, these are the same limitations that hamper the various "thumb-rule" or simple methods based on local information.

The drastic improvements that have taken place in the last half century are associated with two conditions: the substantial increase of knowledge of the physics of waves, and the available computer power allowing its operational application to practical problems. Now-a-days WM is a mature science, with a deep knowledge of the related physics, and with a wealth of applications to practical problems, ranging from the study of a small harbour to the forecast for the global oceans.

At present we can identify two main directions of interest in WM. The first one is the global view of the problem, connected to the use of satellite data and to the long term climatological problems. The other one follows the high density of humanity and economical interests on the coast of the various continents, focusing on aspects related more to the smaller scale, in time and space, of the processes involved in coastal areas and regional seas.

In this report we want to summarise the present state-of-the-art in WM, with particular attention on regional modelling. A broader look will be necessary, as the smaller scales are intrinsically connected to the larger ones, without any discontinuity. Besides, our main focus will be on spectral wave models, the main tool in the daily extensive applications. Alternative approaches will be briefly mentioned where relevant for the discussion.

We begin in Section 2 with a compact description of a spectral model. In 3, we discuss its scales of application, and the derived implications. Section 4 provides a brief description of the most relevant present uses of the models. Sections 5 and 6 are devoted to an analysis of their critical aspects,from the physical and numerical point of view. In 7, we discuss the accuracy of the wind fields and its effect on the wave results. Forecasting is dealt with in section 8, while the final section 9 provides general comments and an outlook on the near future.

The material used for this report is basically taken from our previous works on the subject. For the interested reader, ample reference is quoted and indicated at the end. For those wishing to take a substantial step into the subject of WM, the master reference is the book by Komen *et al.* (1994).

2. The spectral wave model

The basic assumption behind wave modelling is that at a given time t and location ϕ and λ (latitude and longitude, respectively), the wave conditions are represented by the two-dimensional spectrum $F(f, \theta, \phi, \lambda, t)$ where f and θ are the frequency and direction of the specific wave components. The evolution of $F(\,)$ in spherical coordinates is governed by the energy balance equation,

$$\frac{\partial F}{\partial t} + (\cos\phi)^{-1}\frac{\partial}{\partial\phi}(\dot{\phi}\cos\phi F) + \frac{\partial}{\partial\lambda}(\dot{\lambda}F) + \frac{\partial}{\partial\theta}(\dot{\theta}F) = S \qquad (1)$$

where the dots represent derivative with respect to time. Specifically,

$$\dot{\phi} = vR^{-1}\cos\theta$$

$$\dot{\lambda} = v\sin\theta\,(R\cos\phi)^{-1}$$

$$\dot{\theta} = v\sin\theta\tan\phi\,R^{-1}$$

Here v is the group velocity and R is the radius of the earth.

If we operate in a limited area where the earth's curvature is not important, the wave trajectories coincide with straight lines on a flat map, and Eqn. (1) can be reduced to its more familiar Cartesian version,

$$\frac{\partial F}{\partial t} + \vec{v}\cdot\nabla F = S \qquad (1a)$$

The left-hand side of Eqn. (1) represents the advection of wave energy. The physics of waves is described in the source term, S, that summarises all the processes that affect the growth and decay of the different wave components. The improvement in wave modelling has been basically associated with the correct description of this term, that is usually written as

$$S = S_{in} + S_{nl} + S_{diss} \qquad (2)$$

where S_{in} is the energy input from wind to waves, S_{nl} represents the non-linear exchange among the wave components and S_{diss} summarises the various dissipative processes.

A lack of knowledge and of sufficient computer power forced the earlier modellers to seek out simplified solutions for the expression of S. The drastic step ahead came in 1984, when, following the results of the SWAMP tests (SWAMP Group 1985), a group of modellers joined their efforts to produce, within a few years, the first so-called "third generation model". The aim was to avoid any shortcoming and parameterisation, describing the source terms in purely physical terms. The result was the WAM model (WAMDI Group 1988, Komen *et al.* 1994), that was rapidly made of public domain and implemented at many different agencies and institutions. Other generation models followed (*e.g.* WAVEWATCH, Tolman 1991). However, WAM has remained by far the most widely used, and documented wave model, and we will refer to it for a more detailed description of the source terms.

WAM is a very dynamic model, and it has been repeatedly updated and improved (it still is). For a description of S, we will refer to the original formulation (WAMDI Group 1988), quoting along the way the different improvements. A more detailed description of some aspects is given in section 5.

In Eqn. (2) the input term

$$S_{in} = \beta F \tag{2a}$$

represents the input of energy from the wind based on the measurements by Snyder *et al.* (1981) and consistent with the theory of Miles (1957). Following Komen *et al.* (1984), the expression for β has been scaled with the friction velocity, u_*. Specifically, the expression for β is,

$$\beta = \max\left\{0.,\, 0.25\,\frac{\rho_a}{\rho_w}\left(28\,\frac{u_*}{c}\cos\theta_w - 1\right)\right\}\omega \tag{2b}$$

where $\omega = 2\pi f$, ρ_a and ρ_w are air and water density, c is the phase velocity, and θ_w is the angle between wind and wave directions.

This approach was improved by Janssen (1991), who pointed out that the characteristics of the lowest wind profile depend on the small characteristics of the sea surface, hence on the stage of development of the wave spectrum. As in turn the tail of the spectrum responds immediately to any change of wind, a feed back mechanism is implied, and the solution has to be found through an iteration procedure.

S_{nl} represents the non-linear, conservative energy exchanges between all the possible quadruplets of wave components that satisfy given resonance conditions. The evaluation of the involved Botlzmann integral is not possible in an operational application with present-day computing power. In the WAM model, S_{nl} is evaluated using the discrete interaction approximation of Hasselmann and Hasselmann (1985) and Hasselmann *et al.* (1985).

S_{diss} represents the dissipation processes. In deep water the only relevant dissipation takes place through wave breaking, and the corresponding energy loss has been given by Komen *et al.* (1984) as,

$$S_{br} = -2.33 \times 10^{-5}\,\hat{\omega}\left(\frac{\omega}{\hat{\omega}}\right)^2\left(\frac{\hat{\alpha}}{\hat{\alpha}_{PM}}\right)^2 F \tag{2c}$$

Here

$$\hat{\alpha} = E\hat{\omega}^4 g^2 \quad \hat{\alpha}_{PM} = 3.02 \times 10^{-5} \tag{2d}$$

E is the overall energy, and g the acceleration of gravity. The circumflex represents a slight approximation to the actual mean value, as for stability reasons, $\hat{\omega}$ has been obtained from the inverse of the mean period. Together with a slight reduction of the constant, this explains the different values present in S_{br} and $\hat{\alpha}_{PM}$ with respect to the original ones given by Komen *et al.* (1984)

Janssen (1991), in reformulating the input function S_{in} had to modify also the dissipation term S_{br} which is still the main weakness of any wave model. As today we do not have a complete quantified description of the energy loss through white- capping. Truly enough, the basic idea at the base of the formulation by Hasselmann (1974), then updated by Komen *et al.* (1984), is physically sound. However, the final expression includes a couple of constants that need to be determined using the available data (luckily there is a wealth of them). If we modify one of the other source terms, as Janssen (1991) has done with S_{in}, we are forced to a retuning of the two constants in S_{br} to be able to obtain again the same results. This is an open point, but at this moment there is no indication of a breakthrough for a final solution. Good ideas are strongly needed.

