# Wave modelling: The present and the future

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**Abstract**. We discuss the present situation of wave modelling, focusing in particular on the spectral approach. We point out the limits intrinsic in the use of the wave spectrum and explore the ground for possible alternatives. We begin with the very long shot of complete determinism of the sea surface. While capable in principle of taking all the nonlinear processes into account, it turns out that also this approach can only provide a statistical, albeit correct, description of the surface in the sense that only realisations of the intrinsically random process can be obtained. In a more realistic, short term view the determinism can be combined with the present spectral approach by adding random phases to the available model spectra and integrating in time the consequent realisations of the sea surface. At the same time we can expect improvements in the kinetic equations, in so doing providing part of the results unavailable from the pure spectral approach.

Looking for alternatives, we consider the wave group or wavelets as suitable candidates. A group displays many of the characteristics required for theoretical and practical developments. A determinist model describing the sea as a combination of wave groups is a realistic possibility for the relatively near future.

## Why this discussion

The remarkable progresses achieved with wave modelling during the past 60 years stand on the basic idea of spectral approach. The suggestion, derived from other sciences, that the sea surface can be conceived as the superposition of a large number of sinusoids was extremely fruitful. Simple as it is, this approach provides a physical interpretation of what we see on the surface, offering at the same time a mathematical tool suitable for further theoretical developments. So, starting from this background, we had the theories by Phillips and Miles, who aimed at explaining the growth due to wind. Later refinements were based essentially on the same concept.

The results of this approach were very successful, somehow leading people to forget that a spectral description of the sea is only one of a cluster of possibilities, each one with its own advantages and disadvantages.

The aim of this discussion is to slow down, at least for a moment, the race at producing marginally better results and try to take a fresh look at the problem of wave modelling. We want to analyse the limitations intrinsic in the spectral approach and discuss the merits of a statistical versus a deterministic approach. This will help clarifying the respective advantages and disadvantages, opening a way to new ideas and approaches. This will not happen at once. Quoting a sentence by Klaus Hasselmann, “we cannot pay people to get ideas”. However, a critical view of where we are is the first step to take before moving ahead.

## Wave modelling

The progress and the accomplishment achieved during the last ten years are outstanding. Nowadays we are able to estimate and forecast wave conditions, often with great accuracy, throughout the globe and, where required, even with a detailed description of the event. Hindcasts of extended periods of the recent past provide reliable design conditions to engineers for locations previously never considered. Climate information is derived from these long term calculations, even providing useful information for the correction and improvement of meteorological models.

We can be proud of this. After all, wave modelling is one of the few branches of science providing useful and accurate results for immediate practical application. However, we should never forget our role as scientists, and we should always try to give an objective judgement of what we have achieved and of the present state of the art. In recent years there has been in the wave modelling community a growing feeling that not everything is going smoothly. Our improvements have turned out more and more difficult, and we seem to edge more and more slowly towards the ideal target. In a way this should not be surprising. Progress is often a sort of run between Achilles and the turtle, covering at each time step a given fraction of the missing path. However, this is not the way things seem to work. Our results are good if we limit our considerations to the integral parameters (significant wave height, peak and mean periods, mean wave direction), but our capability of reproducing the details of the situation, like the one- or two-dimensional spectrum, is rather crude. Also we frequently miss the peaks of the wave conditions in storms. In addition, the scatter of the model versus measured data does not show any substantial decrease in time.

A strong reason of concern are the different results from different models. Although run under the same conditions (grid and spectral resolutions) and using the same input wind fields, the models often show an apparently erratic behaviour. Moreover, the differences among different models are comparable to the ones with respect to the measurements. There are plenty of examples. Just to quote a few ones. The "Halloween storm", in October 1991, and the "storm of the century", in March 1993, were carefully analysed and the wind fields evaluated using manual kinematics reanalysis. Four different wave models were used, ranging from first to third generation, all based on the spectral approach. There was no obviously better performance of a specific model. A similar extensive hindcast has been performed in the Western Mediterranean Sea, using second and third generation wave models, driven by high resolution winds. The results were compared with satellite and buoy data. Although sensitive to the quality of the wind input, the models were not always consistent in their performance. Also, no model outperformed the other ones, and no model showed the capability of targeting the results. A stormy period in lake Michigan, where a large amount of wind and wave data were available, was hindcast using four different wave models, representing a wide range of sophistication in their treatment of wave growth dynamics. The available data and the careful reconstruction ensured the correctness of the driving wind fields. As expected, all the models reproduced the measured trends, but still with an error margin similar to the differences among the models. Other examples could easily follow.

