OWEN M. PHILLIPS

OCEAN-WAVE PREDICTION: WHERE ARE WE?

A brief assessment is given of various approaches that are presently used to provide wave spectral forecasts, but these approaches cannot provide the more detailed information needed to interpret recent results obtained by remote sensing.

It has been about 40 years since the first attempts were made to predict the characteristics of ocean waves on the beaches of Normandy. The earliest attempts sought to develop simple formulas for the wave height and dominant period; in certain applications, those overall parameters still provide the information that is needed most. However, the variability of the natural wind field in space and time limits the usefulness of the simple formulas. It was not long before other models were developed for calculating the wave spectrum, given the space and time history of the wind input. Although the state of the art of predicting the dominant features of the wave spectrum can hardly be regarded as satisfactory, the stimulus and demands of remote sensing, the need for a better understanding of air-sea exchanges of momentum, heat, and water vapor, and the requirements of oceanic acoustics have led to more detailed questions that we are beginning to be able to answer.

Still, for the purposes of operational forecasting, attention has been concentrated on what might be called gross modeling, the attempt to predict the dominant features of the spectrum. The physics of the problem includes, or should include, consideration of wave propagation, an appropriate specification of the wind input, the effects of nonlinear wave–wave energy transfer, and wave breaking. Most present models do not use all the physics that we know concerning these processes, particularly the last two, but, instead, are set up to stabilize the calculation by forcing the spectrum toward some empirical form when the processes of nonlinear transfer and wave breaking become important. In all of them, the development of the spectrum is specified by an equation of the form

$$\frac{\partial E}{\partial t} + \mathbf{c}_g \cdot \nabla E = \text{R.H.S.} \, ,$$

where E is the spectral density of the wave field, $\mathbf{c}_g$ is the group velocity, and R.H.S. is the right-hand side of the equation. There is little disagreement about the left side of the equation, which simply describes wave propagation, but there is a great diversity among models about what is put on the R.H.S. to represent the wind input, nonlinear transfer, and wave breaking. The various models in present use are conveniently summarized in Ref. 1, which resulted from the Sea Wave Modeling Project (SWAMP). For example, in the VENICE model,

$$\text{R.H.S.} = \alpha + \beta E$$

represents the direct excitation by atmospheric turbulence. This provides linear, then exponential, growth of the wave components under the influence of the wind, with a cut-off of the spectral density at each step in the calculation when a saturation upper limit is exceeded. This can be considered a rough representation of the effects of wave breaking; nonlinear transfer is not considered at all. In two other models, MRI (Japanese Meteorological Agency) and DNS (Scripps-NORDA),

$$\text{R.H.S.} = (\alpha + \beta E) \left[1 - \left(\frac{E}{E_\infty} \right)^2 \right] ,$$

where E_∞ is the Pierson-Moskowitz spectrum toward which the computed spectrum is forced as E increases. The British Meteorological Office model has

$$\text{R.H.S.} = \alpha + \beta E - \Delta f^2 (\bar{\zeta}^2)^{1/4} \, E \, ,$$

where Δ is a constant and f is the wave frequency. As I understand it, in this model one calculates the mean square surface displacement $\bar{\zeta}^2$ at each time step and then, for the next step, reinitializes the spectrum to the JONSWAP (Joint North Sea Waves Project) shape for

Owen M. Phillips is a professor in the Earth and Planetary Sciences Department, The Johns Hopkins University, Baltimore, MD 21218.

this value of $\bar{\zeta}^2$. There is not much physics in any of these models, and while the technique of forcing the calculation toward one or another of the spectral shapes may work reasonably well in the simple situations for which the empirical spectra were found, they will not be able to cope with more complicated situations, and the prospects of their further development are very limited.

Much more promising and more flexible is the procedure of "full" nonlinear calculation pioneered in Europe[2,3] in which the wave–wave interactions are computed explicitly, but in which the parameterization of breaking is still arbitrary. This technique requires considerably more sophisticated computing and can hardly be said to be routinely operational. Nevertheless, if experience with this model indicates, for example, that the higher frequency components of the spectrum can be parameterized simply, the computing requirements may be reduced to such a level that this kind of model, with its ability to handle more complicated wind situations, will become more widely used.