In shallow water, a number of additional processes are possible, depending on the bottom conditions (see, for example, Shemdin *et al.* 1978). In its standard version the model considers only bottom friction. To save computer power, the straightforward introduction of other processes, such as percolation, viscous damping or bottom scattering, is left to the specific applications. As none of these processes is relevant in the Mediterranean Sea, the standard version has been used for the tests described in this paper.

The bottom friction term is given as,

$$S_{bf} = -\frac{\Gamma}{g^2} \frac{\omega^2}{\sinh^2 kd} F \tag{3}$$

a linearized expression obtained from the Joint North Sea Wave Project (JONSWAP, Hasselmann *et al.* 1973), where $\Gamma = 0.038\ m^2 s^{-3}$, k is the wave number and d is the depth. The linearization of Eqn. (3) is accurate enough for large-scale applications and not too shallow water. For small-scale applications and severe storms in shallow water, a non linear expression is required. This subject is dealt with in more detail in section 5.

In its standard version the WAM model considers 25 frequencies in geometric progression ($f_1 = 0.05$ Hz, $f_{n+1} = 1.1 f_n$). The number of directions varies with the necessity of the problem, being usually established at 12 or 24 (30 and 15 degrees of angular resolution, respectively).

3. Scale of the model

A numerical wave model is usually formulated in general terms, without any specific reference to the dimensions of the application space. However, a model and the grid itself must be consistent with the physics reflected in its equations and with the scale of the phenomena we want to represent. The results lose reliability at small scales, when other phenomena, not considered in the model, can be significant for the evolution of the field. A common example is the lack of any consideration of diffraction, present in the lee of an island or a peninsula or, at an even smaller scale, in a harbour. Clearly, a model built with an oceanic perspective is not suitable for dealing with this problem.

On larger scales economical and technical reasons have naturally led to an extension of the grid to the full global scale. For practical reasons large scale models still have a fairly coarse resolution, but they are nevertheless well suited to deal with large-scale phenomena. Typical examples are the large extra-tropical winter storms of the North Atlantic Ocean, originating at high latitudes on the American coast, which gradually move to the east towards Europe, and Pacific swell, which can travel many thousands of kilometers for several days before running onto one of the surrounding coasts.

A coarse-resolution wave model can only be applied meaningfully when sharp gradients in the field are absent. If such gradients arise, as in the case of a hurricane or often close to the coast, the model results provide only an approximate, smoothed description of the actual situation. If in such cases a detailed analysis is required, it is necessary to focus on the area of interest by using a smaller and finer grid. A limited area model (LAM) allows a more accurate study of a given event in a given area. However, for the full exploitation of its capability the input information from the boundary and, in particular, the meteorological model must be sufficiently accurate. If not, we increase the resolution, but we do not improve the accuracy of the results.

The ideal situation for a LAM is a closed basin, without external influences, or, if open to the ocean, a case with offshore flowing information (a growing sea under an offshore wind is the obvious example). Alternatively, boundary information can be obtained by embedding (or "nesting") the LAM into a large-scale model. If all input information is available with adequate accuracy, a LAM is particularly suitable for studying the physics of a model, because the limited area and the improved input conditions allow a detailed analysis of the results and the investigation of the effects of a particular phenomenon.

Present day computer power is not sufficient for running high- resolution global wave models, and even if it were, this would not always be worthwhile, because it is convenient to split the applications into large-scale (coarse) and small-scale (fine). Their respective characteristics and possibilities can then be summarised as follows :

(a) *Large-scale wave models*

— Suitable for the analysis and investigation of large-scale phenomena. In general, the computation of the sea state, even if only for a limited region, requires a proper assessment of what is happening elsewhere in the basin.

— Needed for large-scale applications, such as ship routing, interpretation and assimilation of satellite sea surface observations or coupling with a global atmospheric model.

— Useful for a general estimate of the overall model performance. However, the validation statistics must be interpreted with care and stratified with respect to properly chosen criteria. For instance the bias or the rms error of the H_s estimate in the Pacific Ocean does not tell whether this is due to wrong generation or to incorrect advection and dispersion of swell, nor does it say whether the error is associated more with high or with low values of H_s. A proper analysis of these possibilities requires conditional statistics and is often not very conclusive without further information. The provision of global wave height data from satellite altimeter and two- dimensional wave spectra from satellite SARs should increase the power of this approach significantly.

— Not suitable for a detailed study of a limited area or for the phenomenological analysis of a given event with high space and time variability.

(b) *Limited area wave models*

— Focus attention on a limited area and take the local geometry and the local variability into account, so giving, with respect to large-scale models, a better description of what is going on.

— Suitable for detailed case studies and for the intercomparison of different approaches.

— Sensitive to the specification of the model and, as such, suitable for studying its physics and the related sensitivity of the results.

— Require a higher accuracy in the input and in the definition of the boundary conditions in view of their higher accuracy.

— If nested within a larger scale model, must use grids which extend well beyond the area of interest.

4. Operational applications

WAM, and more in general the different existing wave models, have been used in innumerable applications to study coastal evolution, beach erosion, harbour design, coastal structures, oil rigs, long-term statistics, etc. One of, if not, the most important applications is certainly the forecast of the wave conditions for the next few days. WAM is operative at most of the major meteorological and oceanographic centres of the world. In particular, at the European Centre for Medium-Range Weather Forecasts (Reading, U.K., henceforth referred to as ECMWF), following the daily produced ten-day meteorological forecast, a wave forecast for a similar period is daily produced for the whole globe. The results are available at six-hour intervals, for each point of the grid the available information includes significant wave height, mean period and direction, overall and for wind wave and swell separately, plus data on the local wind and wind stress. Since its implementation, following the introduction of the high resolution T213 meteorological model, WAM has been run at 1.5 degree resolution. However, this resolution has been recently (December 1996) increased to 0.5 degree.

Parallel to the global one, a reduced version is run for the Mediterranean and the Baltic seas, with a resolution of 0.5 degree, recently increased to 0.25 degree. The need for a higher resolution in these enclosed basins has been discussed in the previous section, and it will become more evident in the following one.

5. Relevance of the single physical processes

The standard version of WAM, briefly described in section 2, is suitable for applications at the large scale. However, locally, and especially in regional and shallow applications, a more attentive description of the physics of wave processes is required, if the best results are to be obtained. In this section, we consider a series of examples to illustrate the effect of different physical approaches on the wave model results.

5.1. *Bottom friction*

The energy loss by bottom friction arises from the relative motion between the bottom and the horizontal alternating free stream velocity close to it. A thorough description of the physics of the phenomenon and of the related theoretical approaches can be found in section II.5 of Komen *et al.* (1994).

