Wave Modeling—Missing the Peaks

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ABSTRACT

The paper analyzes the capability of the present wave models of properly reproducing the conditions during and at the peak of severe and extreme storms. After providing evidence that this is often not the case, the reasons for it are explored. First, the physics of waves considered in wave models is analyzed. Although much improved with respect to the past, the wind accuracy is still a relevant factor at the peak of the storms. Other factors such as wind variability and air density are considered. The classical theory of wave generation by J. W. Miles's mechanism, with subsequent modifications, is deemed not sufficiently representative of extreme conditions. The presently used formulations for nonlinear energy transfer are found to lead to too wide distributions in frequency and direction, hence reducing the input by wind. Notwithstanding some recent improvements, the white-capping formulation still depends on parameters fitted to the bulk of the data. Hence, it is not obvious how they will perform in extreme conditions when the physics is likely to be different.

Albeit at different levels in different models, the advection still implies the spreading of energy, hence a spatial smoothing of the peaks. The lack of proper knowledge of the ocean currents is found to substantially affect the identification of how much energy can—in some cases—be concentrated at a given time and location. The implementation of the available theories and know-how in the present wave models are often found inconsistent from model to model. It follows that in this case, it is not possible to exchange corresponding pieces of software between two models without substantially affecting the quality of the results.

After analyzing various aspects of a wave model, the paper makes some general considerations. Because wave growth is the difference between processes (input and output) involving large amounts of energy, it is very sensitive to small modifications of one or more processes. Together with the strong, but effective, tuning present in a wave model, this makes the introduction of new physics more complicated. It is suggested that for long-term improvements, operational and experimental applications need to proceed along parallel routes, with the latter looking more to the physics without the necessity of an immediately improved overall performance.

In view of the forthcoming increase of computer power, a sensitivity study is suggested to identify the most critical areas in a wave model to determine where to invest for further improvements.

The limits on the description of the physics of the processes when using the spectral approach, particularly in extreme conditions, are considered. For further insights and as a way to validate the present theories in these conditions, the use is suggested of numerical experiments simulating in great detail the physical interaction between the lower atmosphere and the single waves.

1. What to worry about

Understanding and modeling the behavior of nature, albeit at different levels, has long been one of the main tasks of humanity. Indeed, great leaps forward have been accomplished during the recent centuries. In particular, sea waves, with their direct influence on seafaring and fishing, have always been at the same time a source of wonder and observations. Humans have always tried to understand the rules behind a certain event, the aim being an improved capacity of predicting the next event.

During the last 60–70 yr, warlike and commercial interests have stimulated a flurry of studies related to wind waves. In connection with the unpredictable development of computer sciences, this has led to drastic improvements in many aspects of this field. Indeed, although I work in this area, I am still amazed knowing that it is possible to know with remarkable detail a few days in advance what the wave conditions will be at a certain time and position on the opposite side of the globe.

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The strong demand for practical results has also led to solutions where the complexity of the problem and the difficulties of getting enough data in the right conditions have required partially empirical solutions. Unavoidably, these solutions often include more parameterizations than we would like to think of, and we are frequently forced to tune some parameters of our physical–mathematical model. At least for practical purposes, tuning is not a problem in itself. However, tuning is generally completed on the bulk of the data. The more rare a special case is, the more likely it is to be poorly represented by the ''tuned'' rule, especially if in these ''different'' conditions the physics of the process does change. Indeed, in wave modeling this is the case of the extremes, that is, in the heaviest conditions, particularly of the most intense storms. Anyone who has witnessed a very severe storm at sea has good reasons to wonder about some of the basic ideas that form the background of most of, if not all, the present numerical models. If indeed the physics is different, then it should not come as a surprise that the models do not perform with the extremes (or, more generally, in very high wave conditions) as well as shown, on the average, by statistics. Of course, a low bias does not exclude positive and negative errors by the model, for whatever reason. This is why we also use correlations and scatter indices. However, a straightforward study of several scatter diagrams or time series comparisons and related statistics will quickly reveal that the models have a marked tendency to underestimate the largest wave heights, and in particular the peaks, more in heavy storm conditions.

Obviously there must be a reason for it—this word certainly summarizing many different aspects of nature and of our way of representing it. In our utopian way of thinking, it would be tempting to try to find a single culprit, in so doing solving the problem with a single stroke. Unfortunately nature does not work this way. The reality that surrounds us is made of wildly different scales, processes, events—all interacting with each other at different levels. Tackling nature is a difficult and wonderful task.

Our common simplistic approach, at least at the beginning, is to isolate one process and to produce a physical model and a theoretical formulation of how it evolves. Having done this for all the processes we consider for a given phenomenon, we like to think that adding the single events may lead to the desired solution. This may be appreciably true for ''low energy'' events (the meaning is obvious), as clearly shown by the daily statistics. However, in ''high energy'' events, our parameterizations are expected to become more fragile and should be expected to fail, simply because our model does not correspond any more to what nature is doing. This is the case at the peak of severe storms.

Of course, with the evidence at hand, we can try to push further our analysis, seeking where to ameliorate our approach and final results. Obviously the first step is to identify the reasons for our errors. This paper is an attempt in this direction for what concerns spectral wave modeling. It is convenient to start recalling (section 2) some evidence about the present state of the art. In section 3 we explore the various processes at work during a storm and our ways of representing them. This leads to a rather long, possibly discouraging, list of potential sources of errors. Having assessed the present state of the art, at least at a qualitative level, with a more optimistic look at the future, we try to discuss where it is possible to act, where work can be done, and which actions could be taken to overcome at least part of the present limitations. These may involve different time scales, in some cases certainly not as short as we would like. However, I find it rather pleasant and stimulating to look ahead and perceive in the mist the top of the mountain we are climbing.

One point needs to be clear. As it is obvious in our community of wave modelers and it will be transparent in the paper, there is a wide spectrum of opinions of where exactly we are and which are the right ways to go. This should not come as a surprise, given that we are working at the frontier of our knowledge in this field. A wide spectrum of scientifically conflicting opinions is an identification of both uncertainty and knowledge and certainly a promise of future actions and improvements. It follows that, if this paper were written by a different person, some aspects would probably be seen with a different perspective. Therefore, this paper simply represents only my opinion and view of the present situation. This does not exclude that these opinions derive and have benefited from the many discussions and interactions along the years with many of my colleagues in this field.

2. The state of the art

It is an obvious fact, as soon as we check the statistics and how they evolve in time, that in the last decade, the results of the operational wave models have reached high levels of performance. Nowadays, the average error of an advanced wave model is easily down to a few, typically negative, percents, with a bias of the order of 10 cm or fewer. However, when we analyze the statistics with respect to wave height (see Fig. 1), it is immediately evident that the average error, both as bias and rms, is strongly dependent on H_s, the largest wave heights suffering underestimates up to 1 m or more. Although the largest figures are not strictly significant because of the limited number of cases in this range, the trend with

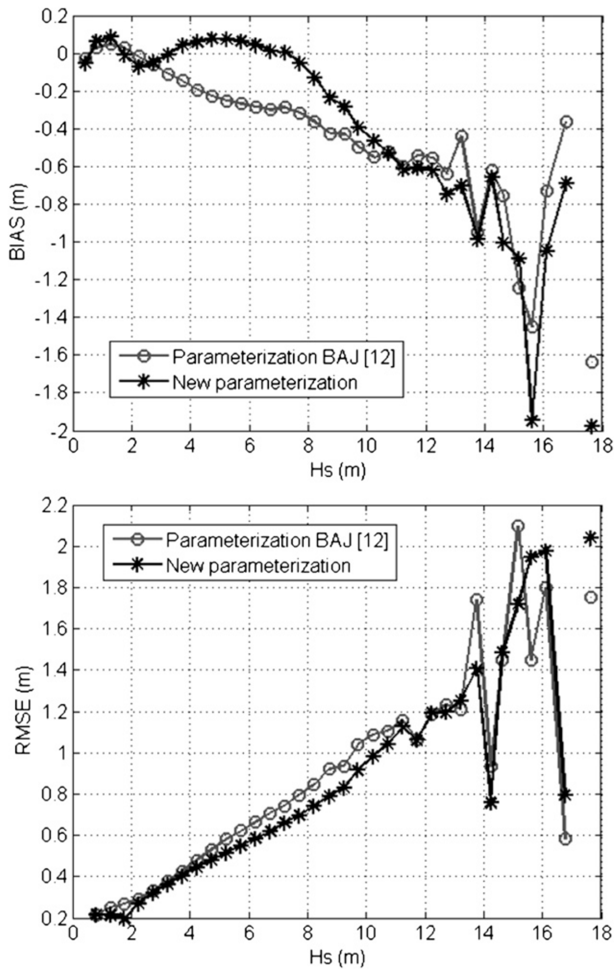

FIG. 1. Bias and rms error of a 0.5° global model forced with ECMWF 6-hourly wind analyses against corrected altimeter data [Jason, *Geostat Follow-On* (*GFO*), and *Envisat*] for the entire year of 2007 (after Ardhuin et al. 2008).

growing wave heights is unmistakable. Notice that in each panel, the performance of a global wave model (WAVEWATCH III; Tolman 2007) is shown according to two different parameterizations of deep-water dissipation. Although in this example, analyzed according to Queffeulou (2004) and Rascle et al. (2008), the new formulation introduced by Ardhuin et al. (2008), as shown in the plot, remarkably extends the low error range, it seems to fail similarly to the formulation of Bidlot et al. (2005) in the high wave height range. We will discuss this further in section 3c.

Compared to the quoted general performance of operational global models, even better results are achieved by special studies, typically concerning some specific storms. In these cases, the improvements with respect to global modeling are achieved by focusing on a specific area, increasing the resolution of the wave model and using higher-quality wind fields. These are typically derived using limited-area meteorological models where the higher resolution, and often the devoted human effort, allows a more detailed description of the surface wind fields, particularly close to coasts with a substantial orography or in areas characterized by strong spatial gradients.

Indeed, the improvements in the description of the surface wind fields, derived from the model's higher resolutions, and an improved description of the physical processes at work, particularly at the air–sea interface, have been key elements in the improvement of the wave results. The sensitivity of the wave conditions F_H to limited changes in the input wind fields F_U ensures that a given percent in improvements in F_U is reflected into a larger, in percent, improvements of F_H. Ever since wave measurements have been available at sea, this dependence has been exploited to derive from the model-measurement wave comparison an estimate on the quality of the driving wind fields. Implicit in this approach was the assumption that the wind field inaccuracy was the main reason for the, typically negative, errors in wave modeling. However, the recent advancements in meteorological modeling, supported by the ever increasing computer power and the overwhelming wealth of satellite data, are such that this attitude is rapidly approaching an end. Although the wind errors should certainly still be considered, wave modelers also have to look into their own machines if they want to decrease further the differences between wave model results and the measured truth.

