WAVE MODELING
Where to Go in the Future

BY LUIGI CAVALERI

Contemporary spectral wave modeling techniques seem to have intrinsic limitations that might be overcome with gradual introduction of new methods toward an eventual deterministic depiction of the sea surface.

The last 60 years have seen tremendous advances in wave modeling. We have progressively moved from the stage when we could barely evaluate the approximate wave conditions at one location to our present capability of time-extended forecast on the whole globe. Nowadays we are able to provide forecasts of when and where strong events will hit or, alternatively, the design conditions for a platform in an area where no measured data are available. A good review of the capabilities of wave modeling is given by Komen et al. (1994) and by the monthly statistics of the results of the operational centers. As an example, for the European Centre for Medium-Range Weather Forecasts (ECMWF, Reading, United Kingdom), a 0.96 best-fit slope and −0.07-m bias with respect to the Envisat data on a global scale are rather reassuring results.

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However, if we look at the subject from a more general point of view, we realize we have reasons for concern. The rate of progress seems to slow down. Although the model results are in general close to the measured data, these differences do not decrease as fast as we would expect from the effort presently put into the matter. Of more concern is that similarly sophisticated wave models using identical input conditions show differences similar to those with respect to the measurements (see, e.g., Cardone et al. 1996; Liu' et al. 2002). Our optimism is significantly reduced if, instead of looking only at the integrated parameters, that is, significant wave height H_s, mean period T_m, and mean direction θ_m, we consider the results for the spectra. The comparison between model and measured spectra is often unsatisfactory, not only in the details, but sometimes also in the general structure.

All this is not new. Roughly a decade ago, analyzing the situation of wave modeling, Komen et al. (1994) concluded that

> Despite the progress, we are not yet able to make predictions that always fall within the error bounds of the observations. One may wonder if it will be possible to ameliorate modelling of the sea state by introducing "better" physics, better numerics or higher resolutions. 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' et al. (2002) go further and question the very spectral approach at the base of the present wave models. They point out that, although obtained in ideal conditions (well-defined geometry and carefully evaluated wind fields), the model results do not seem to converge toward the measurements. Rather, they show a somewhat erratic behavior, not necessarily less pronounced when using more sophisticated models.

So the question is why the spectral models do not perform according to the improved quality of the input wind fields and to the effort (theory, experiments, data, and computer resources) devoted to the problem. The hypothesis by Liu' et al. (2002) of an intrinsic limit in the spectral approach deserves a more careful analysis. This is the subject of the next section.

A DISCUSSION ON THE SPECTRAL APPROACH. All the present spectral models rely on one basic idea: the sea surface can be represented as the superposition of sinusoidal waves, each one characterized by its own height (i.e., energy), period (hence length and frequency), and direction. Indeed, in some conditions, like a long uniform swell on an otherwise calm surface, the sea itself suggests this idea. In any case the concept is very appealing. We have beautiful, mathematically simple functions that we know how to handle in a number of ways. It is no wonder that, shortly after the idea was proposed (Pierson 1955), Phillips (1957) and Miles (1957) devised two complementary neat mechanisms for the transfer of energy from the wind to the single sinusoids. Anyone who has had the chance to watch a stormy sea realizes that this concept may sound a bit far-fetched. However, at least from a qualitative point of view, rather surprisingly, the approach gave good results, and with due modifications [Janssen (2004) gives a complete review of the present state of the art] it is still at the base of the present wave models.

Somehow these positive results helped to crystallize the idea that indeed the sea is the sum of sinusoids and that this concept represents a physically sound approach to the problem. Of course this is not true.

Doubts are not new. Mollo-Christensen (1987) dealt with the subject, but even in 1957 Longuet-Higgins was stating, as opening words of one of his seminal papers (Longuet-Higgins 1957), that

> On observing waves in the open ocean, one is struck by their irregularity: no single wave retains its identity for long, the distance between neighboring crests varies with time and place, and frequently it is difficult to assign to the waves any predominant direction or orientation. Thus although the sea surface may, for some purposes, be treated as a uniform train of waves advancing in one direction only, such a representation is usually far from reality.

Their concern is understandable looking at pictures like that in Fig. 1.

To realize this opposite view it is enough to look at a stormy sea with a critical eye. Breaking crests, foam covering the surface, interacting crossing waves, nonuniform distribution of the shorter waves on the longer ones—everything points more to an apparently chaotic behavior than to the regular superposition of sinusoids. So the opposite question comes to our mind: Given the situation, how come models are so good? To understand the reasons for this, we need to recall what a spectral model is.