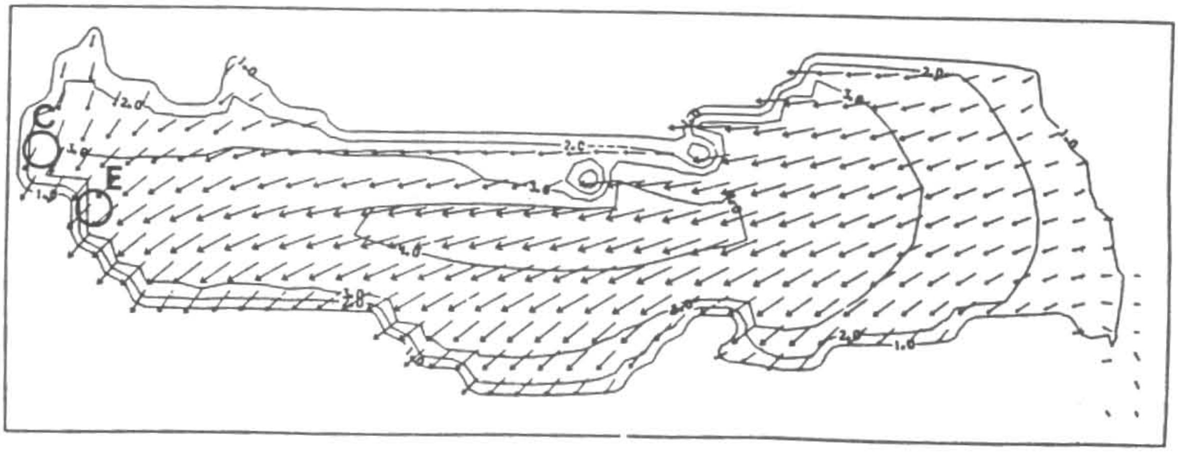
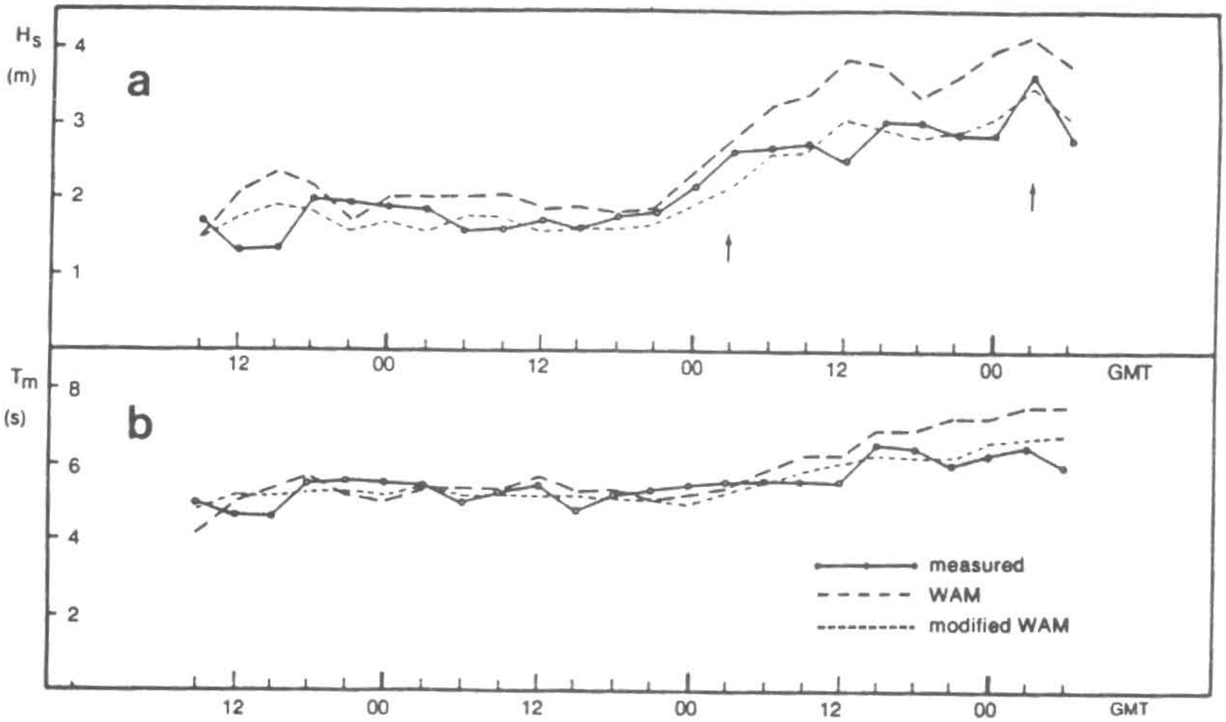


Fig. 1. Wave field in the Adriatic Sea at 00 UTC, 2 December 1982. Isolines at 1m interval (after Cavaleri *et al.* 1989).



Figs. 2(a&b). Comparison between (a) measured and hindcast significant wave height and (b) period at position E in Fig. 1 (after Cavaleri *et al.* 1989).

The WAM model (see section 2) uses a linearized formulation derived from the JOSWAP experiment (Hasselmann *et al.* 1973). Cavaleri and Lionello (1990) have shown that this approach overestimates the loss for low wave height (therefore with limited consequences), but it strongly underestimates it for heavy storms in shallow water. In these cases a more sound approach is required, like the non-linear formulation with a drag law by Hasselmann and Collins (1968) or the eddy viscosity approach by Weber (1989). While

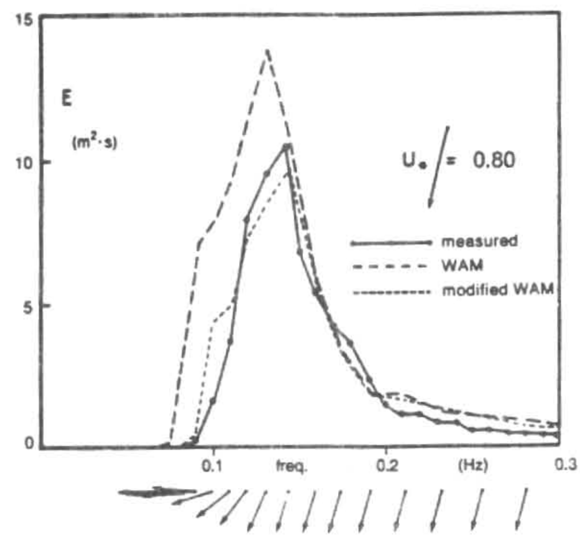


Fig. 3. One-dimensional spectrum at position E in Fig. 1 at 00 UTC, 2 December 1982. The lower arrows show the mean direction for each frequency. The single arrow indicates the local wind (after Cavaleri *et al.* 1989).

these two theories lead to very similar results, the differences from the first one (JONSWAP) can be substantial. Fig. 1 shows a case of swell in the Adriatic Sea, the small enclosed basin, 700 km long, 200 km wide, to the east of Italy in the Mediterranean Sea. Fig. 2 shows the verification of the results obtained with the standard version of WAM and introducing the non-linear description of the bottom drag. The differences are even more evident when looking at the spectra (Fig. 3). Clearly the linearized approach fails to estimate correctly the strong effect of bottom friction on the lower frequency range.

This aspect is crucial for the correct evaluation of the wave conditions close to the coasts, particularly when, like in the delta of the Ganges and Brahamaputra rivers, the continental platform extends well offshore. Here waves run for a long while in shallow water before reaching the coast, and bottom effects become the dominant factor in establishing the actual wave regime.

