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RECENT RESULTS WITH A THIRD-GENERATION OCEAN-WAVE MODEL

Wave researchers from many different institutions, not satisfied with the state of the art in ocean-wave modeling, are working on developing and implementing a so-called third-generation ocean-wave model. With a test version of the model, runs have been made on the CRAY computer at the European Centre for Medium Range Weather Forecasting. First results have been compared with observations; they seem to indicate that the high expectations were justified. The use of wave observations from satellites for model validation and data assimilation is discussed.

MOTIVATION

Ocean-wave research in general, and ocean-wave forecasting and hindcasting in particular, has a variety of applications because sea waves interfere with numerous human activities. First, wave forecasts are frequently used for ship routing, coastal defense construction work, and off-shore operations, all of which have both an economic and a safety aspect. Second, hindcasts are made to help determine the wave climate, which has to be known when estimating possible wave forces for the design of structures. Finally, there is the important geophysical aspect that world climate is determined by the coupled atmosphere-ocean-cryosphere system. Exchange between the atmosphere and ocean is through the sea surface, and that makes a good knowledge of the sea state essential.

Since the 1960s, many numerical ocean-wave models have been developed, and several of them have proven their usefulness in applications. Early models were based on a simplified quasilinear approach to the wave-modeling problem (see, for example, Zambresky's article in this issue). Later, second-generation models attempted to include the effect of the nonlinear resonant wave–wave interaction, which is known to have a strong influence on the shape and evolution of the spectrum. Cardone (in this issue) discusses results from one of the second-generation models in some detail. However, remarkably enough, a recent detailed comparison of 10 different models in the so-called SWAMP study[1] revealed a number of basic shortcomings not only of first-generation models but also of all existing second-generation models. These deficiencies were associated with the inadequate parameterization of the nonlinear transfer induced by wave–wave interaction. In its exact form, this transfer is too complex for numerical integration in a wave model. In fact, parameterizations used in present second-generation models required the shape of the wind-sea spectrum to be largely prescribed, rather than letting the spectrum adjust freely in response to the wind forcing. This also implies that the details of the spectral energy balance, including, in particular, the form of the dissipation source function, are incompletely treated. The resulting inadequacies of this approach are particularly evident in rapidly changing wind fields and in the interaction of wind sea with swell.

The weaknesses appear most pronounced when the models are driven by identical hurricane wind fields. The test is critical because hurricanes have strong and strongly varying winds. The results of the test are given in Table 1, which shows a comparison between the maximum significant wave height obtained in each model. Values range from 8 to 25 meters, a spread that is quite unacceptable. (Some of the models have been subsequently modified.) As a result of the findings of the SWAMP study, of which the cited hurricane test was only one element, a large international group of scientists (the so-called Wave Modeling Group) decided to start work on implementing a new third-generation model.

WHAT IS A THIRD-GENERATION MODEL?

Ocean-wave models solve the energy balance equation for the two-dimensional wave spectrum $F(f, \theta; \mathbf{x}, t)$, which is a function of wave frequency, f, direction, θ, position, $\mathbf{x}$, and time, t:

$$\frac{\partial F}{\partial t} + \frac{\partial}{\partial \mathbf{x}} \mathbf{c}_g F = S_{\mathrm{in}} + S_{\mathrm{nl}} + S_{\mathrm{ds}} . \qquad (1)$$

Here $\mathbf{c}_g$ is the appropriate propagation velocity. The functions S are source terms describing different physical processes: S_{in} stands for the wind input; S_{nl} for nonlinear, resonant, four-wave interaction; and S_{ds} for

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Table 1—The highest significant wave height H_S obtained with nine different wave prediction models when driven by an identical hurricane wind field.

Model	$H_{S,max}$ (m)
MRI	14
VENICE	11
NOWAMO	14
GONO	16
TOHOKU	13
HYPA	8
BMO	25
SAIL	14
DNS	10

Note: See Cardone (in this issue) for an explanation of the acronyms and a further discussion.

dissipation. In second-generation models, either the spectral shape is predetermined (with parametric models) or the source terms and, in particular, the nonlinear source term are treated in an ad hoc, empirical way. A third-generation model does not have these constraints. The construction of a third-generation model was not possible until recently, when a good algorithm for computing the nonlinear transfer became available.[2]

THE WAVE MODELING GROUP[3]

Work on the development of a third-generation model is supported broadly; in fact, about 40 scientists from 17 institutions have participated in the Wave Modeling Group so far. Therefore, several tasks could be undertaken simultaneously, some of which go beyond the actual modeling effort. To this end, several working groups have been formed.