A spectral model is basically a deterministic description of statistical properties of the sea surface. We do not look for a deterministic description of the sea surface, but only for some of its general statistical properties. When comparing the model results with the corresponding measured data, we must allow for some confidence limits. If we focus our attention on the integral parameters (H_s, T_m, and θ_m, these limits will be rather small, and the comparison, provided everything is correct, will be satisfactory. If we consider the spectrum, the confidence limits become much wider, and our comparison will provide more

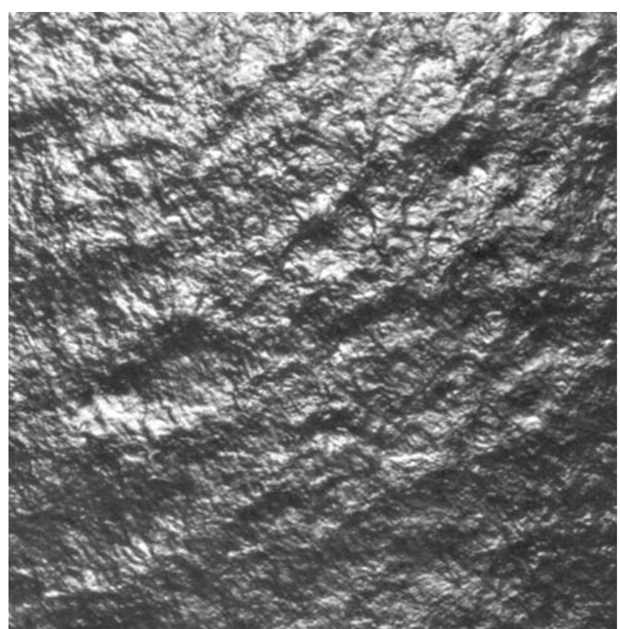

Fig. 1. Aerial view of a wavy sea surface (courtesy of Leo Holthuijsen).

erratic results. However, even this does not justify the differences we find between modeled and measured data. Clearly some fundamental problem stands in our way.

So, how can we improve? We begin our discussion following the spectral approach. Although a lot of theoretical, experimental, and numerical work has been done, which explains the progress of the last decades, there is still a long way to go in terms of improving the physical description implemented in the models.

It is not our aim to enter here into a detailed discussion of the present understanding of the different processes (such a paper is presently simmering in the wave modeling community). However, we want to point out what we believe are some obvious limitations of the present spectral models.

We have repeatedly mentioned the feeling one derives from looking at a stormy sea. It is hard to believe that the superposition of a regular flow over the single sinusoidal components is reflected into the messy interface of a stormy sea. Banner and Melville (1976) pointed out a long time ago the role of the flow detachment from the breaking crests on the intermittency of the energy and momentum transfer from the atmosphere to the sea. Breaking waves, or white-capping as they are commonly referred to in deep water, have not yet been fully understood. While some progress has been made recently (see Banner et al. 2000), we are basically linked to the empirical approach suggested by Hasselmann (1974) more than 30 years ago. In effect, the parameterized white-capping formulation is the tuning knob by which we make our models more or less fit the recorded data.

On top of this we have many different interactions to consider. Nature is fundamentally nonlinear. The foam detaching from a breaking crest affects the air flow, hence the related energy transfer. It is still not clear at all which components to consider when distributing in the spectrum the energy lost with a white-cap. The development of the sea affects the atmospheric boundary layer, which in turns affects the energy transfer (formally this is taken into account; see Janssen 1991, 2004). The different wave components exchange energy among themselves (see Hasselmann 1962—to be discussed later), but their correct computation is out of the range of the present computers.

As any model is necessarily discrete in space, frequency, and direction, we have numerical problems associated with the respective resolutions. A frequently encountered problem is the advection of swell over long distances.

For the point under discussion the relevant question is the following: Are the present inaccuracies of the model results a consequence of the lack of knowledge of the physics of the processes, or are they inherently connected to the spectral approach? Our feeling, as derived from the experience at sea, the present structure of the models, and the history of their performance, is that the truth lies in the middle. In other words, there is still room for improvement, which becomes more and more difficult as we model more and more complicated physics, but, as pointed out by Liu' et al. (2002), there are intrinsic limits in the spectral description of the sea surface.