A number of potentially important effects have not yet found their way into these models. There are suspicions that air–sea temperature differences, particularly in highly stable situations, may substantially modify the energy input from the wind. F. L. Bliven of NASA/Goddard has pointed out to me that the effects of rain may be significant in certain circumstances. One fairly trivial effect is the attenuation that can be produced in a heavy downpour, resulting in the rapid disappearance of short gravity waves. The raindrops striking the forward face of an advancing wave do so with a higher relative velocity than those at the rear, where the water surface is moving downward; this results in a momentum flux, i.e., effective pressure on the water surface that is higher on the forward face than on the rear, so that energy is extracted from the short waves. The attenuation coefficient is simply the product of the rainfall rate and the wavenumber. In addition, the presence of rain may have more subtle effects by modifying the effective mean wind profile; these effects do not seem to have been considered at all.

Certain aspects of a complicated dynamical system can frequently be studied conveniently by examining its response to a perturbation of one kind or another; this involves analysis that is more detailed than the overall models provide. For example, of great importance to the remote-sensing community is the response of an established wave spectrum to passage through a field of variable currents. What is the magnitude of the spectral perturbations at different wavenumbers and what are the characteristics of the recovery of the spectrum after perturbation? Questions of this kind are more conveniently discussed in terms of the action spectral density $N(\mathbf{k},\mathbf{x})$ $= E/\sigma$, where σ is the intrinsic frequency of the component with wavenumber $\mathbf{k}$. In a distribution of current $U_i(\mathbf{x})$, the evolution equation becomes

$$\frac{\partial N}{\partial t} + (c_g)_i \frac{\partial N}{\partial x_i} - k_j \frac{\partial U_j}{\partial x_i} \frac{\partial N}{\partial k_i} = \text{R.H.S.} ,$$

where, again, several forms have been postulated for the right-hand side to represent the effects of wind, wave–wave interactions, and wave breaking. For example, Ref. 4 takes

$$\text{R.H.S.} = \beta N \left[1 - \frac{N}{N_0} \right],$$

where N_0 is the undisturbed spectral level. However, since the processes of wave–wave interactions among the gravity wave components and hence energy loss from wave breaking are cubic in the spectral density,[5] it would be better to take

$$\text{R.H.S.} = \beta N \left[1 - \left(\frac{N}{N_0} \right)^2 \right]$$

for those wave components in the equilibrium range, far from the spectral peak. For them, a spectrally local representation is possible, although that is certainly not appropriate for those near the spectral maximum. It might be argued that for gravity-capillary waves where the wave–wave interactions are quadratic in N, an expression of Hughes' form[4] might be preferable, but that seems to be on weak physical grounds. The triad interactions among gravity-capillary waves are not local on the wavenumber plane and the extent of their spectral range is small, so that a spectrally local expression for the energy transfers is hard to defend.

Be that as it may, a simple model like this seems able to account for the phase and (somewhat less accurately) magnitude of the response of short gravity waves that are sensed by L-band radar when they encounter the surface strain field associated with the presence of strong internal waves. Figure 1 shows results from the SAR-SEX experiment[6] comparing the relative intensity of the SAR image with calculations based on currents comput-
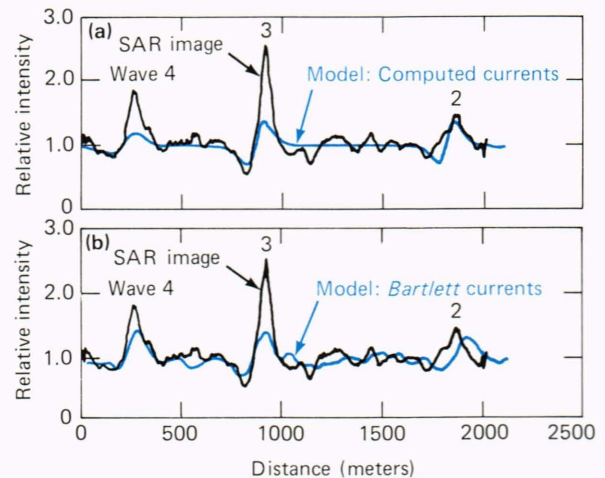