One group will concentrate on the practical problem of further developing, implementing, and validating the new wave model. Their activities will comprise such items as documentation, semioperational implementation (the determination of the mode of operation), and model validation. They will also consult potential users in order to specify further the output format and archiving requirements.

Another group is focusing on more general wave dynamical problems, which have been isolated in studies such as SWAMP, that have suggested further research; the time seems ripe to follow their suggestions. The three main research thrusts are to

1. Reanalyze existing data on fetch-limited wave growth,
2. Study directional properties of the wave spectrum,
3. Investigate the nature of shallow-water limitations to wind sea.

A fourth group will consider the problem of wave data assimilation, which will be discussed separately below.

RESULTS

So far, results have been obtained for three different situations:

1. A global run,
2. A regional hindcast of extratropical storms,
3. A regional hindcast of hurricanes.

Run 1 was made to demonstrate the potential of the model. Runs 2 and 3 were made mainly for validation purposes. In run 2, the model was extended to include certain shallow-water effects. Here we will only briefly sketch methods and results; a full account is presented elsewhere.[4]

In all three cases, the third-generation ocean-wave model solved Eq. 1 numerically. For the source terms, known expressions have been taken. The spectrum was decomposed into 26 frequency and 12 directional bins. Three versions have been implemented: a global one, on a 3- by 3-degree longitude-latitude grid; and two regional ones, one for the northern European continental shelf with a 0.25- by 0.5-degree resolution, and one for the Gulf of Mexico with a 50-kilometer resolution. All versions have about 5000 active grid points. For the propagation terms (the spatial derivatives on the left side of Eq. 1), a first-order upwind-difference scheme was used. In this way, a rate of numerical dispersion was obtained that appeared to be reasonably consistent with the dispersion required theoretically. The theoretical source functions were integrated with an implicit numerical scheme. The time step was fixed at 20 minutes in the global model. The 26 frequencies of the model range from 0.04 to 0.42 hertz on a logarithmic scale with $\Delta f/f = 0.1$, and the 12 directional bands give a 30-degree resolution. Beyond the high-frequency cutoff, limiting the region of the spectrum that was treated prognostically, an empirical parameterization was used.

The Global Run

The output from this run, which covers the period October 13-15, 1983, is given as an arrow plot (Fig. 1), where the arrows indicate wave height and mean wave direction at each grid point. Of course, this is only a fraction of the information available. In fact, we have for every time and every grid point the full two-dimensional spectrum, which may be required for the computation of ship response (see the article by Bales in this issue). However, the spectra are not given here.

The Regional Hindcast

Six storms that occurred in 1983 and 1984 on the European continental shelf were hindcasted with the shallow-water version of the model on a limited area. The details of this comparison have been presented elsewhere.[5] Here, for illustration, we present results from one storm that occurred during January 1-4, 1984. Figure 2 compares modeled wave height and measured wave height for the stations Euro and Statfjord. There is a good match between the model and measurements. Figure 3 is a plot of lines of constant wave height at the maximum of the storm, whereas Fig. 4 gives spectra every 3 hours at Statfjord. Results of the full hindcast have been analyzed statistically. Bias ranges from a few centimeters in the southern North Sea to a maximum of

Figure 1—Arrow diagram output from the global version of the model. Arrows indicate wave height and mean wave direction.

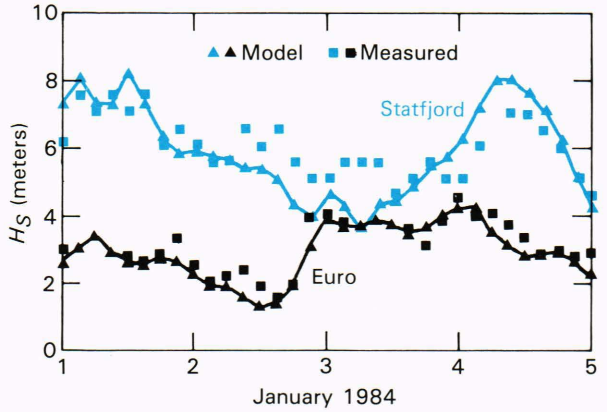

Figure 2—A comparison between model results and observations for two different stations in the North Sea.