There is at least another aspect of the problem that is worthwhile to consider. The spectrum provides a statistical description of the sea surface, but there are conditions for this representativeness. The basic assumption is that the surface is locally sufficiently stationary and uniform for the spectrum to have a physical meaning. Problems arise in the case of strong gradients. If these are present only in space, the spectrum no longer represents the "average" conditions in the area, and the sea is no longer ergodic, but we can still talk about a spectrum in time at each single location. If the sea conditions are also changing rapidly in time, the spectrum loses its meaning, and we are likely to find incorrect results from our spectral model.

Still conscious of our present lack of knowledge of many physical aspects of the problem, we wonder which are the possible alternative approaches. In doing this we make a long step forward and consider the opposite solution, that is, a full deterministic description of the sea surface.

THE DETERMINISTIC DESCRIPTION OF THE SEA SURFACE. We consider the general problem of the evolution of the sea surface starting from a given initial condition. For the time being we neglect any consideration of computer power.

Suppose we discretize the surface at $\Delta = 1$ m intervals. We have the Euler equation (see Witham 1974) and, by integrating it, we can follow its evolution. If our dominant wave length is, for example, 50 m, we can expect to reproduce the evolution of the sea surface for about 20 wave lengths, or about 2 min (for the sake of the argument, the correct figures are irrelevant). Then the truth and the model begin to drift away, while the smaller waves not represented with this resolution begin to affect the results. Therefore we increase the resolution, taking $\Delta = 0.1$ m, and we find that our model is "correct" for 100 wave lengths or 10 min. Then still smaller waves creep in and make model and truth diverge. Of course we can go further, but we rapidly find this to be a never-ending story. It recalls the analogous problem in meteorology, beautifully exemplified by Lorenz (1963) with the progression from the butterfly to the hurricane.

This concerns only the evolution of the sea surface. Of course we can also consider the more complete problem of modeling the atmosphere and its interaction with the ocean. Everything becomes extremely complicated, but we assume for the time being that we are able to model the interactions. For the point we are discussing this can only worsen the problem, shortening the time and spatial scales for which our representation is still following the truth.

So we have a basic limitation in the definition of the initial conditions, independent of their resolutions. Why do wave models suffer such a limitation with respect to other fluodynamical models of the Earth's surface layer, that is, meteorological and ocean circulation models? It is instructive to analyze the basic characteristics and the scales of the three different types of models.

Atmosphere.

- The relevant scale of variability is large (in most of the cases).
- In the spectrum, the energy decreases rapidly with decreasing spatial scale.
- The relevant time and spatial scales are consistent with the ones with which measured data are available—hence data assimilation is very effective.
- The approach is deterministic for the scales of practical interest—a statistical, often parameterized, description is used for the smaller unresolved scales.

Ocean circulation.

- The relevant scale of variability is large, often dictated by the dimensions of the considered basin.
- With the exception of tides, in the spectrum the energy decreases with the considered spatial and time scales.
- The distribution of measured data is consistent with the relevant time and spatial scales of the process.
- The approach is deterministic, with a parameterization of the processes at the smaller scales.

Wind waves.

- The relevant scale of variability, the single wave, is small compared to the dimensions of the basin and to those of the model resolution.
- If we neglect tides, in the open ocean there is hardly any energy except in the wave range.
- Therefore we resort to a statistical description of the sea surface, summarized in the spectrum, and, more so, in the integrated parameters H_s, T_m, and θ_m.
- The available data, mostly as integrated parameters or spectra, are at scales much larger than the waves themselves, consistent with the statistical description of the surface.

The basic difference between the wave versus the other two classes of models is the scale, time and space, at which the relevant process is happening. This clashes with the scales with which the measured data are available, large in most of the cases for all three classes. It should be mentioned that at a limited number of locations (directional buoys and multisensor arrays on some platforms) high-frequency "deterministic" data (surface elevation and cross slopes) are available. However, their number is by far too limited for any large-scale alternative approach.

There is another reason why a statistical description of the sea surface during a storm has been successful. It fits the human eye and the perception we derive looking at a wavy surface. In most of the cases we get only a general impression, a summarized information, that is, H_s. Only in a few cases, and generally for good reasons, do we focus our attention on the single waves.

To summarize the situation, we can, at least in principle, have a deterministic description of the evolution of a sea surface. Our expectation is for this to be feasible within, say, 20–30 years. However, our description will only have a statistical significance, because our realization will be different from the truth. The big advantage will be that our realization carries with it all the nonlinear properties and information we are presently unable to derive from the linear superposition of sinusoids.

Of course, we will make use of the available data for assimilation and correction of the output of our model. If integral or spectral properties are available, we will be able to assimilate them. However, we can go further and expect that in the far future (100 years?) we will be able to provide a continuous deterministic description of the sea surface that, once assimilated, will keep our model continuously on the right track.