Much can be gained by exploring in detail the present errors in wave modeling results. As seen in Fig. 1, the errors are not uniformly distributed throughout the range of wave heights found at sea. Together with a frequent overestimate of the minimum values, as absolute values are considered, we find a clear tendency to underestimate the highest wave heights and hence the peaks.

The message becomes clearer once we look at the details of the time series. We clearly see that the phenomenon is very frequent and not limited to the extreme values. Two examples are shown in Fig. 2. The first one is from Cardone et al. (1996), where they hindcast the so-called storm of the century, 12–15 March 1993, that affected the whole east coast of North America. Although old (the progress in modeling is remarkable; however, here we were mainly in highly generative conditions, and in this respect, the situation is more stable), the example is notable because for the hindcast, done with four different wave models, the best possible wind fields were used, derived with a human–machine interactive kinematics analysis [see also sections 3a(1) and 3c]. Notwithstanding this favorable start, all the models

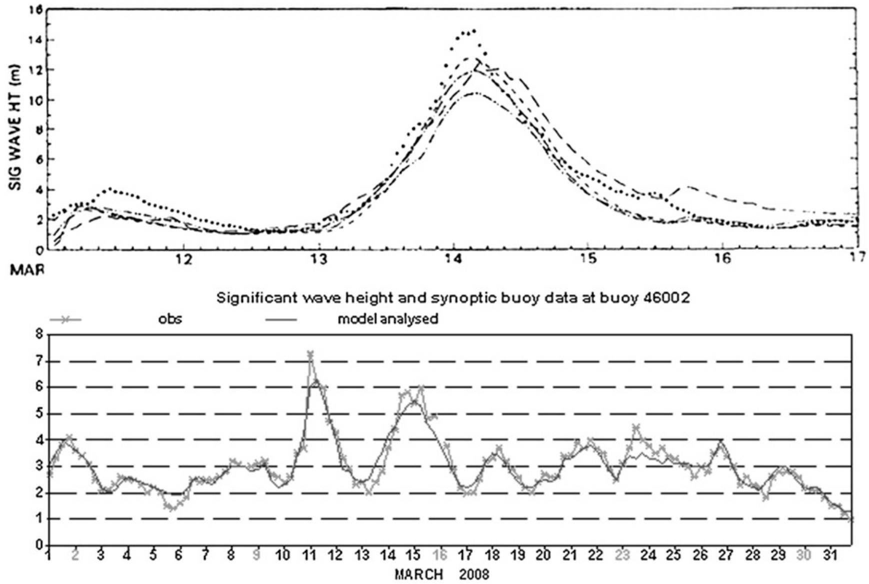

FIG. 2. Comparison between measured and modeled wave heights. (top) Extreme wave conditions during the storm of the century. Four different wave models have been used. Dots show the measured data (after Cardone et al. 1996). (bottom) Monthly time series (March 2008) from the operational ECMWF model.

substantially missed the buoy-measured peak wave height. The second example (courtesy of J. Bidlot, ECMWF, 2008, personal communication) concerns nonextreme conditions at a buoy in the North Pacific Ocean, off the coast of Oregon. The one-month plot (March 2008) shows very clearly the repeated tendency of the model to miss the peaks. Notice that a miss by one model—or better, by one system—does not imply a similar miss by other centers. We will return to the matter of the behavior of different modeling systems.

Another example comes from the long-term hindcast associated with the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40; Uppala et al. 2005). Caires and Sterl (2005a,b) had to make use of statistically determined enhancements of the peaks to match the measured wave heights at a sufficiently good level. Notwithstanding the relatively coarse resolution (T159; i.e., 126 km) of the meteorological hindcast, the ERA-40 surface winds turned out to be of good quality, and they could not be invoked as the only source of errors. The problem is not limited to a specific model or center. In their intercomparison exercise involving five different operational weather centers, Bidlot et al. (2002) noted a general tendency to underestimate the maximum values in a storm.

Strong evidence is also derived by comparing the wind and wave results obtained from running the wave model with the winds produced using the same meteorological model, but at different resolutions. Cavaleri and Bertotti (2006) have used the ECMWF meteorological and Wave Model (WAM) for this purpose, with the latter run at both global and Mediterranean scales. Their results are shown in Figs. 3 and 4 for wind and waves, respectively. The resolution considered for the meteorological, spectral model are T106, T213, T319, T511, T639, and T799, and corresponding to 190-, 95-, 62-, 39-, 31-, and 25-km spatial resolutions, respectively. The WAM model was run with a 0.5° resolution on the globe, and a 0.25° resolution in the Mediterranean Sea. Several stormy periods were considered; the diagnosis summarizes the overall results. The diagrams show the improvements with respect to the T106 reference case. The results are reported for the oceans (NH = Northern Hemisphere; T = tropics; SH = Southern Hemisphere) and for the Mediterranean Sea (MEDIT)—this one is considered to be representative for the inner basins. Focusing on the oceans, we see from the left panels of Figs. 3 and 4 that at the present resolution, T799, the results are almost asymptotic, an indication, consistent with the present statistics, that we are approaching the ideal result. However, our feeling is completely different once we look at the trend of the maxima in the right panels. We clearly see that there is no indication of an asymphthotic trend, the diagrams literally shooting up with increased resolution. This is a strong indication that the model maxima, for both wind and waves, are still far, on the average, from the truth. It is significant that there was no cyclone active on both the hemispheres during the period chosen for the simulation.

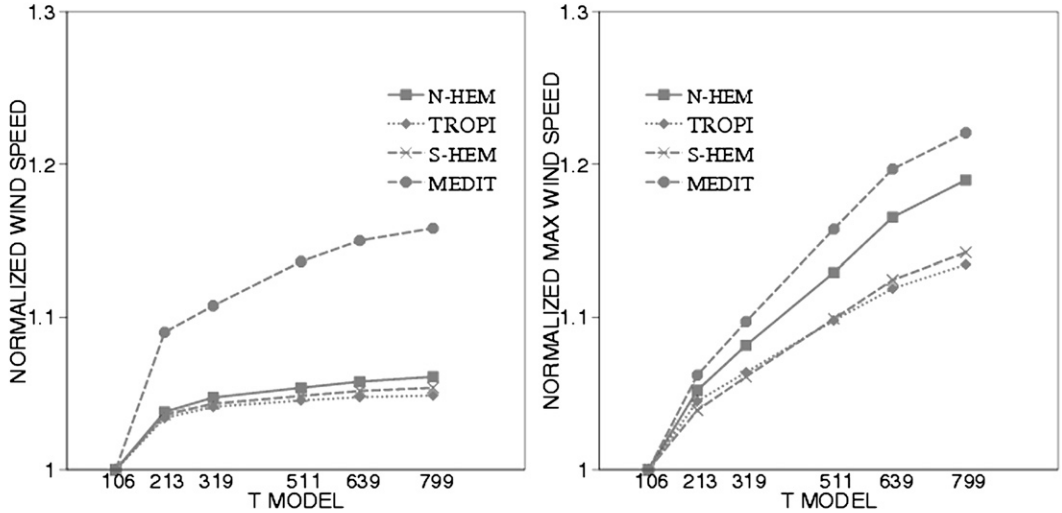

FIG. 3. (left) Relative increase of the wind speeds with the resolution of the ECMWF meteorological model. (right) Same as in left, but for the maximum wind speeds. MEDIT is the Mediterranean Sea (after Cavaleri and Bertotti 2006).

The plots in Figs. 3 and 4 could easily suggest that the wind is the culprit for missing the wave peaks. However, apart from independent evidence, we must think that with increasing resolution the area interested by the wind underestimate is getting smaller and smaller. Because the waves are an integrated effect, in space and time, of the driving wind fields, we should expect to see a progressively reduced effect of these ''wind misses'' on the waves—something obviously not true from the right panel of Fig. 4. Therefore, although the wind quality has obviously an effect, we must conclude that the problem lies also within the wave model itself. This opens a wide spectrum of reasons and possibilities that we aim to explore in the next section.

3. The search for a good reason (where we find we have to deal with a whole plethora of processes)

In a recent paper, the WISE Group (2007, hereafter W), an international community of wave modelers working together for the best results, did a thorough analysis of the present state of the art in wave modeling. As expected, here I will touch on many similar subjects, but all are limited and focused on the capability to model the highest wave conditions and the peaks, and on the reasons for their possible misses.

It is convenient to split the discussion into subjects dealing sequentially with physics, numerics, and more general, or combined, subjects that we can conveniently

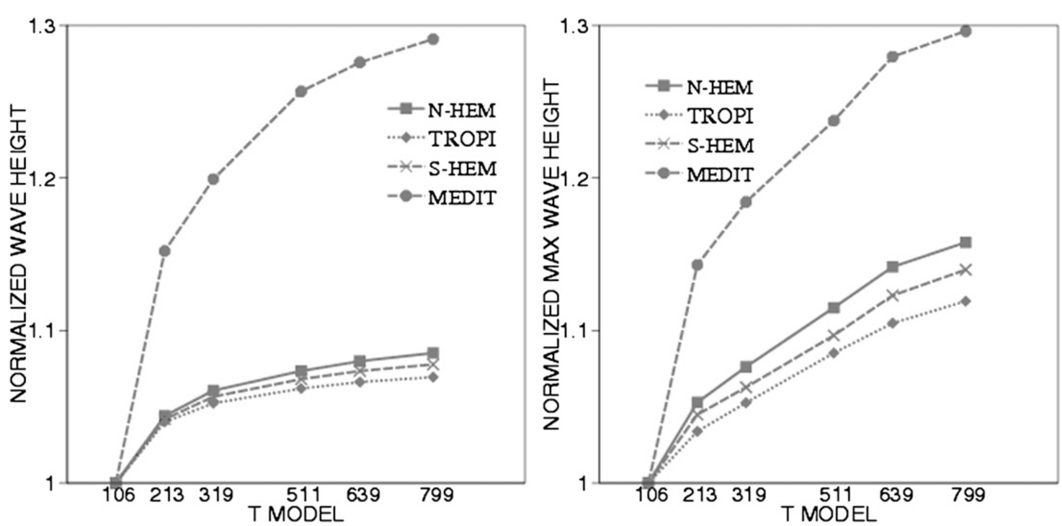

FIG. 4. Same as in Fig. 3, but for wave heights and maximum wave heights.

refer to as modeling. In each subject, several topics will be considered. For each one of them, I will limit the discussion to the "pure" problem, that is, open and deep water without any influence from land. A brief comment on further factors to consider when analyzing maxima in coastal areas will be given in the final discussion in section 4.

a. Physics

Although I have clearly specified in the previous section that wave modelers cannot any more consider the wind errors as the only or dominant reason for their wave misses, it is nevertheless convenient to start with this subject. After all, wind is the source of the energy we find in waves.