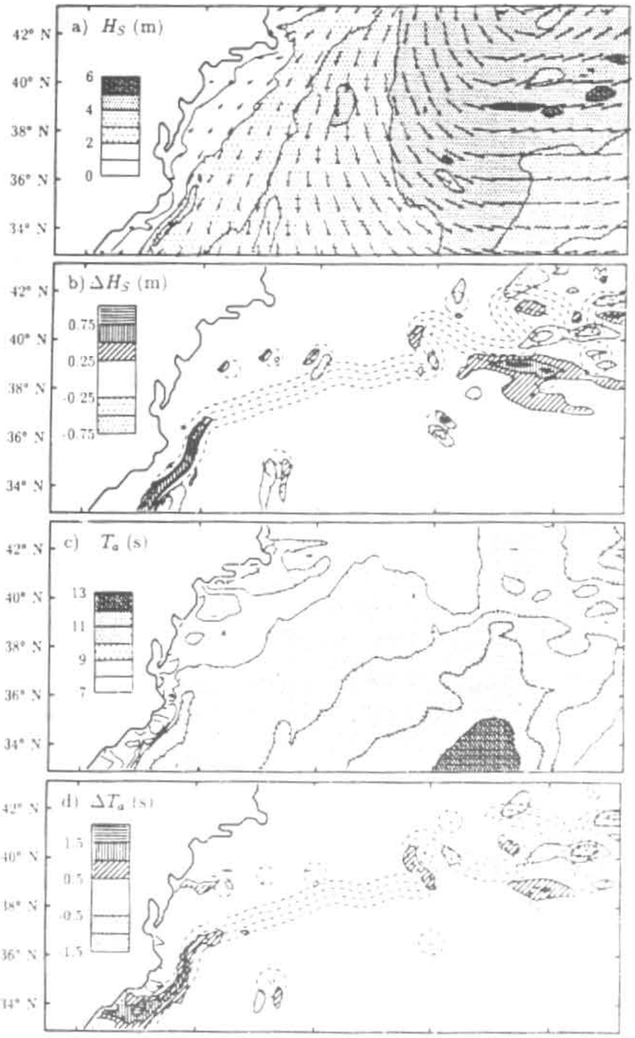
5.2. *Bottom elasticity*

Still along the same line of thought, another process that can have spectacular effect is associated with wave attenuation by bottom elasticity. In standard wave modelling the seabed is considered to be rigid, except for the possible horizontal transport of sand. For a rocky bottom the hypothesis is obviously correct. In case of sand a certain degree of elasticity is present, and the seabed reacts with small vertical movements to the variation of pressure associated with the overlying wave field. These movements have been measured by Rosenthal (1978) and Forristall and Reece (1985). They found the motion to be quite limited in amplitude (order of one centimetre at most), and substantially in phase with the pressure wave at the bottom. The related energy absorption turned out to be negligible, the seabed acting as an undamped spring.

The picture changes completely if the bottom is characterised by a viscous mud layer. In this case a bottom wave, slowed down by viscosity, is pulled by the surface wave. The viscous resistance leads to a large phase difference between the forcing function (the pressure wave) and the resulting oscillation (the mud wave), with a consequent strong absorption of energy. The results can be quite spectacular and the process dominant in the control of the evolution of the wave conditions. With large water waves at the surface in relatively shallow water, the amplitude of the bottom wave can be quite large, up to the level of metres.

Viscous damping is typically present in the extended deltas of some large rivers. Not surprisingly because of the associated oil interest, the most studied area is the delta of the Mississippi, where also remarkable measurements have been made by Forristall and Reece (1985). They recorded attenuation from 8.6 m significant wave height H_s to 2.45 within 30 km, without any depth limitation on wave height.

The theory is well developed (there is a number of papers by Yamamoto, the last one being Yamamoto and Tori 1986). The good news is that the theory suggests for each wave component an attenuation proportional to the existing energy; the process can therefore be rapidly introduced in a wave model. The bad news is that the proportionality constant is not really constant, but it can have sudden and drastic changes of value when, ones set in motion, the bottom sediments change their characteristics. Nevertheless, taking advantage of some tuning from existing measurements, Forristall *et al.* (1990) have obtained quite remarkable results, with error less than 10% for the energy loss at the single frequencies.



Figs. 4(a-d). Model results for 0300 UTC, 28 October 1990 from the regional SWADE grid including the Gulf Stream : (a) H_s distribution, (b) current-induced modulation of H_S (*i.e.*, the difference between model results obtained with and without currents), (c) T_a distribution and (d) current-induced modulation of T_a. Dashed lines in (b) and (d) denote 0.5 m/s and 1.5 m/s contours of the current velocity (after Komen *et al.* 1994).

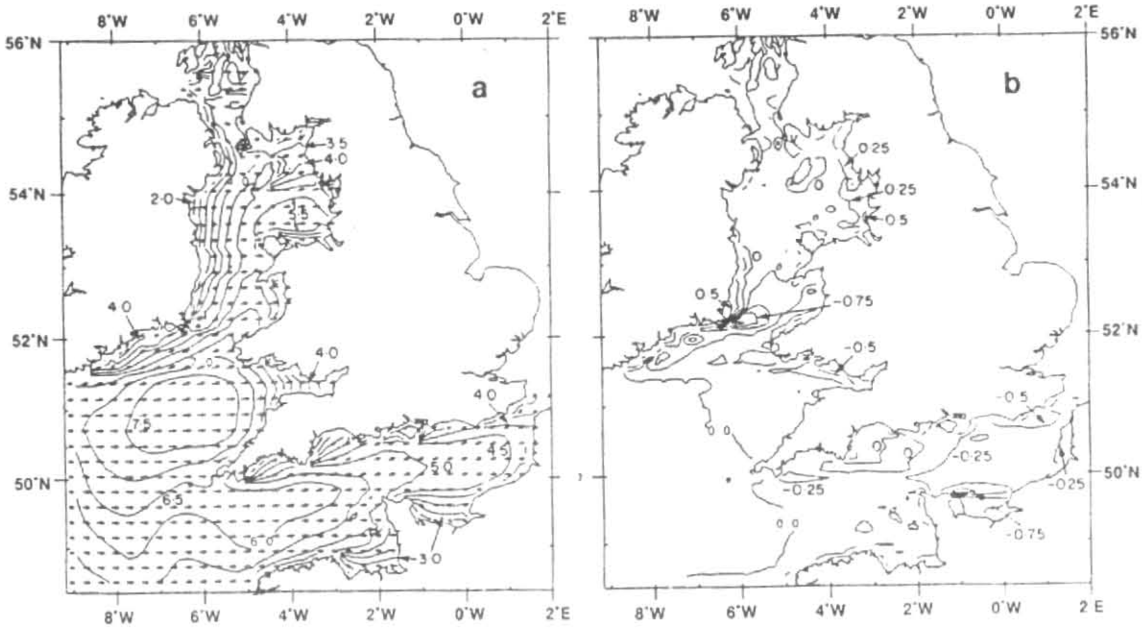
5.3. *Wave-current interaction*

The basic theory of waves is developed for absence of currents. However, ocean water does move, and gradients of current in space and time do affect the distribution of wind waves. As a matter of fact, for most of the surface the currents are low enough not to deserve consideration for this purpose. The conditions can be different in particular areas, like the strong currents of the Gulf Stream, or the Kuroshio or the exit of some large river where (*e.g.*. the Columbia River) the current can be faster than waves, and lead therefore to their blocking. This is not the case in the open ocean. However, the effects can be remarkable and they deserve attention.