So we have at one end our present spectral approach, and at the other end the purely deterministic one, feasible only for the future. The question is, what are the alternatives during this transition period? Therefore, we need to discuss the possible intermediate solutions that would allow us to overcome, at least partially, the limitations we perceive in our present approach.

INTERMEDIATE SOLUTIONS. An obvious step that is well on its way is to ameliorate the wave models by improving their physics and numerics. This is certainly being done and, as already mentioned, it is expected to lead to some further improvements. However, the basic limitations of a spectral approach will still be there.

Consider a wave record, the classical 30-min surface profile. We usually evaluate its spectrum and compare it with the corresponding model estimate. However, there is a fundamental difference. The wave record carries with it all the nonlinear characteristics of the field. Kurtosis, that is, higher and sharper crests versus more flat and longer troughs, is an obvious example. On the contrary, the surface profile we can derive from a model spectrum is intrinsically linear and essentially symmetric with respect to the mean sea level.

A way out is offered by the tendency of the sea surface, when starting from an assigned initial stage, to evolve toward the correct physical distribution. This suggests that we can choose a realization of the surface out of the model spectrum and let it evolve according to the nonlinear equations. This is a well-known process, and we have several examples of it: Euler (see Witham 1974) and its simplified versions by Zakharov (1968), Dysthe (1979), and Schrödinger (see Zakharov 1968). Note that the required computer time increases exponentially when we eliminate the restrictions, like the one of a narrow spectrum, that lead to the simplified versions of the Euler equation. However, as suggested before, let us ignore for the time being the problem of computer time. If we let the system evolve for a sufficiently long time, we will obtain a realistic surface distribution that we can then summarize in its (also higher order) statistical properties.

It is legitimate to ask if these properties depend on the initial realization. This can be easily explored repeating the experiment for different realizations, and eventually deriving overall statistics. This approach has been used by Janssen (2003) to derive from the spectrum, at each grid point of the ECMWF global wave model, the local probability of freak waves. He used 500 realizations of the surface, integrated in time with a modified Zakharov equation. This is beyond the present operational possibilities, but Janssen solved the practical problem 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 normalized width of the frequency spectrum, and to be derived directly from it.

This leads to a subtle question. Given a spectrum, the full nonlinear statistics of the sea surface can be deterministically derived following the procedure outlined above. It is legitimate to ask if, similarly to what was done by Janssen, some characteristics of interest can be related to known properties of the initial spectrum. This is an area that deserves attention.

Another approach is to use the kinetic equations. For every deterministic equation we can derive the corresponding kinetic equation, that is, 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 fourth-order nonlinear interactions derived by Hasselmann (1962) 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 a 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 superposition of sinusoids, and hence symmetric with respect to the mean sea level. However, as Peter Janssen succeeded in relating kurtosis to some characteristics of the model spectrum, there is again the possibility that other characteristics of the real sea can be derived from the model results.

All this concerns only the evolution of the sea surface. Can we do anything similar for the processes of generation and dissipation? Of course this implies having first solved the physical problem, but a detailed modeling would also help to understand the physics of the process.

For wave generation the solution lies in modeling exactly what is going on, that is, modeling the viscous air flow over an irregular sea surface that evolves in time according to the equations previously discussed. This is quite a task, but we do not need to think of it in operational conditions. A number of experiments could be carried out, and there is the possibility that, similarly to what Janssen (2003) has done for freak waves, we would then be able to derive a rule to relate the wind input to the spectrum we started from.

A critical step of any simulation of the evolution of the sea surface is the presence of breaking. We still do not know how to deal with the details of single events with sufficient continuity, but a solution could come from the recent improvement due to Banner et al. (2000), who found a direct relationship between the significant wave steepness γ and the breaking probability. This was explained as a consequence of the hydrodynamical instability that appears at the center of a group when γ is above a threshold value. Banner et al. considered only the breaking probability and did not provide any expression for the energy lost during the process. However, this part of the information is partly available in the literature, at least from laboratory experiments (see, e.g., Rapp and Melville 1990). Following the same line of thinking as the evolution of the sea surface, we could analyze the instability of the single crests in an evolving profile, modifying it accordingly. Our physical perception of what is going on is not yet sufficient (remember this is the least understood part of wind waves). However, the method could provide further insight into the process. Besides, for the time being, during which our computer capabilities will not be able to make them operational, these experiments could potentially provide a rule to relate the loss by white-capping to the spectrum in a way that is more sound than how it is done today.