1) THE WIND FACTOR

Wind modeling—that is, the evaluation, within a highly complex three-dimensional meteorological model—of the surface wind field could easily be another subject suitable for extensive analysis and discussion. Within the framework of this paper, we are interested in the present situation and its relationship to the wave peaks.

By international convention, basically derived from the relevance of wind for sailing, the surface wind speed U is defined as the wind speed at 10-m height, hence U_{10}. Without further discussion, I simply point out this is a substantial inconsistency, as the air–water interaction is taking place at the surface via the wind stress. However, the use of U_{10} was very useful in formulating the first ideas about wind wave generation.

The general situation about the surface wind field (implicitly, we talk about conditions in the open sea) is well represented in Fig. 5, providing comparisons between the ECMWF 10-m wind speeds and the corresponding buoy measured data. Two examples are provided in the figure: a three-month statistics off the East Coast (top) and in the northeastern Atlantic (bottom). We see the extremely good quality of the model data. Indeed, the present global statistics of model against buoys indicate a best-fit symmetrical slope equal to 0.99, a negative bias of 10–15 cm s^{-1} with a scatter index (rms error by measured mean) close to 0.15. However, similarly to Fig. 1, we also notice in the two purposely chosen examples that the comparison is of lower quality, with a negative bias, at the highest wind speeds. Indeed, Bidlot et al. (2002) provide evidence that, albeit at a different level, this is practically the situation for all the models used in the intercomparison. An exception is the Met Office (UKMO), which will be discussed later in section 3c.

Missing the wind peaks is clearly related, but not only, to resolution. This is obvious in tropical storms where

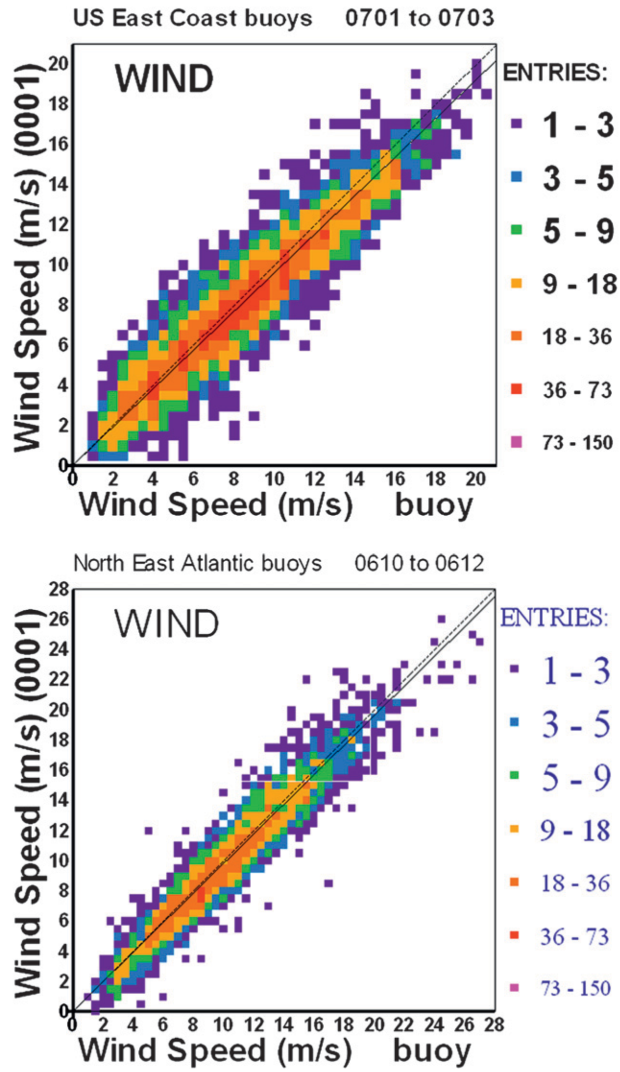

FIG. 5. Three-month comparisons between model (vertical) and buoy-measured (horizontal) wind speeds: (left) off the East Coast and (right) northeastern Atlantic.

the scale for a proper description of the situation, at least in the heart of the storms, is close to 1 km. However, intense extratropical storms may also need a high resolution for a proper description. This is related to gradients. It is easy to find examples of very intense storms with a large scale where, notwithstanding the distributed high wind speeds, the model performs very well. On the contrary, relatively limited events, but with a small scale, hence strong spatial gradients, also happen to be underestimated. In practice a model can handle only so much difference of, for example, pressure or wind speed, across one grid or time integration step; obviously, the two things are related. This is the basic reason why in Fig. 3 we see that by increasing the resolution we obtain better average results, but, at least in the global models, the results are not yet good enough where the maxima are concerned.

An obvious solution is to focus the attention on a given area, typically the stormy one, using a limited-area model (LAM) with higher resolution. Usually this leads to a more detailed description of the field and to higher peak values. An even more efficient, but heavy in manpower, approach is kinematics analysis, in which a man–machine combined effort (see, e.g., Cardone et al. 1996) provides what are probably at present the best possible surface wind fields. However, the effort required implies that this can be done only for a limited number of cases. For the globe and for long-term studies, we have to rely on global modeling.

The routine operation of a global model implies a recurrent use of data assimilation to get from the previous one-day forecast and measured data the best estimate of the situation during the last 12 or 24 h, depending on the cycle of the model. Data assimilation is a very sophisticated process (see, e.g., Rabier et al. 1998) that can lead to a smoothing of the field. Smoothing leads intrinsically to lower peaks. The same thing happens when—as done, for example, at ECMWF—for numerical stability reasons, the surface field is smoothed with a low-pass filter at each integration step. Again, this leads to lower peak values. Still, within data assimilation, some of the most valuable surface wind–measured data are the ones from buoys. Until recently these have been assimilated as such, irrespective of the actual height of the anemometer, often lower than 10 m. This implied measuring and assimilating wind speeds lower than the 10-m truth.

A substantial factor, especially for what concerns the peak values, is the gustiness present in the field. A wave modeler is used to receiving on his computer numbers representing, for example, the wind speeds at a certain time over a certain area, and this field is held valid for the following one or three hours, at most linearly interpolated in time between two sequential data fields. However, whoever had the chance to experience a storm knows pretty well that U is not constant in the short term, but it is characterized by a sequence of more or less pronounced gusts. Indeed, the meteorological bulletins frequently report both the average and the peak or gust values, but the latter information does not reach, or is not considered by, the normal user. The amplitude σ of these oscillations (percent rms deviation from the mean wind speed) depends on the meteorological situation, typically, but not only, on the air–sea stability conditions. In very unstable conditions, with water–air temperature differences of 10° or more, the amplitude of the oscillations can reach 30% or more of the average wind speed (Monahan and Armendariz 1971; Sethuraman 1979; Freilich and Chelton 1986; Tournadre and Blanquet 1994). Abdalla and Cavaleri (2002) have done a detailed analysis of the implications for wave modeling, which will be discussed in section 3a(2) titled "Wave generation." For the time being, it suffices to point out that the present theories (see, e.g., Panofsky and Dutton 1984) are not able to justify these high levels of turbulence in the atmosphere. The maximum σ_U suggested by theory, and embedded in meteorological models, is close to 10% (A. Beljaars 2005, personal communication) and, as we will see, this has profound implications on wave generation. A final point concerns the period, or better the spectrum, of these oscillations. Together with the rapid fluctuations that we associate with the word "gustiness," longer fluctuations, possibly of a different origin, can be present as well, a characteristic, as we will soon see, to which waves are quite sensitive. A clear example is given in Fig. 6, where the otherwise very good hindcast cannot reproduce the large-scale oscillations found in the field.

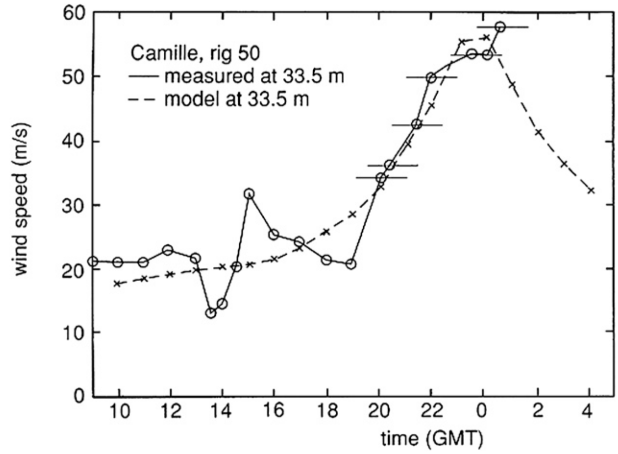

FIG. 6. Comparison between modeled and measured wind speed at Rig 50 anemometer during Hurricane Camille (after WAMDI Group 1988).

The spatial smoothing mentioned above reduces the energy in the upper-frequency range of the atmospheric wind model spectra. A typical atmospheric spectrum (see Nastrom and Gage 1985; also section 2 in W) implies a k^{-3} cascade in the lower-frequency range (k is the wavenumber), followed by a $k^{-5/3}$ decay in the higher range (Cho and Lindborg 2001). The separation is at the 200–300-km scale. On the contrary, in the typical spectrum of a meteorological model, for example, ECMWF's model (P. Janssen 2009, personal communication), the energy drops rather abruptly to 0 at about 200 km. The situation could be improved but, again, only for special areas and cases, with limited-area models using a higher resolution. Indeed, a higher resolution means a more energetic atmosphere, hence higher wind speeds. However, if so, the oscillations we manage to produce may be realistic in the physical sense, but their time, hence spatial, scales, especially in the higher-frequency range, are too short to be constrained by the measurements and the data assimilation procedure. Therefore, they may be significant in a statistical sense but not in the deterministic one. This leads to an increased scatter when compared with measurements, conventionally referred to as "double penalty."