The general perception we derive from comparing model and measured data is that somehow the model data keep wandering around the measurements, without a clear step towards the final target. Truly enough, limited progress is visible here and there, but if we look at the time history of the performance, we see they are getting smaller and smaller.

In their discussion of the problem Liu, Swab and Jensen quote the following comments from the "Summary and outlook" of the WAM book:

> 'Despite the progress, we are not able to make wave predictions that always fall within the error bands of the observations. One may wonder if it will be possible further to ameliorate modelling of the sea state by introducing "better" physics, better numerics or higher resolution. In view of the progress that has been made going from second to third generation models, one should not be too optimistic about the effect of further refinements …'

Liu and colleagues go further and are brave enough to question the spectral approach. They claim that the main reason why we fail to reproduce the details of a storm may be the spectral approach itself. The implicit question is "how far can we push the assumption of considering the sea surface as the superposition of a large/infinite number of sinusoids?"

It is instructive to go back to sea and look at its surface during a storm. We can hardly derive the idea of a sum of regular sinusoids. The accepted theory of generation by wind assumes a smooth flow over the various components singularly considered. The reality, as shown also in laboratory experiments, is completely different. We have a continuous sequence of single waves of different height and length, sharp crests, flow detachment. The real question we should ask is "how come models are so good?" There must be a reason for it.

Under the spectral assumption and working with the energy balance equation, all the nonlinear processes are taken into account by means of some extra terms related to the whole spectrum. The obvious example are the nonlinear wave-wave interactions, where energy is artificially transferred from one component to the other ones. Let us consider white-capping, a highly nonlinear process that is still waiting for a satisfactory solution. The reality is a mess that has nothing to do with the neat sinusoidal decomposition. Some ideas have been proposed, shedding some light on what is going on, but in practice in operational applications we are still left with the thirty year old empirical approach by Hasselmann, whose coefficients are the tuning knob of a wave model: so much in by wind, so much wave growth, and therefore so much has to go out. The general perception is that we have not yet grasped the full physical mechanism.

Given all this, how come the wave models provide good results? There must be a reason for it, an underlying principle, a sort of central limit theorem. However, the method must also have its limits. The physics in the model is only an approximation to the truth. For practical purposes we need a numerical discretisation in frequency, direction, time and space. However, it is correct to ask "how good is this approximation?". The reply is not easy. We can explore, more or less we know, the implications of resolution, but we do not know enough about the physics.

What is a spectral model? It is a deterministic description of statistical properties of the field. We summarise this in a few representative parameters, typically the significant wave height Hs, a period T, either mean, peak or zero-crossing, and a dominant direction. The reason for their success is that they are very representative of the situation. Of course the more parameters we use the better, which leads to the idea of a spectrum. However, for the parameters to be statistically and physically significant we require a condition of stationarity (in time) and of uniformity (in space). Hence the size of the area represented by each grid point and the integration time step of the model equations. Part of these conditions must be relaxed in areas with strong spatial gradients where we need a high resolution grid to resolve the details of the field. The validity of a statistical description still holds because we can consider this to be estimated in time. The problem arises when the process is also evolving quickly, because then the concept of a spectrum of independent components does not hold any more. True enough, any wave model will provide results also in these conditions, but the true evolution of the field is beyond the assumptions at the base of the spectral approach.

The question is not only formal, but it concerns the physics. The nonlinear processes that complement the actions on the single sinusoids have their own time scale. The obvious example is white-capping, usually assumed as locally strong, but weak in the mean. This clashes with the very short spatial and time scale of a high resolution. It follows that the model can only provide a poor representation of the physical truth. In particular, even if, under some sort of averaging principle, the model is able to follow the general trend of the data, the comparison between model and true data must be extremely scattered.