COASTAL AREAS. Until now we have been talking about the open sea—deep water waves. However, a 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 (Mei 1983, 510–512 and 86–89, respectively). For the time being, the applications are necessarily very limited in space, but again for the sake of discussion we can ignore this limitation. Like in deep water, here too the spectral models, [the obvious example is Swan (Booij et al. 1999)], 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, for example, at the entrance of a harbor, and to carry on with the deterministic equation. The question is about the significance of the single realization 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, such as the sensitivity of a structure to the impact of the single wave. The sediment transport is extremely sensitive to the bottom orbital velocity and more generally 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 runs to derive a full picture of the possible situations and of their average results.

The full determinism we had discussed for deep, open sea waters as an ideal, futuristic solution finds more fertile ground here. The distances are limited, and, if not from an offshore deterministic estimate, we can always start from measured offshore conditions. Today measured data are typically available as detailed information (surface profile and cross slopes) at one position or as integrated parameters at many points of a large area. However, with a bit of optimism it is not difficult to envisage in a not too distant future a full remote measuring system for a limited area, after which we will be able to follow the motion of the waves toward the coast or the harbor. 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, fluidization and transport of sediments, and 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 these limitations because the time and spatial scales of the processes involved are in general quite limited. Therefore, the memory of the system is more limited than in open water, and the implications of an approximate treatment of the processes have no or limited influence on the future of our simulations (one exception is the coastal currents).

FOR THE TIME BEING. Whatever we have said until now, discussing the limitations of the spectral approach and the possible solution via the determinism, is something for the future. The question is what we can do for the time being. Is there any intermediate solution or 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 s and 100 m. 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 sometimes called, have attracted the attention of sailors since the early times. They are a definite characteristic of the sea—the interval between two consecutive sets of high waves, the separation between sequential areas of more intensive breaking, the idealized 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, whatever the conditions, although with different characteristics according to the situation, suggests that they are not simply the interference of two close-by frequencies, but that they represent something more fundamental in the air–sea interaction process and in the development of a wave field.

How should we deal with them? Should they 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 may be described 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 satisfactory. Also, we need to give more 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 detail 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. Otherwise 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 modeled system along the right track. We can still think of a deterministic model providing a possible realization, 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 detail the corresponding model. It would not be surprising if some of us had already been working on this. The points we started from, the perceived supposed limits of the spectral approach, are by themselves a strong stimulus to proceed further, and, based on their characteristics, wave groups sound like a possible promising solution.

FINAL COMMENTS. It is worthwhile to summarize the main points of the previous discussion.

The slowing progress shown by the wave spectral models in recent years has caused some concern about the practical possibility of proceeding much further with this approach. Doubts arise 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 improvement still exists in the physics of some of the processes, in the numerics, and 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 describe the ocean in statistical terms. The Lorenz 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 detailed full information on the globe, a situation 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. Provided we act with a sufficient resolution, this would be rather accurate, because all the nonlinear processes, like white-capping and freak waves, would be properly considered. Concerning the long-term evolution and the correspondence between reality and simulation, on 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 would be well established. There will always be some parameterization for the very high frequencies beyond the resolution of the model.

This can be a goal 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 very short) term, complementing the results of the traditional spectral approach. In the long term, the coming into general use of determinism is a serious possibility.

An intermediate alternative, already in limited use, is to combine the spectral and deterministic approaches into a complementary machine. Given the spectrum at a certain time and location, we can choose a possible realization of the corresponding sea surface and let it evolve in time according to the deterministic equation. This can be done either with a single realization or better, but with a much increased computer time, with n different realizations. This would provide robust statistics of the sea surface, inclusive of all the nonlinear processes. An interesting possibility is to relate, via suitable numerical experiments, some nonlinear characteristics to known properties of the initial spectrum.

We can extend this concept and include in our simulations the atmospheric layer above the sea surface (for a more physical evaluation of the wind input) and the white-capping at the surface. Though out of the range of any operational application, a number of these simulations could provide further insight into the physics of the processes, and possibly a more direct and sound link with the spectrum.

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 not far in the future.

Are there other alternatives? It is certainly possible—even likely—but, if this is the case, we are still unaware of them. Research is much needed in this field. Even more than research, however, we need ideas, and it is difficult to anticipate when they will appear. We can perceive that the time is ripe for a new step ahead, but, as with wind waves, we are not yet able to forecast its correct evolution. In a way, this is what makes our work even more interesting.

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