The transfer of energy from the atmosphere to waves depends directly on the air density ρ. The variability of ρ, for instance with air temperature and atmospheric pressure, is not always considered in wave modeling. Certainly this is still the case in most a posteriori applications. However, considering the Northern Hemisphere, some of the most severe storms at high latitudes often involve cold air masses descending from the north. With respect to the standard reference conditions for air density, in these cases ρ can easily be 10% larger, something directly reflected into a corresponding increase of energy and momentum transfer to waves. In the heart of the storm, the low pressure can partially compensate for it, but only to a limited extent and less and less so while we move away from the center.

Summary. Underestimates of the surface wind speeds are more frequent in the high value range. Model resolution is critical. Smoothing of the fields, a frequent practice in meteorological modeling, leads to lower peak values. Gustiness is not properly considered. Air density can vary substantially, directly affecting wave generation.

2) Wave generation

Miles (1957) pointed out and described what is also at present considered as the main mechanism for the transfer of energy from wind to waves. With subsequent better quantifications (Snyder et al. 1981) and improvements (Janssen 1982, 1989, 1992), this theory has been, and still is, one of the pillars of any numerical wave model. In particular Janssen refined the physics of the process, taking into consideration the effect on the wind vertical profile of the energy and momentum absorbed by waves.

All this sounds good. However, we should consider that, in so doing, we practically sit on the shoulders of the measurements Snyder et al. (1981) did in the Bight of Abaco. During the experiment, the wind speed they had to deal with was about 7–10 m s^{-1}. It is natural to wonder if we are allowed, as we presently do, to use the same findings in extreme storms, with winds up to 30 or 40 m s^{-1}, much higher in hurricanes. The nice orderly picture that the Miles process implies is likely not to correspond to the truth once we move to high winds. Indeed, Banner and Melville (1976) had shown that the transfer of energy to waves is characterized by a series of bursts that happen when the surface air boundary layer detaches from the sea surface soon after the crest of breaking waves. In severe, and more so in extreme, conditions this can be expected to be the case for practically each single wave. While the smooth theory by Miles, with the later adaptations, can be, and indeed has been, adapted to reproduce what nature shows in the whole range of wave heights, it is natural to wonder about its capability of reproducing the physics of the extremes. Indeed, the physics changes. The enhanced breaking implies (see Andreas 2004) that large quantities of water droplets are detached from the crests and blown toward the rear of the preceding wave. The acceleration of the droplets is felt by the atmosphere as an increased surface drag. At the same time, again the droplets hit the water surface, killing the short waves—the ones that support most of the momentum transfer. Besides, their kinetic energy, out of phase with the wave cycle, goes mainly into the current.

At the highest speeds, the process changes again completely. Powell et al. (2003) have clearly shown that in this range the production of foam due to breaking, also directly induced by wind, is such that the foam completely fills the troughs between the sequential waves. In these conditions the Miles (1957) mechanism loses its meaning, the wind flowing practically from crest to crest.

All the spectral wave models use linear wave kinematics; that is, the phase speed c of a given spectral component is evaluated on the basis of linear theory. However, the infinitesimal approximation implied and the finite dimension of real waves may lead to appreciable differences. Although we implicitly assume that each component has a very small elevation, there is an obvious physical meaning in the dominant wave in a storm. The corresponding difference in phase speed c with respect to linear theory may be a few percent, particularly in shallow waters (Whitham 1974; Fenton 1985; Fenton and McKee 1990), growing with the steepness of the considered wave. Incidentally, together with the finite lateral extent of a crest, this is at least one of the reasons why on aerial pictures we see a stormy surface as an ensemble of finite curved crests.

A higher phase speed implies a longer wavelength. On the whole this has a double effect. On one hand it decreases the U–c difference regulating the energy flow from wind to waves. This is partly compensated by the reduced steepness, hence breaking (to be discussed later). On the other hand, longer waves mean also higher possible waves. So, although I have never done a specific experiment, I have the feeling that on the whole this can lead to higher wave heights.

In the previous section, we discussed the short-term turbulence of the atmosphere, at the scale not resolved or present in meteorological models. With a terminology derived from the short-term variability, say, with a period of one minute or less, here I also refer to this variability as gustiness. Its consequences on wave growth and evolution need to be taken into account.

The gustiness effect is felt via more than one mechanism. Let us assume as perfectly true the linear relationship between wind input and the wind wave speed difference, $U_{10} - c$, for each single wave component. The symmetrical, practically Gaussian, distribution of U_{10} with respect to its mean value U_m (see Munn 1966; Smith et al. 1990) implies a nonsymmetrical distribution of the friction velocity u_* (u_* grows faster than U_{10}). Because the input depends on u_*, in case of an oscillating gusty wind speed, this implies an enhanced input from wind to waves. In addition, if the wind mechanism, as it seems possible, has some degree of nonlinearity, this further enhances the net input. In practice waves grow faster than predicted by the theory for uniform wind speeds.

The strongest effect of gustiness appears when the phase speed of the waves approaches the wind speed. At this stage, in an oscillating wind field the wind speed becomes alternatively larger and smaller than the wave phase speed. In these conditions what Abdalla and Cavaleri (2002) call the "diode" effect implies a substantial input of energy to waves. This input grows with the amplitude of the wind oscillations. This pushes the wave heights to values higher than what was expected with the "no gustiness" approach. The differences can be significant: straightforward numerical experiments showing that a 30% wind variability can lead, in a longer time scale, to a 30% increase of the maximum significant wave height. What is relevant is that a strong turbulence is often a characteristic of the most energetic storms, typically with a northern inflow component (in the Northern Hemisphere).

Janssen et al. (2005) have devised an efficient method to take this extra input into account in the ECMWF operational model. However, the practical application faces two substantial difficulties, both already hinted to in the previous subsection. On one hand, as mentioned in section 3a(1), the theory, as implemented in meteorological models, does not justify the level of turbulence found in the field [see Monahan and Armendariz (1971) and other quoted references], suggesting a maximum σ of the order of 10% instead of the reported values of up to 30%. On the other hand, some components of the wind oscillations, still not present in the models, have a very long period, say, from one minute to one hour or more. Rather than a de facto increase of the average wind input, the components imply oscillations of the overall wave conditions in a given area, that is, of the significant wave height. These oscillations may be completely absent in the wind fields provided by the meteorological models. As a consequence the actual wave height may reach values much higher than the "non-gusty" model field (see, e.g., Abdalla and Cavaleri 2002). Recall, as already specified in the wind subsection, that, even if a higher resolution model shows oscillations in the fields it produces, these are meaningful only in statistical terms and cannot deterministically reproduce the oscillations found in the field.

Cold, hence frequently gusty, winds are also characterized by a higher air density. As already discussed in 3a(1), this can vary of up to 10% with respect to its nominal value. This has a direct effect on wave generation, with a proportionally larger increase of the resulting wave heights because of the positive feedback mechanism that characterizes the process.

Summary. Doubts exist on the validity of the Miles (1957) theory (although modified) in extreme conditions. The physics does change in such a situation. At present we do not have a good physical, hence numerical, model of what is going on at very high wind speeds.

The finite, large amplitude of stormy waves, particularly the dominant ones, implies a phase speed greater than dictated by linear theory. In the end this may lead to larger wave heights.

The level of gustiness experienced in the field is often underestimated in meteorological models. Therefore, its consideration in wave models does not lead to the related enhancements found in the measured results. Besides, models do not reproduce the possible longer-term oscillations of both the winds and wave fields. In certain conditions, but typically in the very severe storms, this leads to a strong underestimate of the possible maximum values.

Cold, hence frequently gusty, winds are also characterized by a higher air density. Neglecting its variations often leads to an underestimate of the resulting wave heights.

3) WHITECAPPING

This is the least understood and certainly the most poorly represented physical process that contributes substantially to the evolution of a wave field. Notwithstanding the strong interest focused on it in the recent years (discussed later), except for one single exception in practice, all the models are still based on one of the two approaches proposed during the last 30 or 40 yr. The first approach is the highly simplified, but in principle effective, formulation by Hasselmann (1974), complemented by the additional work of Komen et al. (1984). This was further refined by Janssen et al. (2005), with the introduction of a second tunable constant and also a square dependence on the wavenumber to limit the problems arising, in case of superimposed wind sea and swell, from the use of the mean spectral frequency. The second approach was provided by Tolman and Chalikov (1996). If used in their correct software environment, both of these approaches provide reasonable and often good results in most practical applications; however, it is stunning that their quantifications of the process differ by 100% or more, which tells a lot about the difference between sound physics and correct operational results.

During the last decade, more solid and physical approaches have been pursued. Following the pioneering work by Banner and Young (1994), Banner et al. (2000, 2002) have analyzed breaking in relationship to the formation and related instabilities of groups. Babanin et al. (2001), Babanin and Young (2005), Babanin et al. (2007), and Ardhuin et al. (2008) worked on the physics of the process analyzing both laboratory and open-field data. These efforts led to new insights into the process of whitecapping, in a way making even more evident the limits associated with the various parameterizations in use. Ardhuin et al. (2008) have been the first to implement these findings into an experimental then operational wave model. The implications for the results, keeping everything else unchanged, are shown in Fig. 1, where, ignoring for the time being the absolute values, we see clearly the difference between the new approach and the formulation by Bidlot et al. (2005). This is indeed remarkable. However, although the absolute values will be discussed further in section 5, for our present purposes we mention that, notwithstanding its more solid physical background, also the formulation by Ardhuin et al. (2008) requires some parameterization and fitting. The relatively low results in the high value range may also suggest that the constants used in this approach are chosen to fit the bulk of the data, also until remarkably high (8 m) wave height. However, their performance is less favorable (better, the overall system worsens) in the high value range, where, as already discussed, the physics is likely to be considerably different. Babanin and van der Westhujsen (2008) provide a good discussion of the present situation.

One of the key differences between the old and the new formulations for whitecapping is the different dependence of the dissipation of wind sea on the presence of swell and vice versa. On the other hand, as I will soon discuss in the following section, there can be substantial errors in the estimate of when a long-distance swell reaches a certain area. It follows that the possible swell errors imply different errors in the various formulations.