The problem can be approached at various stages, the simplest one being to consider only the one way effect, *i.e.* that of the current on the wave field. This is rapidly obtained writing Eqn. (1) in term of the action density $N = F/\sigma$, with σ the circular frequency, and correcting speed and advection for the presence of current (see *e.g.*, Komen *et. al.* 1994, pp. 207-215)

A good example is given by the hindcast of the SWADE storm (Morris 1991), so-called after the extensive air-sea interaction experiment during which it happened. Fig. 4 shows, in (a) and (c), the wave height and period fields in the north-western Atlantic during the intense phase of the storm, while (b) and (d) show the corresponding modifications introduced by the presence of the Gulf Stream.

The overall picture becomes more complicated when we move to shallow water because (1) the wave-current interaction increases the bottom friction, with effects on both the fields and (2) the waves, through the loss of momentum, affect the distribution of current. This implies that the two models, wind waves and circulation, must be numerically coupled and run together. The order of magnitude of the implications is given in the Figs. 5 and 6, showing respectively, for a storm in the Irish Sea, the wave field and its modifications due to surge, and the change in circulation and sea level due to the presence of waves. We find changes of H_s reaching almost 20% and variation in surge of almost 0.5 m. We should bear in mind that in the very shallow water close to coast the final up-jump of the sea level during a surge is strictly associated with the presence of waves. This becomes critical in some area, the most dramatic example being probably the effect of cyclones in the Bay of Bengal.



Figs. 5(a&b). (a) H_s (contour interval 0.5 m) and mean wave direction at 12 UTC, 26 February 1990 in the Irish Sea and (b) Change in H_s due to tide and surge (contour interval 0.25 m) (after Komen *et al.* 1994)

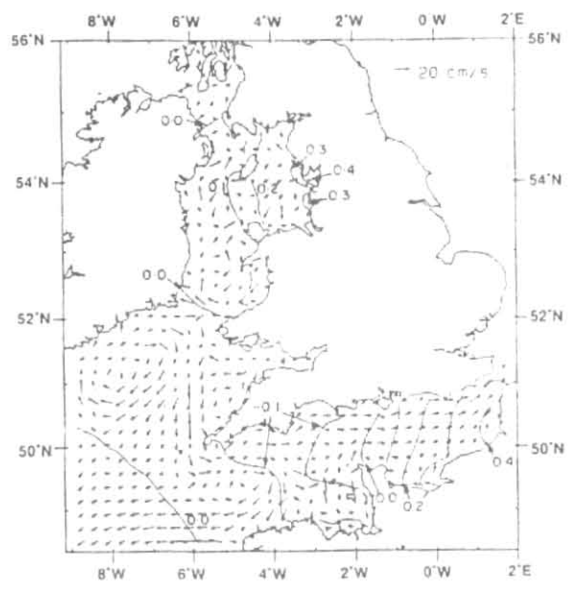


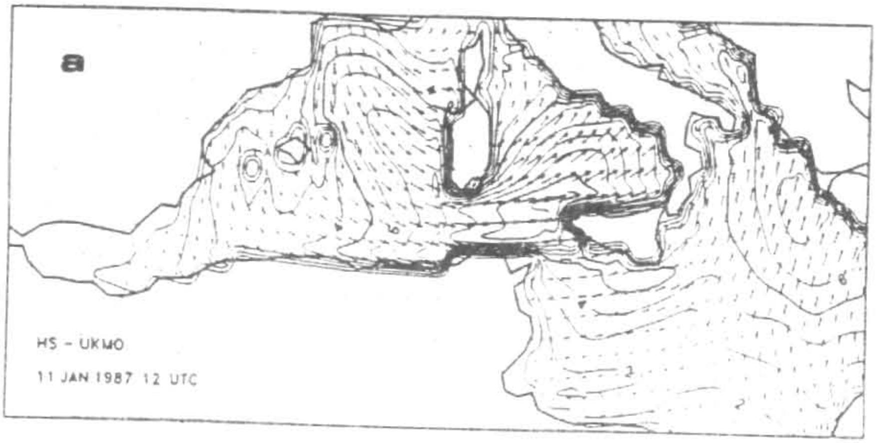
Fig. 6. Change in sea level and depth mean current at the same time as for Fig. 5, due to wave-dependent surface and bottom stress (contour interval 0.1 m): cgs units are used (after Komen *et al.* 1994)

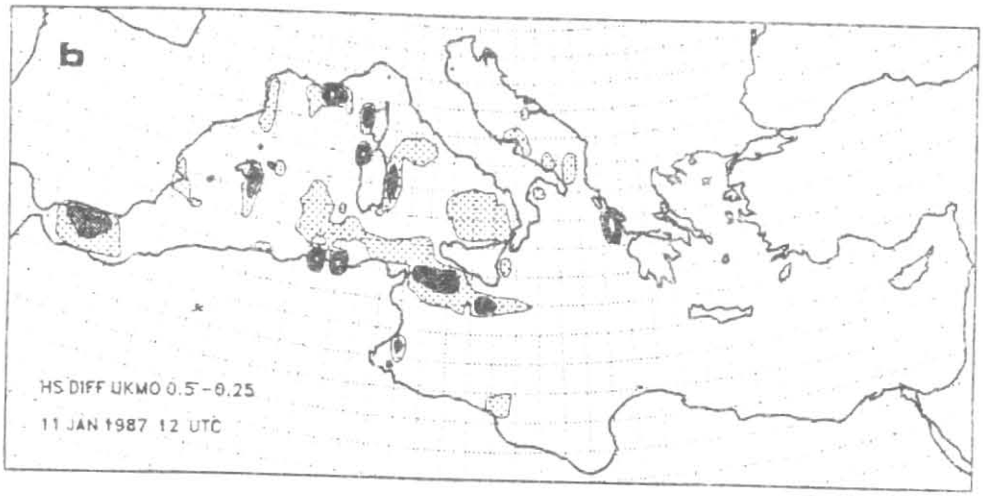
6. Numerics

Once the physics of a model has been decided, there is still quite a bit of work to do in assembling the program with which to perform the task we have in mind. The choices to be done at this stage are by no means of negligible importance, as they can, and do often, affect substantially the final results. In this section, without entering the subtle art of numerics, we briefly list the main choices, mostly trade-off between accuracy and computational efficiency, a user has to do. For those interested in pure numerics, Chapter 3 of Komen *et al.* (1994) gives an overall account of the typical solutions in a wave model.

6.1. *Spatial resolution*

Once we have identified the area of interest, the first thing to do is to lay out the grid. Obviously we would like to make it as detailed as possible by decreasing the grid step size Δx. This can be particularly relevant in regional modelling, where usually we want to improve the accuracy of description of the area or the coast we are interested in. However, we must keep in mind that the overall number of points in the grid is proportional to $(1/\Delta x)^2$. Even more, due to the dependence of the time step Δt on Δx, the computer time increases as $(1/\Delta x)^3$, putting a practical upper limit to the resolution we can achieve with a given computer.