This recalls one of the characteristics of the present model results. The bias is often low, with a decreasing trend, but the scatter with respect to the measured data is still large and hardly decreasing. In a way this should not be surprising. We have two models, wind and waves, working in series, each one with its own time scale. If we look at the spectrum of a meteorological model, we find variability at all the time scales, their energy decreasing with the corresponding wavelength. This implies that the forcing action on the wind waves is not constant also in the short time scales, introducing a variability reflected into the wave field. It turns out this too contributes to the scatter we find in the intercomparisons between model and measured data.

Can we think of reducing this variability? Of course we could increase the resolution of the model. Ideally (we will soon discuss this point) we should be able to resolve all the scales till the order of magnitude of the resolution. However, in so doing, soon or later we run into the just mentioned problem of statistical representation.

I can see two fundamental questions we need to reply to if we want to step further in wave business:

> How good is our present representation of the sea?
>
> Can we derive, from our modelling principles (the spectral approach), at least formally, all the information we would like to have about a storm?

Certainly we can, and must, improve the physics of the models. Although WAM opened the way to a complete physical representation of the considered processes, there is still a lot to do. White-capping has already been mentioned. Another example is the generation in extreme wind conditions, where the physics of the process seems to change substantially.

Let us try to take a more general look at the problem. We have a general two-dimensional surface, defined in its initial conditions, evolving in time. Would we better off with a full deterministic representation of the sea? Let us forget for the time being all the practical problems. We assume infinite power. Would we be able to follow the evolution of the surface? The reply seems to be "yes". We have the Euler equation. Suppose we describe the surface with $\Delta = 1$ m resolution. If our dominant wave length is, e.g., 50 m, we can expect to reproduce the surface for about 20 wave lengths, i.e. about two minutes (for the sake of the argument the correct figures are irrelevant). Then truth and model drift away, while the smaller scales not represented with this resolution begin to affect the overall evolution. Therefore we increase the resolution, taking $\Delta = 0.1$ m, and we find that our representation is "correct" for 100 wave lengths or ten minutes. Then again smaller scales creep in and make model and truth diverge. Of course we can go further, but we rapidly find this is a never ending story. It is like the Lorenz's principle for the butterfly and the hurricane.

This concerned only the natural evolution of the sea surface. Of course things become more complicated when we introduce the air-sea interaction processes. For the time being let us assume we know the physics, not only under the spectral approach, and that we are able to model the air-flow above the single wave crests. This can only worsen the problem, shortening the time and spatial scales for which our representation is true.

So we have a basic limitation in the lack of initial conditions, independently of their resolution. It is instructive to look at the general problem of hydrodynamical modelling in the sea and the atmosphere, i.e. waves, meteorology and currents. Here below we summarise the main characteristics of the three environments and their respective models.

**wind waves**

- full determinism is not possible. We also lack computer power, physics and initial conditions, the relevant scales, the wave period and length, are small with respect to the ones of a basin or a storm,
- therefore we resort to a statistical description of the waves, summarised in $H_s$, T and θ and, at most, the spectrum,
- this turned out to be successful because it fits what perceived by the human eye. Besides the single wave can be relevant for practical purposes, hence the attention at this time scale,
- the highest variability is present at the time and spatial scale of the wave.

**atmosphere**

- fully deterministic model,
- the relevant scale of variability is large, often similar to the one of the basin; this tends to favour determinism,
- in the spectrum the energy decreases rapidly with the decreasing wave length,
- the frequency of information (data assimilation) is sufficiently large with respect to the dominant scales of variability,
- deterministic approach relevant in the low frequency range, but only statistically significant in the high frequency range.

**circulation**

- fully deterministic model,
- overall large scale structure constrained by bathymetry and forcing; this tends to favour determinism,
- general features are very stable; motions are slow with respect to motions in the atmosphere,
- with the exception of the tidal peaks, the energy decreases moving towards the high frequency range,
- three dimensional problem; relatively few data available.