To summarize the situation: the physics of breaking is extremely complicated, particularly in heavy and, more so, in extreme conditions. As we have seen in the section 3a(2), discussing wave generation by wind, the physics changes when we move to very high wind speeds. Therefore, given the present use of parameterizations, it should not come as a surprise that we have problems venturing in this area. In any case, at present it is difficult to anticipate what will be the effects of using a physically correct formulation of whitecapping on the possible maxima of a storm. Certainly, and this point will be discussed later in greater detail, very small changes in the input or output budgets may have substantial effects on the resulting wave heights, simply because, notwithstanding the natural ''healing'' capabilities of the system to move to a new equilibrium, the overall wave growth results from the difference of these two large, relatively similar, quantities and more so at the peak of a storm.

Summary. During the present decade, progress has been made in understanding the physics of breaking waves. These results have only recently found their way into one operational model. Notwithstanding these advances, there is still a good level of empiricism in the way we attack the problem, and most of the operational models still cling to very empiric, often totally inconsistent, approaches. All the proposed and used solutions require some tunable constants. As such, they are tuned to the bulk of the results and may fail in extreme conditions, when the physics of the process is likely to be substantially different.

4) Nonlinear interactions

Nonlinear interactions are probably the best-known subject in the physics of wave modeling. There is no tuning or uncertainty here, and a workable solution, albeit under some strong hypotheses, has been provided by Hasselmannnn (1962, 1963a,b) and independently by Zakharov (1968). The problem is that even with this solution, the computations required for the full calculation in operational conditions exceeded, and still exceeds, the available computer power by orders of magnitude. Strongly interested in having a wave model formulated as much as possible in physical terms (see WAMDI Group 1988; Komen et al. 1994), a practical solution was provided by Hasselmann and Hasselmann (1981) and Hasselmann et al. (1985). The so-called discrete interaction approximation (DIA; a full discussion can be found in chapter 3 of W) has provided for almost two decades one of the pillars of the so-called third-generation models. However, to be relatively cheap in computer time, the solution does come with some approximations, and the relevance of using the full ''exact'' solution was already shown by Banner and Young (1994). This is where we focus our attention.

Considering for the time being its frequency distribution, we find (see W) that this is too wide. In practice, for our present concern, the DIA transfers too much energy to the low-frequency side of the spectrum. Of course this transfer is essential for wave growth, but, if in excess, part of the energy is found in wave components that move faster with respect to the ''right'' ones, hence with less input by wind. Here the implications depend on the structure of the storm. Should this be very extensive, in space and time, the shift toward lower frequencies could give the possibility to develop longer, hence higher, waves. However, the scale of most of the storms, also the most extreme ones, is usually much shorter, and the net effect of DIA is to decrease the input to the wave system.

Considering the directional spread, here too the DIA provides a too-wide distribution. Because the generation depends on the wind component along the wave direction, this too leads to a lower input.

Much effort has been put in recent years into devising new and more complete formulations of the nonlinear energy transfer; see chapter 3 of W and Resio and Perrie (2008) for a new solution. However, all these new approaches rely on considering more frequency combinations in a spectrum than done by DIA. Unavoidably, the computer time grows accordingly, linearly with the number of components in the case of DIA, with its square plus consideration of the inner loop and of the reduction factor in the case of the full evaluation [see Van Vledder (2006) for a full discussion]. At present the available computer time and the hoped-for solutions are edging their way toward each other, and they should meet soon. Of course these new approaches are approximations, and experience has still to show how closely they represent the true distribution and the implications for wave growth.

There is, however, a more fundamental problem. The nonlinear interactions in wind wave models, even if the Hasselmann (1962, 1963a,b) model is exactly implemented, are not exact. First, the model is a large time limit closure and neglects near-resonant modes that can change the spectrum on much shorter scales (of the order of e^{-2}, with e the wave steepness) and in a region of rapid changes. This may be a very relevant mechanism for our present discussion, namely, extreme conditions. Second, the Hasselmann model presumes a homogeneous and Gaussian sea state, which is of course an idealization, especially in heavy and extreme conditions. Third, it is a truncated model of a weakly nonlinear system. In other words, it includes the lowest-order resonances, whereas on longer time and space scales, other nonlinear contributions may become important [see, e.g., Annenkov and Shrira (2006) for a relevant discussion].

Summary. Beside its sometime incorrect spectral distribution, the present widely used DIA approximation leads to too-wide energy distributions in the spectra, both in frequency and in direction. This decreases the wind input to waves. New, better solutions are on the way. It is expected that these solutions will be implemented in operational models in the near future. However, all these solutions are still approximations, based on some strong hypotheses that are likely not to be satisfied in heavy and extreme sea conditions. The related implications for wave modeling have not yet been explored.

b. Numerics

The classical energy balance equation (see, e.g., Komen et al. 1994) splits the wave modeling problem into a physical part, that we have discussed in the previous section, and numerics. The latter has the task to import into the spectral energies the inputs-outputs derived from the physical processes, and then to advect the resulting energy in the direction of the specific components. The problem is amply discussed in chapter 8 of W. For our present purposes, we focus on the items related to the extremes.

Framed into its essential point, the problem is very simple: we are concerned about the diffusion associated with the advection; the larger the diffusion in both time and space, the lower the peaks. Quite a bit of effort has been put into devising new advection, higher-order algorithms, and better integration systems, and remarkable results have been achieved. A good example, using a third-order scheme, is given by Tolman (1995) in his WAVEWATCH model. However, the problem is unavoidably linked to the discontinuity associated to a grid, and this is something with which we have to live. The WAM model (Komen et al. 1994) uses the first-order, implicit, upwind scheme that is rather diffusive. However, an inherent diffusion has as partial compensation the capability to reduce, if not to cancel, the consequences of the garden sprinkler effect associated to the finite number of frequencies and directions. Because of their reduced diffusion, the use of higher-order schemes is more prone to the consequences of the garden sprinkler effect, and remedial action is required, as shown by Booij and Holthuijsen (1987) and Tolman (2002a). Note also that higher-order schemes can easily lead to wiggles in the spatial distribution, another undesirable effect.

The practical consequences for the maximum wave heights follow the logical sequence of arguments already discussed for wind in section 3a. The key element is the gradient. A large-scale storm will be marginally affected by diffusion. However, a strong isolated peak will be substantially decreased during advection, its energy being redeployed at the neighboring grid points.

In some numerical schemes, the spreading due to diffusion can be reduced by using a higher-resolution grid or, where possible, using larger integration time steps, that is, reducing their number in a given time interval. However, apart from the practical limitations posed by the Courant number, we should realize that this is by no means the case for all the schemes, in practice for all the wave models. The reason is the possible different increase of the ''diffusion by time step'' with respect to the ''time step size.'' Petit (2001) provides a very keen picture of the situation, discussed also in chapter 8 of W. In each practical case, a careful analysis is required to achieve the best balance between diffusion and overall integration time.

A high spectral resolution, both in frequency and direction, is crucial for the correct advection of energy, typically swell, over large distances. The typical resolutions for the global model are 15° in direction and 1.1 progressive increments in frequency. In most practical cases, this can be sufficient, because we are not acting with a single component but with a large spatial distribution of energy, distributed in frequency and direction. Therefore, the discontinuities that arise during the advection of one single wave component are superimposed on those from all the other spectral components that are differently distributed. The resulting wave field is generally rather smooth. However, if very large distances are involved and the single wave components are by then well separated, the 15° and 1.1 increment may turn out to be rather coarse. The latter may become crucial for the correct evaluation of the arrival time of the swell with a given frequency. The implications for white-capping have been identified in the previous section.

Obviously it is a matter of computing time. There is the frequent suggestion of passing from 1.1 to a 1.05 progressive frequency increment. Clearly, a similar argument may also be put forward for the directional resolution. Two lines departing from a certain position at a 15° angle will be quite far from each other after a few thousand kilometers. Of course, specific numerical tests are required to decide where best to put the effort. Note that doubling the number of frequencies would imply not only a double integration time but also a substantial increase of the necessary computer resources [see 3a(4)] associated with the evaluation of the nonlinear wave–wave interactions, for which, by the way, a suitable algorithm is not yet available at this resolution.

Another source of error for swell is related to the subject of this paper, that is, to the missing of the extremes. As a rule a lower H_s also implies a lower peak period and in turn an underestimate of the consequent swell period, hence group speed. In any case, given the usually limited height of swell, it could appear that a better advection is not relevant for the extremes of highly severe storms. However, the keen reanalysis of the original storms leading to the Pierson–Moskowitz spectrum (P–M64) done by Alves et al. (2003) clearly shows how swell, superimposed to a local storm, may contribute to the local wave heights. Therefore, it is clear that, for different reasons, the correct advection of swell may happen to be of relevance for our present discussion.

Summary. Diffusion, unavoidably associated to the use of discrete grids, leads to a smoothing of the fields, hence to an underestimate of the extremes. Although higher-order schemes may improve the situation, they often do so at the expenses of other details. Engineering solutions have been devised for practical applications.

Higher-resolution grids or, Courant number permitting, larger time steps may help. However, in each case a careful analysis is required to be sure that the introduced changes act in the right direction.

A higher spectral resolution would also be beneficial, especially for long-distance swell. This could be relevant in cross-sea conditions.

c. Modeling

Having discussed the situation in the various items that, together, make up a wave model, it is now time to look at the system as a whole. In a way, this is what I had mentioned in the first section about our hopeful idea that, adding the single descriptions of the various processes at work, this would be enough to create a proper hindcasting–forecasting machine. As discussed in the previous section, clearly the experience indicates this is not the case.

To start with, the sea on which we propagate our waves is not uniform and undisturbed. Rather, the oceans are characterized by currents that interact with the wave field. Most of the currents we find in the sea are not strong enough to affect at a significant level the waves that characterize a storm. However, in certain areas where the current speed is not negligible with respect to the group speed of the relevant wave system—typically the Gulf Stream, the Kuroshio and the Agulhas Current—the interaction with currents may substantially enhance the height of the waves. Taking the Agulhas as an example, two processes concur here to the frequent reports of exceptionally high wave conditions (see, e.g., Lavrenov 1998). Granted the local, often severe, wave conditions, the waves can interact with and be trapped in the current stream (see chapter 7 of W and Tolman 1990) and exhibit a large reduction of their wavelength and a consequent increase of their wave height and steepness. Alternatively, focusing by a meander can lead to high wave conditions in a limited area, certainly higher than in the surroundings.