Figs. 7(a&b). Wave field in the Mediterranean Sea at 12 UTC, 11 January 1987. Isolines at 1 m intervals; (b) modulus of H_s vector difference between wave fields evaluated using 0.5 and 0.25 degree resolution respectively. Shading interval is 0.5 m (after Komen *et al.* 1994)

The details with which we describe a coast are obviously relevant for the accuracy of the results close to it. Also the physics is affected by Δx. In areas with strong spatial wind and wave gradients a smaller Δx usually implies higher wind and wave peak values. Fig. 7(a) shows the wave situation in the western Mediterranean Sea during a severe storm that happened in January 1987; Fig. 7(b) shows the wave height differences deriving from using, with the same input wind, 0.25 degree resolution instead of 0.5. Apart from expected differences close to the coasts and on the lee of their corners, there are substantial differences, up to 10% in the peak area of the storm. This is a typical figure of the kind of error we can expect by using a too large Δx.

6.2. *Nesting*

The solution to the above problem is to increase the resolution only locally where it is needed. This means to set up two grids, one inside the other, the smaller one with a smaller Δx, practically zooming on the narrow area of interest. This is a very effective technique, and definitely worthwhile to consider, notwithstanding the numerical complications it implies. However, we need to remember that a higher resolution does not necessarily imply higher accuracy. The boundary information on the nested grid is derived from the output of the large scale model. The accuracies of the two grids are, therefore, strictly connected. There is no way that a high resolution local grid can correct for the errors eventually derived from the evaluation on the large scale.

6.3. *Distribution of frequencies*

The number of frequencies that we are allowed to use depends on the available computer power. The question is how to distribute them to optimise the calculations. In the past a uniform distribution, with constant Δf, has often been used. However, what we must aim at is to concentrate the frequency values in the range where most of the action is taking place. For a wind wave spectrum this is around the peak. The problem is that the peak frequency exhibits drastic changes during the evolution of a storm. These changes are very rapid in the early stages, when the peak is in the high frequency range, and they slow down as the peak moves towards lower frequencies. Therefore, it is convenient to concentrate the frequency values in the latter range, where the peak dwells most of the time during storm conditions. This has been obtained in WAM by distributing 25 frequencies in a geometric progression with a ratio of 1.1. This corresponds to a ratio of about 10 between the last frequency and the first one. The lowest value can be adjusted to the environment in which the model is to be applied. The standard global version of the WAM model has a prognostic range starting at 0.042 Hz and ending at about 0.4 Hz. One of the consequences of having a limited number of frequencies is the need to add a diagnostic tail to the high frequency part of the spectrum, to be able to evaluate the non-linear transfer in the prognostic frequency range.

In a basin of limited dimensions, such as the Mediterranean Sea, the Baltic Sea or the Great Lakes of North America, we expect higher frequencies than in the open ocean. The frequencies in the model must be chosen accordingly. This goes hand in hand with the choice of a smaller grid step, because higher frequencies will be found at the first grid point off the coast in the case of an offshore blowing wind. The smaller the grid step, the higher the possible frequencies. This argument becomes relevant in nested modelling, when used in an area with an offshore blowing wind.

6.4. *Directional resolution*

The standard direction resolution, 30°, used in many wave models, may seem too coarse at first. Therefore, it is of interest to check the eventual improvements arising from a better directional resolution. These can be expected in areas of strong generation, in swell propagation and around sharp coastal features.

TABLE 1

Intercomparison statistics with buoy wave height measurements, obtained with the WAM model with 15 degree angular resolution. In brackets are the numbers for the standard 30 degree model. The period is November 1988 (after Günther *et al.* 1992)

Parameter	Alaska	Hawaii	U.S. East Coast
Number of data	356	356	367
Mean H_s buoy (m)	4.10	2.57	2.18
Bias (m)	–0.36 (–0.49)	–0.32 (–0.40)	–0.30 (–0.35)
STD (m)	0.79 (0.87)	0.47 (0.45)	0.45 (0.44)
Scatter (%)	19 (21)	18 (18)	21 (20)

The accuracy of the discrete distribution can be checked against that of the continuous one in a theoretical case. The result is quite reassuring. For a $\cos^2$ distribution, taken as representative of generation conditions, the overall energy evaluated with a 12 direction distribution (30° resolution) is correct to within several digits. A similar conclusion holds for the wind input. However, it is clear that the conditions can be quite different in real cases, with asymmetrical, often peaked, distributions.

A thorough test has been carried out by Günther *et al.* (1992), who have run a full global test, comparing the results obtained with 30 and 15 degree resolution versus measured data. The results are summarised in Table 1. Basically the higher resolution let to an increase of 0.11 m in the mean global wave height. Changes of up to half a metre could be observed at individual grid points and times. Similar results were obtained by Bertotti and Cavaleri (1993) in the Mediterranean Sea, for the same storm shown in Fig. 7. The shift to 15 degree resolution meant an average increase of H_s of 0.16 m. The changes were mostly located in the lee of the sharp corner features.

Regional modelling means coastal, hence often shallow, waters. Refraction, a key shallow water process for many locations, is substantially affected by the

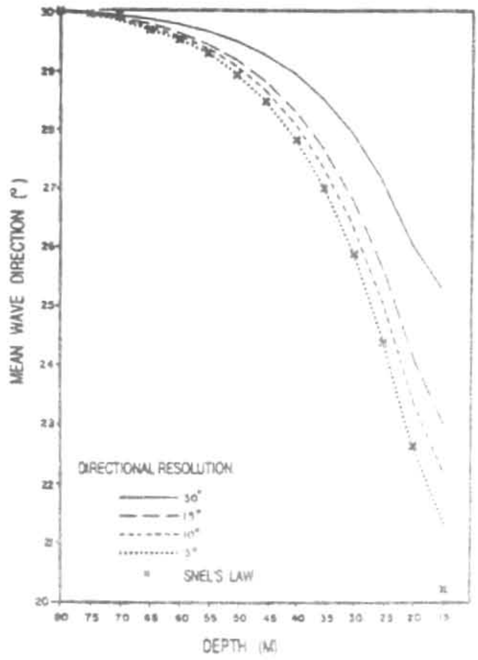


Fig. 8. Refraction on a sloping bottom as a function of directional resolution (after Hubbert and Wolf 1991)

directional resolution. The question has been analysed by Hubbert and Wolf (1991), who have compared the output of WAM, used with different directional resolutions *versus* the theoretical, Snel's solution. They used a very mild slope of 1: 10^4 with a 10 s swell approaching the straight coast at an angle of 60° with the isobaths. The results are shown in Fig. 8. While we need to go down to a 5 degree resolution for a perfect fit between theoretical and numerical results, it is clear that the 15 degree resolution produces perfectly acceptable results. With 30 degree resolution the error is not negligible, but it is clearly up to the user to decide about their relevance and therefore, on how to approach the specific problem.

