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SYMPOSIUM OVERVIEW

SETTING THE STAGE

Intelligent management and appropriate use of our coastal environments could not proceed without detailed knowledge of the characteristics and climatology of water waves. Over the past 40 years or so, the scientific and engineering communities have developed an impressive arsenal of theoretical and experimental tools to describe the ocean surface in terms of probability distributions and spectra. With few exceptions, the wave data collected have been time histories of surface elevation (or related parameters) at selected locations yielding statistics of extremes that could be used to estimate forces on structures and responses of ships (*Bales**). Although it is clear to the most casual observer that wind-waves are short-crested with appreciable spread in propagation directions, experimental methods to assess the directional properties of waves have become practical only in the last few years. Their operational use is still quite uncommon. Of the many methods that have been devised and applied as research tools, only accelerometer buoys meet the practical needs of deep-water operational wave monitoring.

CONVENTIONAL METHODS

Accelerometer (heave) buoys and their directional counterparts (heave-pitch-roll buoys) have become wave-measurement standards. However, their directional resolution is relatively coarse, and typical time histories are too short to yield sufficient degrees of freedom for accurate spectral estimation (*Pierson*). Nonetheless, a great deal of the store of general wave information has been derived from buoy measurements, and immediate local information is most readily obtained therefrom. For example, disposable buoys can be useful in tactical naval operations (*Bales*); someday, they may also provide useful information for commercial shipping in high and confused seas. Planning of ship routing must, of course, rely on wave forecasts provided by numerical models that are based on wind forecasts. Such predictions (*Cardone, Zambresky, Komen*) are cast in the form of medium-resolution directional spectra, typically 15 degrees and 0.01 hertz. However, wave spectra by themselves are inadequate descriptions of wave groups (*Mollo-Christensen*). More detailed information is required in order to assess the likelihood of extreme waves and nonlinear responses of ships and structures and to understand wave-group dynamics.

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*Parenthetical italicized names refer to the articles/comments by authors/panel members later in this symposium record.

UNIQUE CONTRIBUTIONS OF REMOTE SENSING

Modern remote-sensing methods have shed new light on the characteristics of wave propagation. Trizna et al.,[1] using shore-based HF radar, have demonstrated that the directional spread is considerably narrower than had been suggested by buoy measurements. Fine-resolution airborne systems[2,3] have confirmed these findings, as have spectra from multigauge arrays.[4] The surface contour radar (SCR) has been used to track the approach to full development in an offshore wind (*Walsh et al.*). Hitherto, the concept of full development has been accepted on the basis of single-point time histories that suggest that the phase speed of waves at the peak of the spectrum seldom exceeds the average wind speed by more than 20 percent. Airborne measurements from the SCR provide the first unequivocal evidence for approach to full development. The same airborne measurements can also resolve the highly confused sea in the vicinity of hurricanes.

The primary radar-scattering mechanism at moderate wind speeds and incidence angles away from zero is believed to be Bragg scattering. Its high selectivity for a particular vector wavenumber provides a method for exploring the behavior of wavenumber spectra of short waves, for measuring wave phase speeds, and for determining surface currents.[5] Such techniques have revealed that upwind-traveling waves always exist on wind-disturbed water surfaces, a phenomenon unsuspected from buoy measurements. Although the energy contained in these waves is very small (less than 1 percent in moderate winds),[6] they provide sensitive probes of the air/sea interface.[7]

REACHING FOR A GLOBAL PERSPECTIVE

As important as these contributions from shore-based and airborne remote-sensing systems are to wave research, they can never hope to provide the global perspective needed for many applications. The importance of a global perspective to our understanding of the effect of air–sea interactions on the coupled ocean–atmosphere systems as a whole is pointed out several times in the panel discussion. For example, cyclogenesis often occurs near oceanic fronts (*Mollo-Christensen*); gas transfer from ocean to atmosphere and mixed-layer deepening are important wave-related effects (*Kitaigorodskii*). A knowledge of sensible and latent heat fluxes from the ocean is important for storm prediction (*Donelan*). All these processes are influenced by the state of the sea. Thus, if they are to be understood in enough detail to impact weather forecasting or our knowledge of global climate, the influence of surface waves must be included. This can only be done if adequate global measurements of surface waves can be obtained.