Can we learn anything from this? Which are the reasons why we cannot have full determinism in waves? A basic reason is the different distribution of energy with frequency. In atmospheric and ocean circulations the bulk of energy resides in the low frequency range, where we can carry on in the long term with data assimilation and/or with orographic / bathymetric forcing. The spatial and time scales of assimilation are comparable to or smaller than the ones of the process. This is not the case in wind waves, where the distribution of energy with frequency is discontinuous with a strong peak around 0.1 Hz. Therefore data assimilation is possible at the larger scales, hence for the statistical parameters or, a more recent application, for the spectrum. Can we conceive for wind waves something similar to what is done for circulation, i.e. a data assimilation system working at the dominant time and spatial scales of the process? Certainly not for the time being, but nothing impedes such an approach to be followed in the future (100 years?) at the global scale or, in a nearer future, for a harbour or a basin.

What can we do for the time being? While carving out small improvements in the usual wave modelling, we need to think openly of new possibilities. As said at the beginning, we do not have a direct answer at hand. However, we can argue freely about some possible experiments.

A wave record carries with it the full information about energy, period, skewness, kurtosis. (for the sake of the discussion we can limit ourselves to one dimension; there would be no basic difference in two dimensions). Also neglecting the information on phases, the spectrum we derive from a record carries with it the information about the degree of nonlinearity. This appears, e.g., as energy at the higher harmonics of the peak. Therefore the actual record allows us, in addition, to determine skewness and kurtosis. In a model spectrum the situation is different. Formally it is similar, we have a spectrum and we can formulate expectations of skewness and kurtosis. However, the basic physical assumption of the spectral model is the linear superposition of the components. Therefore the complete information about skewness and kurtosis is not there. The spectral model is essentially symmetric with respect to the mean sea level.

A way out is offered by the tendency of the sea surface, starting from an assigned initial stage, to evolve towards the correct physical distribution. This suggests that, given a model spectrum, we can choose a random realisation of the surface (with a random choice of the phases) and let it evolve according to the nonlinear equations. This is a well known process, and we have several examples of them (Euler, Zakharov, Dysthe, Schrödinger), although still out of the range for operational or long term applications. When we release all the hypotheses, like the one of a narrow spectrum, that leads to simplified versions of the basic Euler equation, the "out of range" condition increases exponentially with the completion of the equation. However, as said before, let us forget for the time being any computer limitation. We have infinite power. If so, starting from one possible surface realisation of a given spectrum, we can integrate in time the Euler equation reaching after a sufficient time a realistic surface distribution that we can then summarise, if we wish, in statistical parameters and a spectrum. Of course our specific surface distribution depends on the specific initial conditions. We have two choices. If we believe that our process has reached an equilibrium stage, we can let the system evolve and pick up every now and then its surface distribution. This would provide n samples of the surface that, for n sufficiently large, we could use for a more stable statistics. Alternatively we can work with the ensemble technique. We can choose a different initial condition and let the system evolve accordingly. From n different realisations we can derive a full picture of the possible states of the surface. Neither of these will be deterministically true because we do not know the true full initial conditions, but we will have a true statistics, without the limitations implied by a model spectrum. In particular we would derive full information on the probability of freak waves, their distribution, their duration, etc. Peter Janssen has followed this approach to derive from the spectrum, at each point of the ECMWF global wave model, the local probability of freak waves. He used 500 simulations of the surface, integrated in time with a modified Zakharov equation. Then he succeeded in relating the probability of freak waves at one grid point with the local Benjamin-Feir instability index, a quantity defined as the ratio of the mean square slope to the normalised width of the frequency spectrum and to be derived directly from the spectrum.

The ensemble technique is widely used in meteorology, either to test the reliability of the operational deterministic forecast or to derive statistical predictions of the meteorological situation months ahead. Each simulation is obtained perturbing the official analysis and letting the system evolve. The perturbations are not random, but, to increase the sensitivity, they are done along specific multi-dimensional directions derived from the eigen-vector analysis of the system. It is natural to wonder if a similar more aimed choice could be done for the wave simulation. Rather than acting only on the phases, we could act on the spectrum, both as amplitude and directions. Besides, similarly to what is done in meteorology, the perturbations could be done not at random, but acting, e.g., on specific groups of components, chosen according to the situation. In meteorology the range covered by the results of the n simulations is a good indicator of the reliability of the operational forecast. In particular there can be cases when there is more than one possible output of the forecast, the actual final solution depending on minor details of the field. Can we expect a similar situation for wind waves? It depends on the scale we argue about. On the larger time and spatial scales the thing seems less likely because of the smaller scale of the basic element of study, the wave, and of the conditions implied by the forcing wind field. Definitely it can be in the shorter scales, like the formation of freak waves.