Figure 1—A comparison of the predicted (a) and measured (b) L-band SAR modulations produced by subsurface internal waves, from the SARSEX experiment.

ed from a simple model and on surface currents measured. These comparisons are encouraging but are still not definitive; a careful study of the response to such perturbations might in fact enable us to determine the wind-coupling coefficient, β, more precisely than present methods involving analysis of spectral growth permit.

At X band, however, we have a problem. For short waves in the gravity-capillary range, β is very large. These wavelets respond very rapidly to the wind; their time scale for response is much shorter than the time taken to traverse the strain field, so they are always very close to their equilibrium value. Their memory is so short that they do not know that they are in a strain field. Yet, as Fig. 2 indicates, the measured X-band response is quite comparable to the L-band variation. One thing is quite clear: whatever produces the X-band modulation is not the direct interaction of centimeter-scale waves with the variable current.

Do we therefore infer that whatever produces the X-band return is not Bragg scattering from the centimeter-scale waves? This may be partly or largely true, but not necessarily. It is conceivable that modulations in the longer, but still short, gravity waves surrounding the L-band waves might secondarily produce modulations in parasitic capillaries or other small-scale wave features. But that hypothesis is rather tenuous and difficult to subject to a rigorous test. The question is an important one. Sea-surface features at these scales are responsible for scatterometer signals upon which wind-speed measurements depend; the fact is that we do not know with any assurance what mix of sea-surface features produces the signals. Bragg scattering may sometimes not play a dominant role at all. There are several independent sets of measurements that indicate this. A number of years ago,
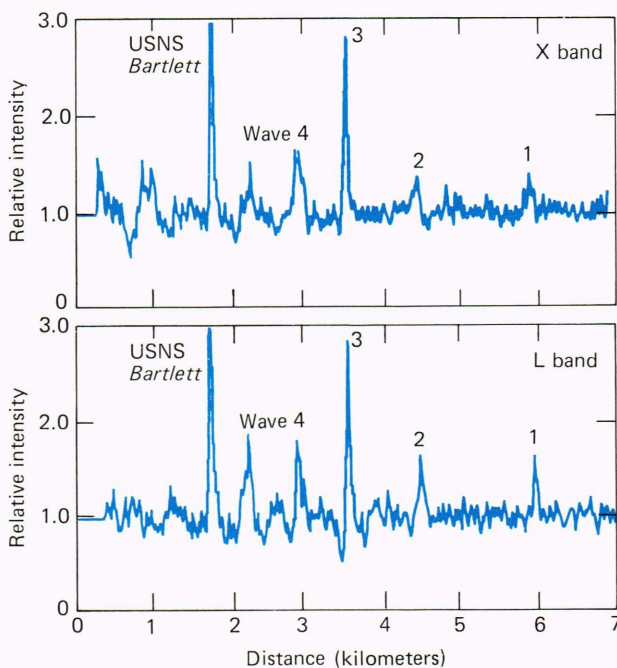
Lou Wetzel of the Naval Research Laboratory identified sea spikes as a prominent part in the return. They are intermittent spikes of high return, with a Doppler shift associated with longer wave speeds and lifetimes of fractions of a second. He suggested that the spikes may be returns from individual breaking events. Under certain conditions, they constitute a substantial fraction of the total return. Laboratory measurements by Banner and Fooks[7] have confirmed that individual breaking events in the laboratory produce intense returns; Kwoh and Lake[8] at TRW have performed calculations that indicate the same effect.