The need for a global wave climatology is stressed repeatedly in the panel discussion. Also, a several-year record of accurate wave measurements on a global scale is necessary if naval architects are to take the next step in improving ship design (*Bales*). Such a climatological base is also necessary for the design of fixed and floating platforms important to the oil industry and other marine commercial ventures. A single satellite cannot provide an adequate base for such climatology, no matter how accurately it measures directional wave spectra, because the time necessary to obtain complete global coverage or to repeat a measurement at a single location will be several days or even weeks. The probable alternative to an expensive, multisatellite wave-measuring system will be a combination of global satellite measurements with advanced wave-prediction models to obtain the necessary climatology.

Wave models capable of making global predictions of directional-wave spectra have only recently become available (*Cardone, Zambresky, Komen*). In the past, assessments of model accuracy have been carried out either by comparison with buoy measurements of significant wave height and nondirectional spectra or by comparison with other models (*Cardone, Zambresky*). Only recently have comparisons with remotely sensed directional wave measurements become possible; they indicate some problems in model predictions of both direction and height when not tightly coupled to auxillary measurements (*Beal*). Wave breaking is one source of error that may be difficult to incorporate correctly (*Phillips*). In any case, model improvements will be necessary if their results are to be used along with sparse satellite measurements to develop an accurate global wave climatology.

In several ways, the satellite measurements themselves can provide a major avenue for the improvement of wave models. At present, most models are self-initialized from their own previous forecasts, a method that encourages the propagation and growth of model errors. Assimilation of accurate global measurements of directional spectra into wave-prediction models for initialization and updating will alleviate this problem. Already the assimilation of in-situ measurements has been shown to improve model predictions (*Komen*). Global wave measurements will further allow important special, possibly simple, conditions to be identified and used for systems-simulation experiments (*Cardone*). For example, wave measurements made in regions of variable fetch or turning winds could be compared with model predictions to facilitate model assessment and improvement.

The most important factor in predicting accurate directional wave spectra is probably the accuracy of input wind fields; here again, global estimates of directional wave spectra are important. Satellite-based scatterometers currently offer promise of providing global wind fields for use in wave prediction. Evidence is accumulating, however, that long surface waves affect the relationship between the radar backscatter measured by scatterometers and the wind vector that is the final product. To date, the assumption has been that the most important long waves affecting scatterometry are those generated locally by the wind, and that those waves have had sufficient time and fetch to reach their equilibrium condition. Recent aircraft measurements are beginning to call this assumption into question.

Satellite-based estimates are indicating that the local waves are rarely in equilibrium (*Beal*). Thus satellite-based wave measurements made simultaneously with scatterometer measurements will probably be necessary in the future in order to obtain accurate wind fields in many of the most important conditions, such as stormy areas near fronts. Long waves affect the growth of the wind sea (*Donelan*); the pronounced changes observed in the laboratory may be due to modifications in nonlinear transfers in the wind–sea spectrum caused by the presence of long waves. This fact, together with the possibility that nonequilibrium wave fields may modify the wind–wind stress relationship (*Cardone*), further underlines the need for satellite-based measurements of the longer waves.

Other studies (*Irvine*) indicate the strong possibility that global wave-prediction models will not be highly accurate until global circulation patterns are included in the models. The modification of wave fields by current shears certainly occurs, but it has been little addressed in most wave models. Developments in wave–current interactions and wave dissipation may lead to the next generation of wave models (*Green, panel discussion*). Such wave–current interactions are probable sources of the extreme waves that can severely damage ships. Study of these interactions is difficult in the laboratory and appears to be feasible in the field only with the aid of remote-sensing techniques. Applied on a global basis, these techniques will allow such interactions to be studied, understood, and included accurately in wave models.