For every deterministic equation we can derive the corresponding kinetic equation, i.e. a deterministic equation for the spectrum. Either in their full form or a reduced one, these equations have been widely used , the classical example being the $4^{th}$ order nonlinear interactions derived by Hasselmann from the Zakharov equation and extensively used in the operational wave models. However, the still open question is if, and, if so, how much and under which conditions, the numerical evolution of a spectrum evaluated with the kinetic equation corresponds to the spectrum obtained with the full integration of the equation starting from the actual surface distribution. An obvious difference is the same one previously mentioned between measured and model spectra. The former ones include all the nonlinearities of the system, while the latter ones are by definition linear superpositions of sinusoids, hence symmetric with respect to the mean sea level. However, as Peter Janssen succeeded in relating kurtosis with some characteristics of the model spectrum, there is the possibility that other characteristics of the real sea can be derived from the model results.

Till now we have been considering only the natural evolution of a surface, neglecting any effect of the generation and dissipation processes. Consider white-capping. For practical applications the approach commonly used is still the one proposed thirty years ago, then only slightly modified, by Hasselmann. The process is very sensitive to the wave steepness. Using records taken at different locations, Banner, Babanin and Young found a direct relationship between the significant wave steepness $\gamma$ and the breaking probability. This was explained as a consequence of the hydrodynamical instability that appears at the centre of a group when $\gamma$ is above a threshold value. Banner and colleagues considered only the breaking probability, and did not provide any expression for the energy lost during the process. However, this part of information is partly available in the literature, at least from laboratory experiments. Following the same line of thinking as the evolution of the sea surface, we could analyse the instability of the individual crests at any instant of a possible realisation, allowing, where required, white-capping to appear, and modifying accordingly the surface profile. We do not have yet the full theoretical capabilities, and we still lack a full physical perception of what is going on. For instance, Banner, Babanin and Young claim that the surface shear and the wind have a very limited influence on the white-capping. However, the physical evidence at sea is that breaking eventually disappears as soon as the wind decreases. In stormy conditions this happens within the time scale of a few dozen seconds, hence a few wave periods. Here we do not want to argue specifically about the physics of white-capping. Our point is to show where new knowledge is required, and how it could then be possible to evaluate the energy loss by means of the deterministic simulation of the sea surface.

A similar argument applies to the generation by wind. Our present conceptual view corresponds to a smooth flow over the regular sinusoids of each component. However, there is evidence that the process is much more complicated, with the fundamental presence of flow detachment over the most sharp crests. Whoever has been at sea during a storm and has looked critically at what is going on at the surface, can only wonder about how come that the linear superposition of idealised linear flows over regular waves can lead to acceptable results. How can we get a better view? The solution lies in modelling exactly what is going on, i.e. the viscous air flow over an irregular sea surface that is evolving in time according to the equations previously discussed. This is quite a task, but the results would provide the full reply to the interaction of wind with waves. Deriving from the simulation the exchange of energy between the atmosphere and the ocean, we would then be able to fully validate the Miles/Janssen approach.

As a matter of fact the situation is not so simple. There is a plethora of associated effects to consider, like the foam detached from the breaking crests and affecting the air flow. In stormy conditions also the sea surface is not well defined. The upper layer is full of air bubbles, and this affects its reaction to the forcing wind. In general, in a severe storm the whole interface between water and air is poorly defined, which complicates tremendously the fluid dynamics (air and water) near the sea surface.

Similarly to what was discussed above for the evolution and statistics of a surface, the single realisation we can obtain from a spectrum, although evolving in time under the action of wind, is indicative of what is going on in the real world, but not statistically significant. We need to proceed with the ensemble technique, repeating the simulation starting from different realisations, to derive reliable statistics representing on the average what is going on at the surface. This would also provide full information on the probability and statistics of the overall exchanges and a complete description of the evolution of a wave field under the action of wind.