The process is nonlinear, in the sense that in a severe storm under a strong wind, an enhanced height, hence steepness, will lead to an increase of the energy exchange in the various processes. Although the net effect depends on the specific conditions, this may well lead to a further increase of the wave height.

The problem behind this is that the actual current fields in the oceans are not well known, at least not with the accuracy required for an accurate evaluation of their effect on waves. For instance, the focusing that may derive from meanders of the Agulhas current is highly sensitive to small variations in the current spatial distribution. Little changes may move the focus to a different place, where as a consequence we will underestimate the wave height or defocus the system as a whole.

There is more than one reason for such a situation. Modeling currents in a wide space is a three-dimensional affair, much more complicated than dealing with waves, at least on the practical side. It is also relevant that, beside their scientific interest, wave data are much more in demand in general, which has pushed the practical applications toward better results. Finally, wave modelers enjoy a wealth of, mostly accurate and widely distributed, data not reflected in a corresponding situation for ocean circulation.

Moving again toward pure waves, one of the classical references in scientific literature is the paper by Pierson and Moskowitz (1964), in which they describe the analysis and formulation of the data collected under special conditions with the shipborne wave recorder on board four ocean weather stations in the North Atlantic Ocean. Indeed, P-M64 has been the reference for the other icon spectrum, the Joint North Sea Wave Project [JONSWAP; Hasselmann et al. 1973]. In nature, observations suggest that developing seas represented by JONSWAP would evolve to the P-M64 form, whenever fetch and duration allow. Analytically, this was obtained formulating JONSWAP as a generalization of P-M64, to which it would collapse when the peak enhancement factor drops to 1. Before the formulation of the third-generation wave model, initiated by WAM (WAMDI Group 1988) and where the spectrum is left free to evolve according to the input–output at the difference wave components, JONSWAP was the reference spectrum, also used in parametric models (see Hasselmann et al. 1976; Gunther et al. 1979). Although the fetch and duration conditions rarely allow the sea to reach fully developed conditions, it sounds reasonable to expect that, given the possibility, the present widely used third-generation wave models—WAM (Komen et al. 1994), WAVEWATCH (Tolman 1991), or SWAN (Booij et al. 1999; Ris et al. 1999)—would have their spectra progressively evolve toward P-M64. Surprisingly, as shown by direct tests, this is not always the case. For instance, under a constant and uniform 18.45 m s^{-1} wind ($H_{P\text{-}M}$ slightly less than 8 m), WAM, in the ECMWF version, will be still growing after several days, approaching 11 m significant wave height. On the other hand, even though they represented at the time a remarkable achievement, the measurements with the shipborne wave recorder that led to P-M64 cannot be compared, for accuracy, with the ones we have now have available. The very nice work by Alves et al. (2003) in reanalyzing the original P-M64 data, although acknowledging the good work of Pierson and Moskowitz, implicitly stresses the approximations involved in the data, also for the driving wind fields. Indeed, because approaching fully developed conditions is an asymptotic process, we can always argue how close we were during the considered events. More in general, the very concept of fully developed conditions is still a matter of debate (see, e.g., Glazman and Pilorz 1990; Glazman 1994; Hwang and Wang 2004). As Alves et al. (2003) point out, the present convenient use of P-M64 is more a matter of a lack of conclusive evidence in either direction than scientific truth.

The level of approximation present in a wave model should be soon clear to anyone dealing in detail with one or more of the subjects discussed in the previous section. However, some aspects of a model as a whole, particularly when applied to extreme conditions, also reveal the intrinsic limitations. One obvious aspect is the use of limiters to control, in certain conditions, the energy exchange during wave evolution (see, e.g., Tolman 2002b; chapter 8 in W for a discussion on the subject). This is a strong indication that our formulations hold within a given range, typically the most common one, and that our physics is not a good representation of nature in all its possible ranges. For the already mentioned argument that our models are fit to the gross bulk of the data, it is natural to wonder about the capability to simulate the extremes.

Probably the best proof of the level of tuning present in each wave model is the impossibility of exchanging part of the physics, or, more in general, large sections of two wave models. I do not refer to the trivial, for our discussion, problem of adapting, for example, a subroutine to the structure of another model. It is much more serious. We cannot, if we want meaningful results, take for instance part of the physics of WAM, for example, the whitecapping subroutines, and plunge it into WAVEWATCH. Surprisingly, at least the first time, we find that the H_s results may change up to 40%. So, although declared to be based purely on a physical description of the processes that govern the evolution of a wave field, we still need to play with one or more handles to tune our model to the desired representative level. Once more, it is clear this turns out to be sufficiently true only for nonextreme events. In particular, as already mentioned in section 3a(4), the sensitivity of the results to the use of the exact expression for the nonlinear interactions was clearly shown by Banner and Young (1994).

This takes us back to the model bias shown in Fig. 1. These data have been obtained by plugging the physics of the WAM model, as used at ECMWF, into the structure of the WAVEWATCH model (Tolman 1991, 1995; Komen et al. 1994; Bidlot et al. 2005). Then Ardhuin et al. (2008) substituted the white-capping formulation with their new approach, obtaining the second bias distribution. The diagram shows clearly how a different formulation can change the final results. However, its absolute value is a different matter. The corresponding test done with the integral ECMWF approach, that is, WAM with Bidlot et al. (2005), indicates a different answer, showing that the present ECMWF model slightly overestimates H_s with respect to the altimeters. Although these comparisons involve the calibration of the altimeter data that we are not going to discuss here, the suggested evidence that the straightforward use of one model physics into the structure of a different one can lead to different results is, again, something about which to think.

An even more forced tuning was present in the wave model the UKMO used until a few months ago (Golding 1983; Holt 1994). This was a second-generation wave model, whose approximations imply on average an underestimate of the wave field (Bidlot et al. 2002). However, in daily operational applications, this was compensated by an overestimate of the driving wind speeds (Bidlot et al. 2002) derived from the UKMO meteorological model. Here, too, it is natural to wonder how much a fit can hold in a highly severe storm.

A good example of how crucial certain aspects can be in special conditions is given by the dynamical generation. With this I mean the case when the heart of the storm, that is, its more energetic waves, moves with the weather system that generates it. This happens when the group speed at the spectral peak equals, or it is close enough to, the speed of the storm (not the wind speed). In this example, the wind continues acting more or less on the same wave system that can reach unpredictable heights. This is exemplified by the so-called storm of the century that, starting from the Gulf of Mexico, hit the whole East Coast plus part of Canada between 12 and 15 March 1993. Figure 7 shows the path of the storm. Cardone et al. (1996) report that a Canadian buoy South of Nova Scotia measured peak significant wave heights exceeding 16 m (this was true also for the famous ''Halloween storm'' on 26 October–2 November 1991, better known to a wider audience as ''the perfect storm''). Maximum crest-to-trough amplitude exceeded 30 m. It is instructive, and a posteriori perhaps also amusing, that such wave heights exceeded the local current, at the time, estimate of the 100-yr return period wave height extremes by about 50%. The measured peak period, around 15–17 s, suggests a peak group speed around 12–14 m s^{-1}. This is close enough to, although still lower than, the speed of the heart of the storm estimated by Cardone et al. (1996) ranging between 13 and 17 m s^{-1}. This is close enough for triggering dynamical generation. However [recall section 3a(2)], the correspondence between the two speeds increases if we consider the enhanced phase and group speeds due to the finite, actually much larger, height of the waves. Indeed, notwithstanding the extremely careful kinematic analysis of the wind fields (two jet streaks were identified, which were responsible for the two peaks of the storm), all the wave models substantially underestimated the measured peak values (Cardone et al 1996). Clearly, the storm was so extreme that many of the factors discussed in the previous section, including the accuracy of the wind fields, may have contributed to the hindcast underestimates. In any case, the crucial role of the model phase and group speeds in similar conditions should be

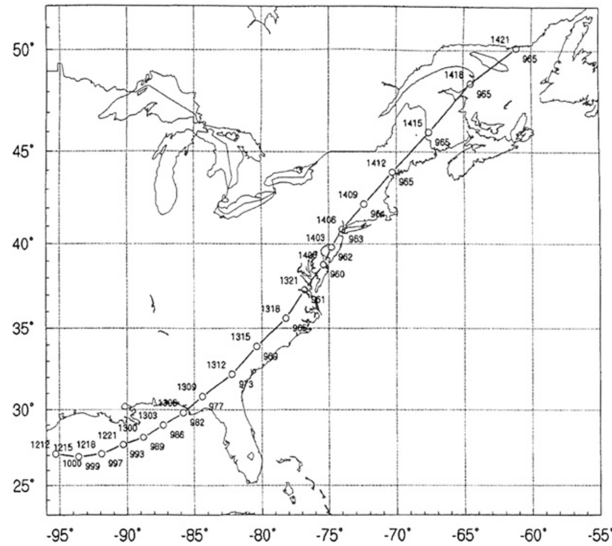

FIG. 7. Track and central pressure of the storm of the century (after Cardone et al. 1996).

clear. The other example I have in mind of an exceptional dynamical generation is the storm of 10–11 January 1987 in the western Mediterranean Sea. The storm began in the Alboran Sea, close to the Gibraltar Strait at the western end of the basin, and, with sustained winds of more than 25 m s^{-1}, propagated parallel to, and slightly offshore of, the African coast to Sicily and the Tyrrhenian Sea. The best winds available at the time for this area were the product of the European version of the UKMO meteorological model. On this basis Cavaleri et al. (1991) estimated more than 13-m significant wave height at the west end of Sicily. Similar, although slightly lower, figures have been recently obtained by L. Bertotti (2009, personal communication) using the high-resolution version, T799, of the ECMWF meteorological model and the ERA-40 database. Compared to these figures, it is interesting to note that the highest-buoy-recorded H_s value in the Mediterranean is very close to, but still lower than, 10 m.