7. The accuracy of the input wind fields

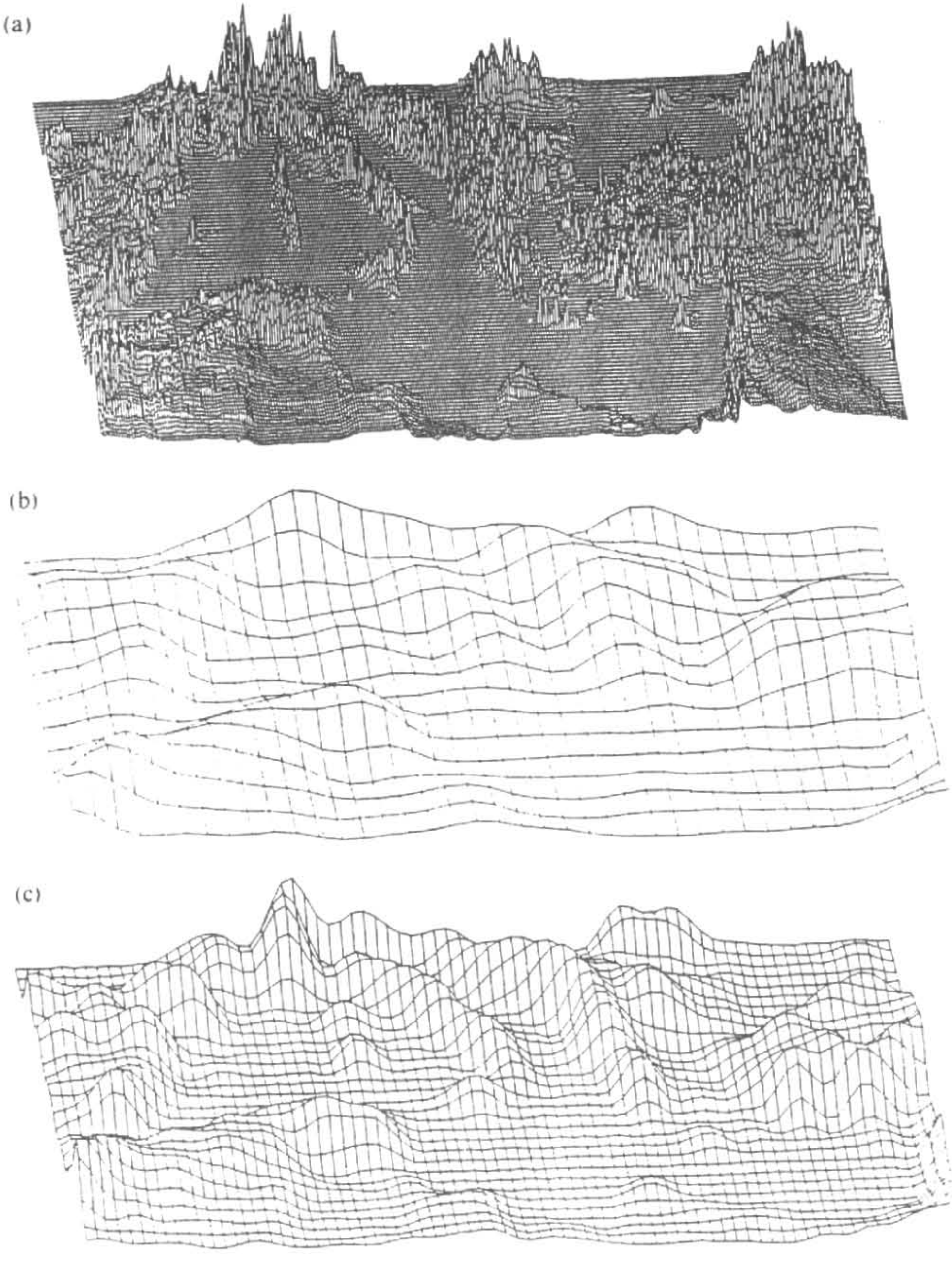
Wave height, and hence correctly the results of a numerical wave model, is extremely sensitive to the details of the input wind. In a fully developed case $H_s \equiv U^2$, so that in practical cases a mature sea depends on the wind speed U with a power between 1.5 and 2. The problem is that an accuracy of 10% in wind speed is already a very good result from the meteorological point of view, but this already implies a 15-20% error in wave height, a figure beyond the desirable level of accuracy for H_s. In more general terms the problem is that the present accuracy of an advanced wave model is higher than that of a meteorological model. This poses a practical limit to the presently attainable accuracy with the calculations of wave height in the ocean.

The commonly used winds are the product of the global model of one of the major meteorological centres. Being global, these models cannot go beyond a certain resolution, presently between 60 and 100 km. While probably sufficient for the ocean, such a resolution is not yet enough for regional modelling, being of the same order of magnitude or larger of the orographic features that control the gradients and the temporal development of the meteorological field. A good example is given in Fig. 9, where the orography of the Mediterranean basin is shown with three different resolutions, the last two being the ones embedded in the T106 and T213 (the present one) versions of the meteorological model of the ECMWF. It is clear that the overall wind field is going to be substantially affected by the lack of details and smoothing of the overall orography.

A theoretically interesting, but somewhat disheartening, point for the regional wave modeller is that there seems to be no end to the amount of details that we can discover in a storm. Fig. 10, from Shapiro *et al.* (1991), shows the structure of the ERICA 10P-4 cyclone, as derived from the intense related measurements campaign. The complexity is certainly better described by the words of Shapiro *et al.* (1991) who, on describing the details of the frontal area, state:

"These internal motions and associated physical processes induce along-front variability and instabilities: cross-front moist and dry-symmetric instability; vertical and slantwise-convective precipitation systems; air/sea interactive processes, including sea-state (ocean-wave) atmosphere interactions; mesoscale moist baroclinic instability; pre- and post-frontal banded precipitation systems; cloud microphysical and radiative processes; isentropic potential vorticity concentration and dilution processes."

It is clear that a 100 km resolution model, even with the correct physics, cannot detect and reproduce such a complexity. We need here resolutions of order 10-20 km, together with an accurate representation of the three dimensionality of the processes. The obvious



Figs. 9(a-c). (a) Orography of the Mediterranean basin at 1/12 degree resolution and its representation in (b) the T106 and (c) the T213 spectral models at ECMWF (after Cavaleri *et al.* 1991)

reply, similarly to wave modelling, is to pass to nested models, technically referred to as LAM (Limited Area Models): These are extensively used for a detailed, and hopefully accurate, description of the wind fields in a certain area. Even more than in wave modelling, and granted the correctness of the input from the large scale, in meteorology a higher resolution means a better accuracy, particularly when strong gradients are present in the field. A suitable example is offered by Dell'Osso (1990), who has hindcast the evolution of hurricane Hugo with three different resolutions of the ECMWF meteorological model. Starting from the same initial and boundary conditions. Fig. 11 shows the different deepening of the cyclonic low, the minimum pressure value lowering from 994 hPa to 963 and 954 hPa respectively. Correspondingly the maximum wind speed