Till now we have been talking about the open sea, deep water waves. However, large part, if not most, of the work on waves is done close to the coast. Here a full range of new processes appears, all intensively dealt with in the literature, at least within the spectral approach. The deterministic approach has some history here, see the Boussinesq and mild-slope equations. For the time being the applications are necessarily very limited in space, but again for the sake of discussion we can forget this limitation. Like in deep water, here too the spectral models, the obvious example is Swan, have achieved remarkable results and can, at least in principle, deal with most of the processes. However, it is especially in this transition area, where the gradients are larger and nonlinear processes often dominate, that the spectral approach becomes more questionable. This is one of the reasons why the shallow water deterministic equations have been the first ones to be more widely used. If we move to determinism, the typical application is to derive from a spectral model the wave conditions offshore or, e.g., at the entrance of a harbour, and to proceed then with the deterministic equation. The question is on the significance of the single realisation and of the associated results. Of course the reply depends on the process we are considering. For a weak nonlinear process the statistics in time derived from the single run may be sufficient. However, this may not be the case for strongly nonlinear events, like the sensitivity of a structure to the impact of the single wave. The sediment transport is extremely sensitive to the bottom orbital velocity, more in general to the kinematics and dynamics of the single wave. Therefore the results we obtain may vary rather conspicuously from one simulation to the next, and we need a large set of them to derive a full picture of the possible situations and of the average results.

The full determinism we had discussed for deep, open sea waters as an ideal, futuristic solution finds here a more fertile ground. The distances are limited, and, if not from an offshore deterministic estimate, we can always start from measured offshore conditions. Today usually measured data are available at only one point, which means that in practice, perhaps with the exception of a harbour entrance, we have only the offshore spectrum, and we would be back at the case of offshore model spectra that we just discussed. With a bit of optimism it is not difficult to envisage in a not too far future a full remote measuring system for a limited area. The real problem we face with determinism in coastal shallow water areas is the physics of the processes involved. Breaking, coastal currents, wave-current interactions, fluidisation and transport of sediments, nonlinearity. Most of these processes are often dealt with in an empirical way, particularly under the spectral approach. However, this limitation is not essential, and we could attack the problem accepting some limitations, even with the present ones, because the time and spatial scales of the processes involved are in general quite limited, the memory of the system is more limited than in deep water, and the implications of an approximate treatment of the processes have no or limited influence on the future of the simulation (one exception are the coastal currents).

Whatever we said till now, discussing the limitations of the spectral approach and the possible solution via the determinism, is something for the future. The question is ‘what can we do for the time being?’. Is there any intermediate solution, alternative to the present spectral approach? The problem is again connected to the scale of the process we consider. A storm may easily involve areas of the order of 1000 km or more, but the key element we are dealing with, the one where the energy is concentrated, has a scale of the order of 10 seconds and 100 metres. Is there any intermediate, significant scale we can deal with, something with a physical significance, that we perceive in the sea? The only reply I can think of is “groups”. Groups, or wave packets as they are sometime called, have attracted the attention of sailors since the early times. They are a definite characteristics of the sea, the interval between two consecutive sets of high waves; the separation between sequential area of more intensive breaking; the idealised sections of a wavy sea where energy is kept and played within. They are mathematically defined, with a scale an order of magnitude larger, in space and time, with respect to the single wave. Their constant presence on the surface, whichever the conditions, although with different characteristics according to the situation, suggests they are not simply the interference of two close-by frequencies, but they represent something more fundamental in the air-sea interaction process and in the development of a wave field.

How to deal with them? If they are going to be the cornerstone of a new approach, we need to develop new theories for them, as we have done in the past for the single sinusoidal wave components. Groups grow in time as a storm develops, so generation by wind is quite feasible. Groups dissipate energy, with breaking mainly concentrated in their highest waves. Energy is redistributed within the group, with nonlinearity playing a fundamental role, possibly also in the exchange of energy between different groups. What about dimensions? The sea surface can be described (this has been done time ago) as the superposition of an infinite number of groups, somehow like the sinusoids we are used to. In a way this would bring us back to the spectral approach, although on a different scale. This would not be highly satisfactorily. Also, we need to give better consideration to the directional distribution. Probably it would be more realistic to consider wave packets of finite dimensions, not only in the direction of propagation, but also in the transversal one, parallel to the crests. The sea surface would then be described as the superposition, or better the addition, of wave groups, each one with its own identity and characteristics. If we succeed in describing in sufficient details the dynamics of a group and its interaction with the atmosphere, we would then be able in principle to describe the evolution of the sea.