Another hotly debated subject concerns the tail of the wind wave spectrum in wave models. Because of the limited number of frequencies a model can consider, a tail is required. Besides, it is commonly accepted, and justified by the experimental evidence (see, e.g., Hwang and Wang 2001, 2004), that in a generative sea, a tail can be considered beyond a frequency n times the peak frequency. The opinions differ about the value of n, varying between 2.5 and 5, and the power of the tail, if f^{-4} or f^{-5}, where f is the frequency (notice that the two subjects are related). The matter is relevant for several reasons. First, it implies possible H_s differences of some tens of centimeters, particularly in heavy and extreme conditions, when the cutoff can be at a relatively low frequency. Second, because the tail supports most of the stress, it defines the level of input according to Janssen (1991). Third, at least in the form of Bidlot et al. (2005), it affects the value of the mean frequency, hence the estimated loss by whitecapping. In principle the matter should be decided comparing the model-derived mean square slope of the surface (mss) against the corresponding buoy and satellite data. These seem to favor the $n = 5$ and f^{-4} solution. However, the correctness of the comparison is debated because of the different representations of the spectrum in a model and from a buoy. For advection a spectral model considers separately all the spectral components, the motion of each one independent of the other components. This is not the case for a buoy, especially in the high-frequency range, where the single components ride on top of the larger and longer ones, with a potential nonnegligible influence on their spectral representation. Similar, albeit different, arguments apply to the satellite data. Therefore the debate is open, with contrasting opinions (see, e.g., Hwang and Wang 2001) reflected in the different approach used by different groups.

Summary. A highly detailed knowledge of the distribution of currents in the oceans is required for a proper evaluation of the wave–current interactions, hence the possibility of enhanced or focused wave fields. Such knowledge is not yet available.

Even when fetch and duration allow, wave models do not necessarily converge to the classical Pierson–Moskowitz spectrum. On the other hand, given the present level of accuracy of wave models and measurements, one could wonder about the accuracy of the data that led to this spectrum. Also the very concept of fully developed conditions is still a matter of debate.

The use of limiters is in itself a strong indicator of the approximation with which the physics is represented in wave models, especially in extreme conditions; similarly so for the impossibility of exchanging sections of the programs representing the same physical process between two different models.

The importance of accurately representing the phase and group speeds in extreme conditions becomes apparent in the case of dynamical generation.

The frequency after which to apply a tail and the slope of the tail is still a matter of debate. This may imply a nonnegligible contribution to the overall energy of the system, hence to the resulting wave height.

4. General comments

This paper deals with various physical, numerical, and modeling aspects of a wave model that can affect the estimate of the largest wave heights we can find during our applications and daily operations. As such, the paper cannot be considered exhaustive for what concerns the possible errors of a wave model. When scrutinizing the various aspects of our machine, many more problems come to light. Easy examples are the theoretical approximations implied in modeling, and the convergence and the accuracy of the numerical procedure. More problems come to light when we move to shallow and coastal waters, where a whole new plethora of processes must be considered, concerning both wind and waves. Purposely, for the sake of clarity and also because the largest wave heights are found in the open ocean, this is where we have focused our attention. For most of these deep and shallow water processes, the interested reader is referred to the extensive W paper. For our present purposes, having discussed the various aspects of a wave model that may affect the extreme values of our hindcasts and forecasts, it is now useful to detach ourselves from the specific items and to consider the problem along a more general perspective.

If we consider the positive and negative budgets of a wave field, we soon realize that we face the following basic problem: the growth and evolution of a wave field depends on small differences between two large quantities. On one side we have the large input by wind. If the energy and momentum stayed within waves, these would grow very rapidly. However, most of the energy and momentum, more than 90%, is soon lost by breaking, ending in turbulence and currents. These are very relevant processes, and they affect the mixed layer (see, e.g., Melville et al. 1998; McWilliams and Sullivan 2000; Qiao et al. 2004; Noh et al. 2004) and the general circulation (Melville 1996; Sullivan et al. 2007), respectively. However, their relevance does not make our problem easier. We are left with large quantities, one of which, breaking, is still insufficiently known, and we expect, or hope, to reach a few percent accuracy on results that depend directly on their difference. We succeed, within limits, because the system is self-regulating. For instance, if at a certain time breaking is underestimated, the wave conditions rapidly grow to a level where breaking becomes impelling again, bringing the system under control. Indeed, this is the tuning knob I have repetitively mentioned. The sensitivity of the output to even tiny variations of such a regulator makes it ideal for bringing the model to a convenient equilibrium. On the other hand it is also clear that such a dynamical equilibrium between input and output is very delicate. It is also clear that a form of the loss by breaking—even if based on a good physical approach, but involving one or more parameters, and as such tuned to the bulk of the data—cannot hold with the same accuracy throughout the range of the possible conditions, more so at the extremes where the physics of most, if not all the, processes, including generation, is almost certain to change.

I must also mention that the combined use of the improved physical description of whitecapping [see section 3a(3)] and a suitable parameterization, although still underestimating the highest wave heights, has recently led to a further extension toward the upper values of the "good" range shown in Fig. 1a (F. Ardhuin 2009, personal communication). So, how far we will be able to go with the present approaches is still a matter of debate. However, it is worthwhile to mention that quite often, although the H_s results may offer some reasons for optimism, the much more critical look at the spectral energy distributions, model versus measurements, will better reveal our frequent crude approximation to the truth. I have purposely not extended the analysis in this direction. The result would have been an even longer paper. However, the point should be kept in mind.

The earlier considerations lead us to a different problem. Notwithstanding the earlier criticism, as I have mentioned at the beginning of the paper, the present results of the operational wave models are in general surprisingly good. Although less so for the extremes, this favorable state has been reached edging our way by a sequence of small steps and of many trials and errors. The dominant rule in practical applications is the following: a change to a model becomes permanent if and only if its effect is positive, that is, the score of prolonged applications improves. Of course this makes sense. However, let us suppose that all of a sudden we have at our disposal a piece of software that describes completely and without errors the energy balance of a certain process. It would be natural to think to stick it at once in our wave model, removing the previously crude approximation. Contrarily to our hopes, it is likely that the results will worsen rather than improve. The point is that the present models, good as they are, represent a careful balance among the different processes, each one with its larger or smaller inaccuracies. Having one process correct and all the other ones with their own previous approximations does not necessarily imply better results. Of course from a scientific point of view this is the way to go; however, clearly operational applications, with their need to get better and better results, are a different story. The two approaches must proceed as parallel routes, and this is even truer for the extremes of the possible range.

The very accuracy reached by the third-generation models, including the driving wind fields, makes difficult to judge additional progress, at least in general. The point is that the three quantities typically intercompared—model, satellite, and buoy data—have, or will soon have, accuracies often comparable to each other. Buoys are generally considered, at least for waves, as the reference truth. However, when the improvements we seek are similar or smaller than the accuracy of our references, any result can be a matter of debate. This is certainly true in the case of the extremes, when the accuracy of both model and instruments is likely to deteriorate. Although there is obviously a greater deficiency of the models in this range, the matter is of growing relevance for judging the progressive improvements.

A final consideration concerns the basic idea that stands behind all our spectral wave models. We are so used to dealing with wave spectra, both in measurements and models, that we tend to assume that, granted their sound mathematical background, this is also the correct way to analyze and model the related physical processes. As we have seen in the previous sections, this is not always the case. Discussing the general use of spectra in wave modeling, after bringing in several arguments, Liu (2000) concludes his paper with the following:

> Based on the results presented here, it may now be necessary to seek alternative conceptual paradigms for wind waves to make further progresses in understanding wind wave processes. In conclusion, to answer the question posed on the title of the paper, it is my opinion that the current wind wave frequency spectrum is outdated.

Needless to say this happens at a dramatic level when the wave conditions grow beyond certain limits. As a matter of fact, there is a certain level of uneasiness in the wave community, and arguments are exchanged about the alternative ways to go. Liu (2000), Liu et al. (2002), and Cavaleri (2006) discuss this point and consider possible alternatives. Granted that these doubts are justified, any progress along any alternative route is still far away. In any case we still face, but at a greater extent, the same problem just discussed in case of the perfect formulation of one process. It is clear that any revolutionary approach will no doubt worsen dramatically, at least at the first attempts, the overall results. Therefore, these alternative approaches should be pursued as alternative brave attempts, hoping the time will come, if scientifically sound and the conditions allow, that they will become the standard tool of the future. For the time being, we will have to stick with the present spectral approach, ameliorating it wherever possible, step by step, but never forgetting the insecure ground where we stand.

In this respect I would like to conclude this picture of the situation, quoting a paragraph from Komen et al. (1994):

> 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 . . .

Clearly, much improvement has been achieved with respect to 15 yr ago. However, I think that, mutatis mutandis, this phrase represents well the difficulties we are facing at present. Given that we need, and want, to improve, it is now time to discuss where the future efforts should go. This is the subject of the next and final section.

5. Where to act

Somehow the arguments discussed in the two previous sections have already pointed out the deficiencies of the present approach to spectral wave modeling, with an explicit interest in the extremes. Now we need to analyze the possible ways out from the present limitations, last but not least considering the practical limits we face in our daily activity.

Starting as before with the wind, the most obvious possible improvement, particularly for the most intense areas of severe and extreme storms, is an increased resolution of the meteorological models. This is crudely a matter of computer power, each additional step ahead α in resolution implying a much larger increase, α^3 or α^4, of the computer capabilities. Presently, the computer power seems to advance more by crude force, typically parallel multiprocessor machines, rather than, mutatis mutandis, by the elegant smart solutions that characterized, the example is mandatory, the early Cray computers. Although Message Passing Interface (MPI) parallelization may be more flexible of the formerly used vectorization, the use of larger and larger arrays of machines is becoming more and more cumbersome. In the near future, the number of processors is expected to grow up to hundreds of thousands, thus the model improvements should not be expected to proceed with the same speed of the computer power. In any case we must not forget that, with the exception of the kinematic analyses, there are larger scientific and social interests driving the advance of the meteorological models, interests for which the wave modeling community is probably a minority. It is by now evident, especially for climatic purposes, that the future atmospheric and ocean models will act in a fully coupled mode, their energy and matter exchanges modulated by the wave conditions at the surface. Already now—see, for example, ECMWF—the medium-range forecasts are produced with fully coupled atmospheric and wave models. Of course this is very stimulating, also because some of the processes we have discussed in the previous sections have a direct effect on the exchanges at the surface. On the other hand, this puts our needs of wave modelers on a different perspective, not necessarily of first priority, as somehow we have to compare our needs with those of parallel disciplines. However, this approach has a longer time scale, and for the time being it is worthwhile to focus on ''our'' problems and seek possible solutions. Therefore, what can we expect? The present typical advance is for doubling the resolution of the meteorological models every five years or so, which is of course good news (I am talking about global models). Of course this will move the results closer to truth but without reaching the final target. Conditions are much more favorable for limited-area models and more so when using the kinematic analysis, especially in view of the growing wealth of data to be derived from satellites. Alas, these applications cannot be general and permanent. Indeed, high-resolution models are now a regular product for specific areas, so that, still within the model limitations, the conditions here are more favorable.