It seems that, for some applications, we need to have a much more detailed understanding of the structure of the sea surface than a simple overall spectrum can provide, even when combined with knowledge of the probability structure of the sea surface. One question is this: what is the expected length $\Lambda(\mathbf{c})d\mathbf{c}$ of the breaking front per unit area of sea surface, associated with breakers in the interval $\mathbf{c}, \mathbf{c} + d\mathbf{c}$, of speeds of the front's advance? The scale of breaking is characterized by this speed of advance, and operators of a drilling platform would like to know the expected rate at which breaking dominant waves will encounter their structure under extreme conditions. At the other end of the scale, microscale breaking does not produce air entrainment but turns the surface over and generates small-scale structures that can produce X-band returns. In the equilibrium range, we have a theoretical prediction[5] of this quantity:

$$\Lambda(\mathbf{c}) \; d\mathbf{c} \; = \; (\text{const}) \; \cos^{3/2} \theta \; u_*^3 \; g \; c^{-7} \; d\mathbf{c} \; ,$$

where u_* is the friction velocity, θ is the angle to the wind, and all other terms have been previously defined. There are no observations with which this prediction can be compared, and we have as yet no direct indication of its accuracy or range of applicability.

What is the relative modulation in the density of breaking events at various scales induced by variable currents or by internal waves? This is a question that can be addressed using recent models for the dynamics of the equilibrium range. The models may produce a framework in terms of which the SARSEX[6] X-band results can be interpreted, and, by inference, shed light on the surface features responsible for scatterometer returns.

Questions abound. Is there a high wavenumber cutoff for short gravity waves? Theory suggests that there might be under high wind conditions; short gravity waves may be erased from the ocean surface, and that effect, if it occurs, also has profound implications for remote sensing. There are not yet any observations pertinent to this question. They would require small-scale measurements of the wavenumber spectrum or of the structure function; there are worthwhile attempts to make the measurements. They do, however, rely on the same stereo-photographic techniques of wave measurement pioneered by Pierson many years ago, and the labor and expense of analyzing the stereo pairs are much the same now as they were then.

What are the physical laws governing subsurface bubble generation by breaking waves? How do the charac-

Figure 2—L-band and X-band slant range traces; *Bartlett* track, pass 6 of the SARSEX experiment.

teristics of the breaking wave determine the number density, size distribution, and depth dependence? I do not know any good theoretical ideas pertinent to these questions, but observations are beginning to be made using sonar. To be valuable, the measurements must be coupled with detailed and simultaneous measurements of wave-breaking events; this poses quite substantial logistics, measurement, and analysis problems.

To be sure, wave prediction has come a long way in the last 40 years, but there are still many unanswered questions.

REFERENCES

[1] SWAMP Group, *Ocean Wave Modeling*, Plenum Press, New York (1985).

[2] G. J. Komen, S. Hasselmann, and K. Hasselmann, "On the Existence of a Fully Developed Wind-Sea Spectrum," *J. Phys. Oceanogr.* **14**, 1271-1285 (1984).

[3] S. Hasselmann and K. Hasselmann, "Computations and Parameterizations of the Nonlinear Energy Transfer in a Gravity Wave Spectrum," *J. Phys. Oceanogr.* **15**, 1369-1377 (1985).

[4] B. A. Hughes, "The Effects of Internal Waves on Surface Wind Waves, 2. Theoretical Analysis," *J. Geophys. Res.* **83**, 455 (1978).

[5] O. M. Phillips, "Spectral and Statistical Properties of the Equilibrium Range in Wind-Generated Gravity Waves," *J. Fluid Mech.* **156**, 505-531 (1985).

[6] D. R. Thompson, "Intensity Modulations in Synthetic Aperture Radar Images of Ocean Surface Currents and the Wave/Current Interaction Process," *Johns Hopkins APL Tech. Dig.* **6**, 346-353 (1985).

[7] M. L. Banner and E. H. Fooks, "On the Hydrodynamics of Small-Scale Breaking Waves and their Microwave Reflectivity Properties," in *The Ocean Surface*, Y. Toba and H. Mitsuyasu, eds., Reidel, Dordrecht, Holland, pp. 245-248 (1985).

[8] D. S. Kwoh and B. M. Lake, "The Nature of Microwave Back Scattering from Water Waves," in *The Ocean Surface*, Y. Toba and H. Mitsuyasu, eds., Reidel, Dordrecht, Holland, pp. 249-257 (1985).