0.5 meter in the Norwegian Sea (with a mean observed wave height of about 6 meters). Scatter indexes (root mean square error/mean observed value) are between 10 and 20 percent, which is considered good.

The Hurricane Hindcast

When we discussed above the motivation for the development of a third-generation model, we saw how critical test hurricane wind fields can be. Therefore, the third-generation WAM (Wave Modeling Group) model was implemented for the Gulf of Mexico, and three hurricanes were hindcasted, using wind fields that had been carefully analyzed. A full account is in Ref. 4. Figure 5 shows a comparison between observed and computed wave heights for hurricane Camille. Agreement is good, even up to significant wave heights in excess of 12 meters.

SATELLITE OBSERVATIONS

Wave observations in general, and satellite wave observations in particular, are useful for a variety of reasons. A primary application is model validation. Not only are satellites able to measure wave heights globally, they also can observe the full two-dimensional spectrum (for the long waves). This is important because directional relaxation effects are such a crucial element in wave forecasting. For example, Beal, elsewhere in this issue, shows some of the first examples of aircraft and spacecraft directional wave spectra that were useful in verifying the U.S. Navy first-generation model (GSOWM). Other remote observations (see the article by Gonzalez et al. elsewhere in this issue) can also be used to this end.

Satellite wave observations can be assimilated into numerical wave models in real time to improve wave nowcasting and forecasting. Not much research has been done on the subject so far, and the general usefulness of the approach requires demonstration. However, there are indications that wave data assimilation can improve wave model results. One indication is the fact that people making subjective wave analyses now attempt to use wave observations from ships and other sources. A more concrete indication is given in Fig. 6, where for one particular situation (swell in the southern North Sea) a hindcast[6] has been made with the Royal Netherlands Meteorological Institute operational wave model (GONO), with and without data assimilation from a station in the central North Sea. The value of the assimilated data is clear. Further research on data assimilation is under way at several places.

A next step would be to consider the joint problem of satellite wind and wave data assimilation in numerical atmosphere and wave models. In fact, it is now realized[7,8] that "the effective application of satellite wind and wave data for climate studies requires the implementation of a complete, quasi-real-time, operational end-to-end system, starting from satellite sensor algorithms operating on the (calibrated and collocated) physical sensor data on the input side, and producing as output continuous, global wind and wave fields with the space–time resolution appropriate to operational high resolution atmospheric and wave forecast models." The