Finally, at least two additional areas exist in which global wave measurements are important. First, such measurements can provide data with which to improve transoceanic ship routing, with obvious implications for maritime safety and economy of operation. Directional-wave information is not only important in overall route planning but in local maneuvers that can save ships in heavy seas: a change of heading of as little as 30 degrees may be enough to save a ship from damage (*Bales*). Second, surface wave motions are responsible for much of the acoustic background detected by sonars (*Phillips, panel discussion*). With global monitoring of directional waves, the connection could be made quantitative, and predictions of global levels of surface-generated acoustic noise levels might be feasible.

TECHNIQUES FOR GLOBAL REMOTE SENSING OF DIRECTIONAL WAVE SPECTRA

Several remote-sensing techniques can estimate directional wave properties (*Plant*). Of these, the Radar Ocean Wave Spectrometer (ROWS), the Three-Frequency Airborne Radar (TRIFAR), and the Synthetic Aperture Radar (SAR) are all possible candidates for spaceborne application. However, all three have the disadvantage of yielding wavenumber spectra with a 180-degree ambiguity in the direction of wave travel, a problem that will have to be addressed in their applications. All three techniques yield spectral estimates with a large number of degrees of freedom (i.e., high statistical precision) and with directional resolution never before possible (*Plant; Pierson, panel discussion*). Their high statistical precision is offset, however, by the fact that none of them measures wave height directly. Spectral density must be inferred using an estimated or modeled transfer function, so their overall accuracy depends on an accurate knowledge of their transfer functions. The appropriate analysis of remote directional spectra must be performed carefully and in the context of comparisons with buoys (*Pierson*).

For ROWS and TRIFAR, the transfer function is rather well known. ROWS has been aircraft tested for several years and has been demonstrated to estimate directional spectra accurately. TRIFAR is only now being developed into a routine wave-measurement system, although the technique has been demonstrated from both fixed platforms and aircraft.

SAR is the only one of the three techniques to have been flown in space. Comparisons of its output spectra with those of airborne sensors have demonstrated that its ability to resolve waves traveling in its flight direction is severely restricted at shorter wavelengths. This problem can be alleviated by choosing a low spacecraft altitude with a lower range-to-velocity ratio. SIR-B was in such an orbit and produced wave spectra whose spectral shapes usually agreed well with those obtained by aircraft sensors. However, the most favorable comparisons resulted from wave systems of relatively low dominant slope. Serious questions remain about the fidelity of SAR-produced spectra for steep wave slopes (*Lyzenga, Monaldo, Beal*).

A candidate low-altitude operational satellite designated "Spectrasat" (*Beal and following articles*) would combine three instruments: a SAR, a ROWS, and a radar altimeter. While the radar altimeter would provide absolute calibration of total wave-height variance, the fidelity of the SAR spectral shapes is still subject to the concerns noted above. Also, the absolute calibration method could be subject to substantial errors in rapidly changing seas, since the SAR and altimeter would typically be offset from each other by 150 kilometers. One alternative to Spectrasat for the operational monitoring of directional spectra might be a satellite carrying ROWS alone. That vehicle would not be restricted to such low orbits and thus could be implemented in a more conventional (low-drag) orbital configuration. On the other hand, of the three viable spacecraft approaches, only the SAR provides an image of the surface that might allow an estimate of extreme wave statistics as well as their spatial "groupiness" (*Tilley*), so that for research purposes of the sort addressed by *Mollo-Christensen,* the SAR may be the best solution at present.

TOMORROW

The collection of articles in this record highlights the tremendous potential of global directional-wave measurements. From the perspectives of many researchers with overlapping interests, it is clear that we are close to being able to make wave measurements of types and on scales never before possible. We are left with several challenges for the future. We must continue to test, evaluate, and apply the sophisticated remote-sensing techniques that are now available for directional-wave measurements. But we must also decide how to obtain, archive, and exploit the huge amount of data that would be produced by a satellite system. Finally, and most importantly, we must persuade those who would ultimately use global wave measurements that the benefits of the information greatly outweigh the cost of obtaining it.

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