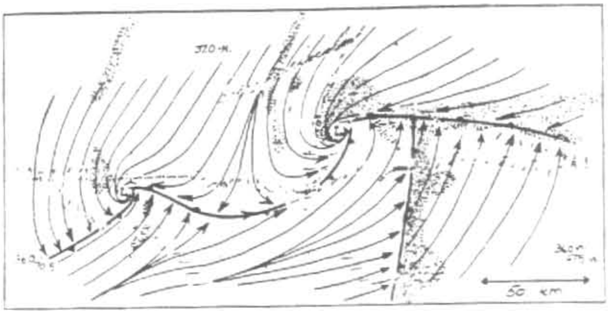
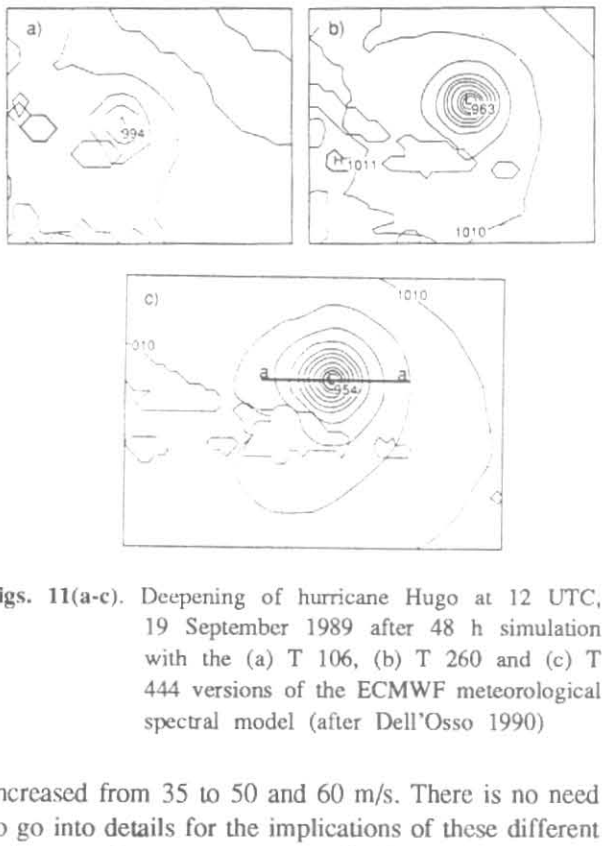


Fig. 10. Mesoscale vortices in the ERICA IOP-4, 4-5 January 1989 cyclone bent-back warm front (after Shapiro *et al*. 1991)



Figs. 11(a-c). Deepening of hurricane Hugo at 12 UTC, 19 September 1989 after 48 h simulation with the (a) T 106, (b) T 260 and (c) T 444 versions of the ECMWF meteorological spectral model (after Dell'Osso 1990)

increased from 35 to 50 and 60 m/s. There is no need to go into details for the implications of these different values on the estimated wave fields.

Even if we have at hand a very accurate wind field, for a profitable use the information needs to be fully passed to the wave model. Quite often, because of the different grid distributions, a sorting or an interpolation of the input fields is required. This has consequences.

An interesting experiment has been done by Holt (1991) who has examined the impact of an increased resolution on the results of the global wave model run at UKMO (Ross 1988). The wind was available on a geographical grid with resolution 1.5° latitude × 1.875° longitude.

Three different wave grids were used for the same model, A (3° × 3.75°), B (1.5° × 1.875°) and C (0.833° × 1.25°). The B grid is identical to the original wind grid. Both A and B are staggered with respect to C. For grids A and C at each wave grid point the wind was evaluated by bilinear interpolation from the four surrounding wind grid points. The test covered a two week period in July 1989, including a somewhat a typical vigorous depression in the North Atlantic Ocean with more than 8 m significant wave height. The validation was done against buoy data.

The best results were obtained by B, with equal and co-located wind and wave grids. As expected the coarser solution A missed the peak of the storm, with an underestimate of 3m/s for U and up to 2 m for H_s. More surprisingly, also the high-resolution hindcast C missed the peak, although by a smaller amount, because the necessary interpolation smoothed out the peaks in the wind distribution. The conclusion is that, if for any reason we want to use a high-resolution grid, we must make sure than the grid points of the input wind grid are also points of the finer grid. However, Holt (1991) points out that even in this case the non-linearity of the process, combined with the smaller area where the highest winds are assumed to be present, will cause an underestimate of C with respect to B.

8. Forecasting

While analysis fields, *i.e*, produced a posteriori on the basis of all the available data, are extensively used for hindcast studies, one of the most interesting and highly required applications is the forecast for the wind and wave conditions. Each major meteorological centre provides daily a forecast of the next few, typically ten, days. The limit is given by the lack of reliability of the present model results beyond such length of time. These wind fields are nowadays regularly used for correspondingly long wave forecast. A typical resolution is between 0.5 and 1.0 degree, with higher resolutions used for smaller basins (*e.g*., the Mediterranean model of ECMWF is run with 0.25 degree resolution). However, recalling the strong dependence of wave height on wind speed, it is clear that, increasing the advance time of the forecast, the wave model results deteriorate more rapidly than the metereological one. The conditions are quite different in the ocean and in regional modelling.

With the exception of some particularly critical cases, typically a meteorological model is wrong in misplacing, in space and time, a certain event. In the oceans the corresponding wave system will be similarly misplaced, but the same pattern can probably be recognised in the overall map. The result is a low bias and a more or less large rms error. Typical figures for the oceans at three day forecast are 0.1 m and 0.5 m respectively.

The situation is completely different in regional modelling, where the limited fetches, the influence of the coast, the more limited dimensions with respect to those characterising the wind fields, all contribute to make the accuracy of the wave forecast critical with respect to the possible meteorological error. The result is a lower score for wave forecast in regional seas. As an example, in the case of ECMWF quoted above, while the ocean wave forecast extends for the full ten days, the Mediterranean one is limited to five days. The potentially available second half of the forecast is not deemed reliable enough to deserve its calculation and distribution. Error figures are larger than for the ocean, but strongly varying with the dimensions and orography of the specific basin.

9. General comments and outlook

On the whole the situation for wave modelling and its applications looks pretty good. Drastic advances have been made during the last decades, both in meteorological and wave modelling. Furthermore, there is no sign that the progress is slowing down, fuelled by the new theoretical advances and the ever increasing computer power. At present the accuracy is sufficient for most practical purposes, with some decrease of the overall quality in regional areas. Here, if high accuracy is a mandatory condition, the solution is linked to local higher resolution models.

While there is still room for some improvement in wave modelling itself, any further substantial advance is strictly linked to those of the meteorological models that provide the input wind fields. Medium term plans suggest this is possible, particularly for analysis fields, through an increased resolution and the assimilation of the wealth of data coming from satellites.

At present there is a focus of activity on coastal and shallow water areas. This is connected to the strong economical, political and social interests. WISE (Waves In Shallow Environment), a follow-up of the former WAM group, joins in a yearly meeting all the scientists active in the subject, with the aim of developing third generation shallow water wave models, pushing them till the shore. Two models are presently freely available: WAM, with the introduction of further shallow water physics and an increased numerical efficiency, and SWAN (Ris 1997), a complete recent product of the Deft University of Technology. Substantial progress in this area is expected for the near future.

We want to end with a look at a larger, more general perspective. It has become more and more evident in recent years that the ocean and the atmosphere interact heavily not only on the long, but also on the short time scale. The drag of the wind on the sea surface depends on the state of development of the sea. The wind profile depends on air and sea temperature. The number of salt particles ejected into the atmosphere depends on the intensity of white-capping, hence on the sea state and the wind speed. All this is leading to a full interaction between oceanographers and meteorologists. The view in the future is that of a single model describing the circulation of the oceans and the events of the atmosphere, through the interface of wind waves. It is a long shot from regional modelling, but nature works at all the scales, with mutual interactions. On the other hand to look at nature as a whole is probably the best way to appreciate, and hence to understand, its beauty and its physics at all the scales.

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