Which kind of model could we expect? Most likely, some sort of group spectra would be possible, although questionable given the size of a group. Then we are back to determinism. The size of a group makes this approach less dramatic than for the single waves. Given that we are talking about what to do in the near future, we can neglect the futuristic view of data assimilation at the global scale to keep the modelled system along the right track. We can still think of a deterministic model providing a possible realisation, statistically significant, of the time evolution of the surface. In practice it would be a model similar to the present ones, where the variable is not given by the wave spectrum, but by the wave group.

This approach will require substantial theoretical work before we are able to formulate in details the corresponding model. It would not be surprising if some of us had already been working on this. The point we started from, the perceived supposed limits of the spectral approach, are by themselves a strong stimulus to proceed further, and, for their characteristics, wave groups sound like a possible promising solution.

## Comments

The slowing progress shown by the wave spectral models in recent years have caused some concern about the practical possibility of proceeding much further with this approach. Much doubt arises from the evidence that, even if working with accurate, carefully evaluated wind fields, the wave model results show a scatter not justified by the known uncertainties in the input information. Room for improvements still exists, in the physics of some of the processes, in the numerics, in the quality of the operational input wind fields. However, there is a growing feeling that we cannot go much further in the present direction.

Looking for alternatives, the long term solution can be a substantially more deterministic approach. We have deliberately chosen the long shot of a global determinism, where the sea surface is described wave by wave. Clearly not possible for the time being, we envisage that this could become a reality within 20-30 years. However, even this approach would only be able to discuss the ocean only in statistical terms. The Lorenz's principle, applied to waves, ensures that, whichever the initial resolution we use to describe the wave field, its numerical evolution will rapidly diverge from the one observed in the sea. Keeping the system on the right track would require the continuous availability of a detailed full information on the globe, a fact not conceivable for a long time.

It turns out therefore that also a deterministic description of the evolution of the sea surface would only be able to provide a statistical description of it. Provided we act with a sufficient resolution, this would be rather accurate, because all the nonlinear processes, like whitecapping and freak waves, would be properly considered. Concerning the long term evolution and the correspondence between reality and simulation, at the large scale, the wave field is controlled by the forcing wind field. Therefore, for a given evolution of the atmosphere, the general pattern of the wave field is well established. There will always be some parametrisation for the very high frequencies beyond the resolution of the model.

This can be for the future. For the time being we can expect further theoretical advancements with the kinetic equations, succeeding in representing some of the processes or phenomena not directly present in the spectral approach. So, to a certain extent both the deterministic and the kinetic equation approaches lead to a statistical description of the surface. The latter will be more successful in the short, but not so short, term, complementing the results of the traditional spectral approach. In the long term the coming into general use of the determinism is a serious possibility.

An intermediate alternative is to combine the spectral and deterministic approaches into a complementary machine. Given the spectrum at certain time and location, we can choose a possible realisation of the corresponding sea surface and let it evolve in time according to the deterministic equation. This can be done either with a single realisation, or better, but with a much heavier computer time, with n different realisations. This would provide a robust statistics of the sea surface, inclusive of all the nonlinear processes.

In the meantime an intermediate solution can be given by the theory of groups, this being the intermediate scale where determinism can be applied to the groups themselves, while retaining a statistical or subscale description of what they contain. This will first require suitable theoretical developments, possibly already on the way. As for the computer power, the approach is already feasible for small areas, with the possibility of an extension to larger or global scales in a not far future.

Are there other alternatives? It is certainly possible, even likely. For instance, the option is presently being studied to compute the phase spectrum in SWAN such that the model will be predominantly linear in oceanic waters and predominantly nonlinear in coastal waters, with the corresponding possibility to simulate realisations of the surface where and when required. When the progress depends on new ideas, it is hard to anticipate them. This is obvious for the ideas themselves, otherwise they would not be new. It is also hard to guess when a new one will pop up. Using an example from our field of application, the process is highly nonlinear and discontinuous. We can have a perception of when the conditions are ripe for something new, but certainly we do not have a theory for saying when a new theory/idea will appear. In a way this is what makes our work even more interesting.