The just mentioned limitations include, of course, the inability to model gustiness at the correct level. There is not much we can do until the theory, as embedded in the meteorological models, comes up with a solution. Of course empirical solutions can be found. On the basis of open-sea measurements, Abdalla and Cavaleri (2002) have related the bora gustiness in the northern Adriatic Sea, east of Italy, to the local air–sea temperature difference. Although this is certainly a key element of the problem, we cannot take it as the only one element in general applications, and a more comprehensive solution is required. In any case we will still be left with the problem of the long-term oscillations of the wind fields that lead to similar ones in the wave fields. Granted it is practically impossible to follow them in a deterministic way; also in this case, the problem is in the physics and numerics of the meteorological models and in their present incapacity to properly model the spectrum of the atmosphere. For the time being, Abdalla and Cavaleri (2002) have suggested a method to estimate the possible gusty wave maxima. However, their results are based on a limited number of tests, and as such they cannot be considered of general validity. More tests in this respect would be useful.

Moving to waves, the first item is, of course, an increased resolution. Here, too, an α increase implies an α^3 increase in computer time. The natural solution is to increase the resolution only where needed, hence in areas with strong gradients. Indeed, more than one solution has been devised, which include a locally higher density latitude–longitude grid (Gomez Lahoz and Carretero Albiach 1997), curvilinear coordinates [Holthuijsen et al. 1997; Beji and Nadaoka 2004; Van Vledder et al. 2008; see also the user manual of SWAN cycle III, version 40.72ABC (available online at http://vlm089.citg.tudelft.nl/swan/online_doc/swanuse/swanuse.html)], and finite element grids (Benoit et al. 1996; Hsu et al. 2005a,b; Roland 2008). However, what we really need is a flexible, most likely finite element, dynamical grid whose density in space is able to adapt continuously to the local gradients while the wave system moves from one area to another. This solution has already been implemented in circulation models (Fang et al. 2006; Piggott et al. 2008), and in my view it is a promising, if not necessary, solution for the future wave models.

Definitely a better spectral resolution, both in frequency and direction, and improved advection algorithms are key elements to reducing the smoothing of the fields, the consequent lowering of the maxima, and the error in the swell arrival time in a certain area. Although the former is only a matter of computer power, the latter one is a subtle compromise with the need to avoid unnaturally patchy fields. For swell, a promising possibility is the use of the ray technique (see O'Reilly and Guza 1993). However, because of the wider distribution and of the acting strong nonlinearities, this approach is not suitable or efficient for wind waves. Therefore, for the extremes it would be relevant only in the case of cross-sea conditions.

The argument about the phase speed of the dominant waves does not have a straightforward solution, not even in principle. Here we touch on the heart of the idea of a spectrum. Several approaches are possible, and one possibility would be to increase the phase speed according to the energy in the peak spectral components. Tests are required.

The nonlinear interactions are probably the single item where the problem we face is the lack of sufficient computer power. The various algorithms as an alternative to DIA presently under test should be able to enter into routine use within a limited number of years. However, we should not forget that the Hasselmann approach (1962, 1963a,b), of which the DIA and the other proposed approaches are approximations, is in itself an approximation based on a number of simplifying hypotheses that are likely not to be true in extreme conditions.

An improved definition of the ocean current patterns is a subject where, as wave modelers, we can only wait, at most expressing our needs. The problem for the circulation modelers has its roots both in the physics of the processes at work, in the computer power for higher resolution, and in the lack of data. Also, where the satellite altimeters provide a profile of the surface elevation, this is only the vertical integral over the ocean depth, a far cry from the on-the-spot H_s measurements at 7-km intervals enjoyed by wave modelers. Definitely, the quoted dynamical grids (Fang et al. 2006; Piggott et al. 2008) are a very promising approach and are expected to become more popular in the future. However, one of the dominant interests pushing toward an improved description of the ocean circulation is for climate studies. This is obviously welcome, but in these cases a deterministic model with a statistical distribution of the details, for example, the vortices (the parallel with gustiness is natural), would suffice the needs. Unfortunately, this would not be good enough for the wave modelers who need to know where, when, and how big the vortex is going to be to evaluate correctly the wave–current interactions. However, and the parallel with gustiness occurs again, we do not have enough data at our disposal to have a continuous deterministic picture of the oceans. It seems that, at least for certain aspects, we will have to live more and more in a probabilistic world.

Two second-order effects, but relevant at the level of accuracy we are presently discussing, are the proper consideration of the Stokes drift (Stokes 1847) and of the ocean currents in the estimate of the true wind speed with respect to the sea surface, hence to waves. However small, but not so in the mentioned strong ocean currents, given the sensitivity of the wave conditions to also small variations of the forcing wind, these effects should be properly considered. One of the practical difficulties seems to be the frequent separation existing between centers working on atmospheric and wave forecasts and on ocean circulation modeling. Tested at the kinematic level already in the early '90s (Tolman 1991) and more recently, for example, at the French Naval Oceanographic Center (F. Ardhuin 2009, personal communication), the role of currents on the "true" wind with respect to waves has only recently been properly analyzed at ECMWF (Hersbach and Bidlot 2008) and should soon be part of the operational suite. Note that its proper consideration requires a two-way interaction, and it is therefore possible only within a fully coupled atmosphere–waves–ocean system. As for the Stokes drift, its consideration is still at an experimental level (P. Janssen 2009, personal communication). Note also that, although the positive or negative action of the ocean currents depends on the relative direction between wind and current, the effect of the Stokes drift will always be a decrease of H_s, because it will always be in the steep wave direction. However, although opposite to what we are presently looking for, a correct physics implies its proper consideration.

The repeated mentioning of the limits imposed by the computers leads naturally to the following question: granted the future availability of a given computer power, where should we choose to invest it? Our declared aim is a better understanding of the physics and ultimately to get the best possible results from our wave model. I expect that the natural solution will be to distribute it among the different problems. However, a more rational way could be to analyze the sensitivity of the final results to a refinement in the various processes and decide to invest along the most sensitive lines (note that we could similarly argue about manpower). Granted that before acting with brute force we need ideas, it is not immediately obvious which elements the model is more sensitive to. Remember that there is a feedback by the system on practically all the processes, and that the final result we care about is their overall integral. It seems that a sensitivity study would be a useful exercise.

It is clear that many of us have played, more or less extensively, with one process or another. However, a systematic exploration of the sensitivity of the results to changes on all the parts that make up a wave model is a problem with a different scale. Sophisticated methods for model reproduction based on a Bayesian approach have recently been proposed—see, for example, Craig et al. (2001), Oakley and O'Hagan (2004), and O'Hagan (2006). However, the sheer complexity and variety of the possible situations suggest that this is not a practical way, especially when we expect, as we presently do, to go beyond the classically integrated parameters H_s, T_m and Θ_m (mean period and direction, respectively) and on to argue about the structure of the spectra. A satisfactory solution could be to limit the tests (of the real wave models) to the simpler cases or to a defined set of cases, as, for instance, the cases chosen for the Sea Wave Modelling Project (SWAMP) study (SWAMP Group 1985). Historical and well-documented cases, both for input (wind) and output (wave data), would be particularly useful.

Can we go beyond the standard spectral approach, at least to a stage where we can verify some of our fundamental hypotheses, such as the separate input to the different spectral components? I believe a possibility is offered by the direct numerical simulation of what is going on in the sea. Consider the basic subject we are discussing: extreme storm conditions. Assume we are modeling a storm and at an advanced stage of its development we have evaluated the spectrum and can estimate the present input by wind. We can also obtain a physical realization of the corresponding wavy surface.

Even a two-dimensional realization (i.e., a vertical section of the atmosphere and the sea surface), although with its limitations, would be a valuable start. Given these high waves, we could model the wind flow over it and evaluate from basic principles how much energy is passing from the atmosphere to the waves. Of course I do not mean mild sinusoidal waves. If so, we would be back to Miles's (1957) theory and following works. I mean steep waves, possibly asymmetric and with an incipient breaking, where the airflow may detach from the crests and the air-to-water energy transfer is a rather discontinuous and irregular process. Should we succeed in such an experiment—and I believe it is possible—we would get great insights into the physics of the process.

The numerical simulation of natural processes is a never ending story. A much more complicated problem is breaking, just because of its discontinuity. I have already mentioned the basic difficulty intrinsic in modeling a growing sea: the net growth corresponds to a small difference between two large quantities, the input by wind and the loss by breaking. If we consider that these two processes are also physically coupled (remember the burst of energy on the lee of a breaker), it would indeed make sense to deal with them as a whole. Possibly, the net input would then come out naturally and not as the difference of two large processes.

What should be the final target—the ultimate experiment? Obviously, the full simulation of air and sea, possibly starting as before from already developed conditions and modeling their physical evaluation with all the processes at work: wind, boundary layer, vortex shedding, waves, breaking, limited crest length, foam, turbulence, shear currents, and so on. Would we be able to carry out a physically complete simulation? I doubt it, and more so for the near future. This, too, would be a never ending story. Nature is infinitely complex. On the other hand, a limited advance would also probably reveal much of what we want and need to know.

So, although the spectral model machines keep producing daily useful, and probably progressively improving, results, someone, either by himself for intellectual curiosity or as part of an organized effort, should venture into these new territories to provide, soon or later, the seed that will be the basis of the future wave models.

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As I have clearly stated in the introduction, much of the opinions I express, and certainly most of the facts I quote, are the result of the interactions with, and of the work of, many of the colleagues in our community. Were it not for the different opinions that arise when we venture out of the known territories, this could have easily been a collective paper.

Some interactions deserve a special mentioning. Alex Babanin (Sasha) provided a clear picture of the present situation about the physics and modeling of whitecapping. Jean Bidlot, with whom, together with Peter Janssen, I frequently discuss the performance of the ECMWF meteorological and wave models, has kindly provided much enlightening material from the Centre operational archive.

Many useful clarifications have come from Leo Holthuijsen, Erick Rogers, Miguel Onorato, and Henrique Alves. Three reviewers—two anonymous—have provided many useful criticisms and suggestions, helping to streamline the paper, correcting and adding where necessary, and deleting not fully concerning subjects. Part of the discussion on the nonlinear interactions is an extract from the comments of one of the reviewers.

Finally, I enjoyed showing the paper to John Ewing, both for refurbishing the language and for having the valuable opinion of one of the frontier wave modelers of the previous generation.

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