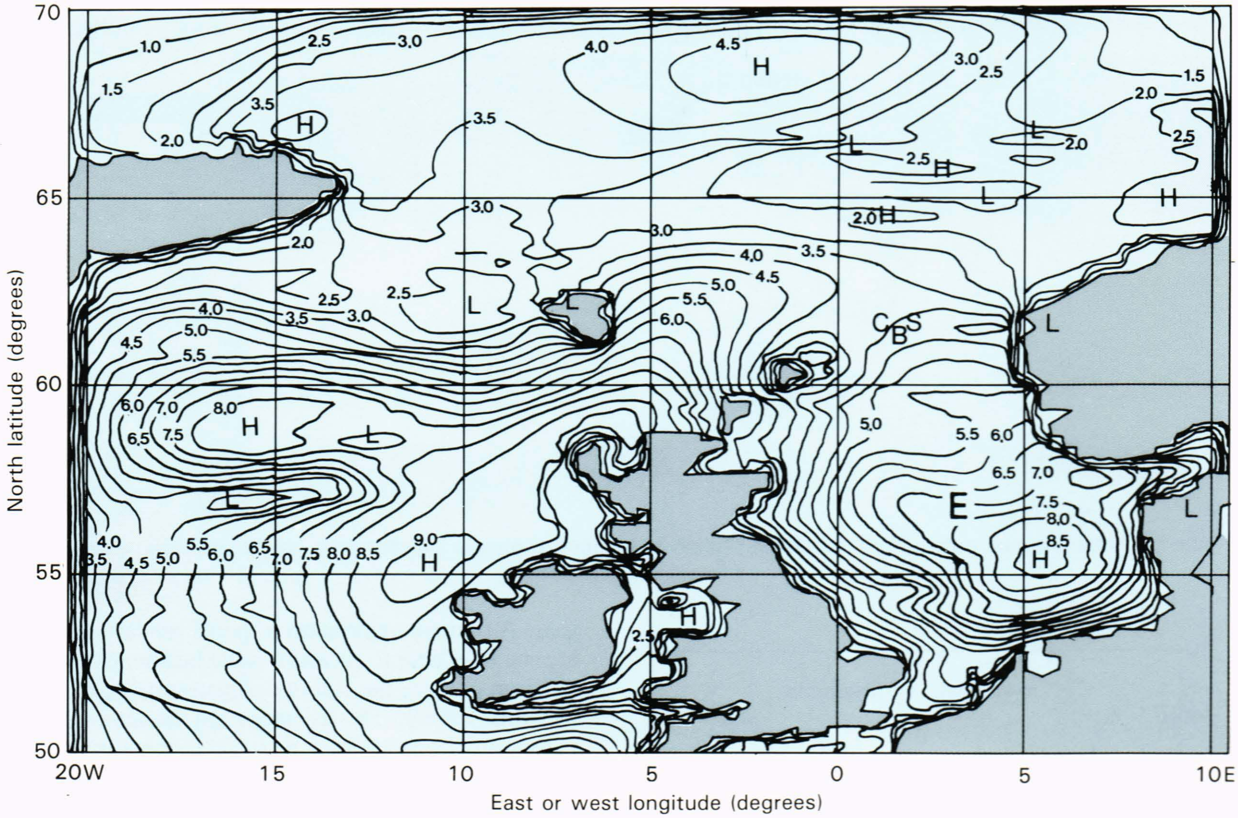

Figure 3—Isolines of significant wave height (meters) at 1200 GMT on January 2, 1984, during one of the hindcasted storms. The location of station Ekofist is designated by the E. Maxima in wave heights are indicated by H and minima by L.

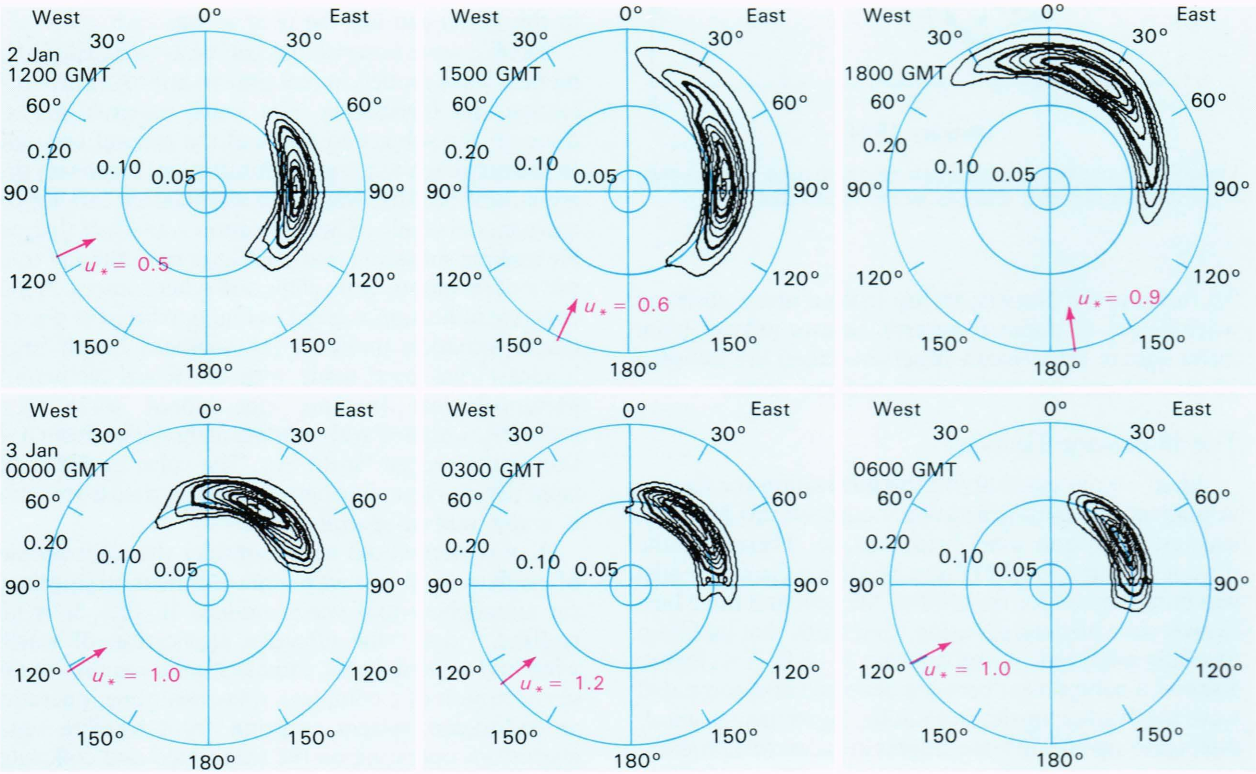

Figure 4—An example of two-dimensional spectral output from the model. Spectra are given for location E on Fig. 3 at intervals of three hours. Plotted are isolines of equal spectral density level. Distance from origin is frequency (hertz); the angle is wave propagation direction. The local wind direction is designated by arrows, and the magnitude of the frictional wind velocity is designated by u_* ($\approx$ 1/30 the wind magnitude at 10 meters height) with units in meters per second. (The model output at 2100 GMT is not shown.)

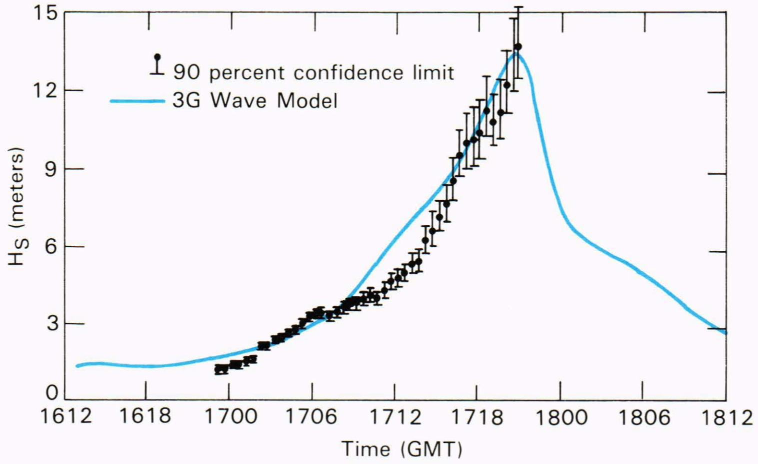

Figure 5—A comparison of calculated and observed wave heights during hurricane Camille in 1969. At the height of the storm, the wave sensor broke down.

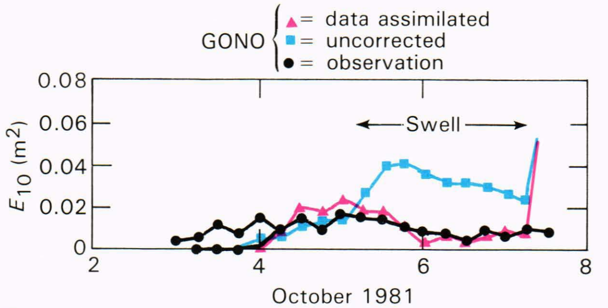

Figure 6—A comparison between predicted and observed swell-energy levels, with and without data assimilation. (Details are given in Ref. 6.)

wind fields can then be used to drive coupled ocean–atmosphere models and to investigate the response of the ocean to global atmospheric forcing, a crucial element in the climate problem. An interesting byproduct of the real-time availability of wave information can be its use for extracting winds from scatterometer observations through improved sea-state-dependent wind algorithms (see Donelan's article, this issue).

CONCLUSION

We have a reliable third-generation wave model, compatible with our present physical understanding of ocean waves. However, much work remains to be done. Further development and implementation work are under way, and the model is already being used as a research tool. Finally, we are preparing for the use of satellite observations, such as will become available from ERS-1, soon after 1990.

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