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WAVE BREAKING IN DEEP WATER

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INTRODUCTION

Every mariner is aware that dangerous large breaking water waves occur on the world's oceans. The scope of this review is somewhat greater. Wave breaking occurs at a large range of scales and we do not restrict ourselves to the deep ocean. "Deep water" in the context of water wave studies implies water sufficiently deep that the surface waves are unaffected by the direct effects of variations in bed topography. Thus even a small pond can support breaking deep-water waves. Shallow water breaking is reviewed in Peregrine (1983).

Some comments on the visual aspect of breakers are in order, since direct observation still has a role to play in the study of this complex phenomenon. The most dramatic breakers are plunging breakers where the breaking commences by the wave overturning and forming a forward moving sheet of water which plunges down into the water in front causing splashes, air entrainment, and eddies. Although plunging breakers are common on beaches they are less common on deep water, so much so that some people have argued that they do not occur naturally. However, read Coles (1991) for a distillation of an experienced yachtsman's account of waves at sea.

Most other breakers are described as spilling breakers. From their

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initiation, "white water" falls down the front face of the wave. The falling water appears white because of entrained air bubbles and drops created at the surface. On a small scale, say wave crests less than 4 cm high, surface tension is sufficiently strong to prevent air entrainment. Such small breakers are as a result often overlooked. However, recently their significance has been realized and the term "microscale breakers" is being used (see Figure 1).

The water waves are usually generated by wind with breaking playing a significant part in the growth of waves. In addition, the turbulence directly associated with breaking is dominant in mixing processes beneath the free surface and thus is crucial to the transfer of heat and mass. This transfer is vital—on small scales for aquatic life and water quality, and on global scales it is an important factor in the Earth's weather and climate. Transfer of CO_2 to the oceans is one influential factor in the debate on global warming.

Of more obvious concern to the layperson is the safety of vessels and structures at sea. Modern ships are not immune to severe damage, or total loss due to breaking waves. Smaller ships such as trawlers capsize; larger ships suffer structural damage which may be life threatening. For routing commercial vessels away from severe wave conditions remote sensing of the sea surface gives valuable data. Radar signals backscattered from the

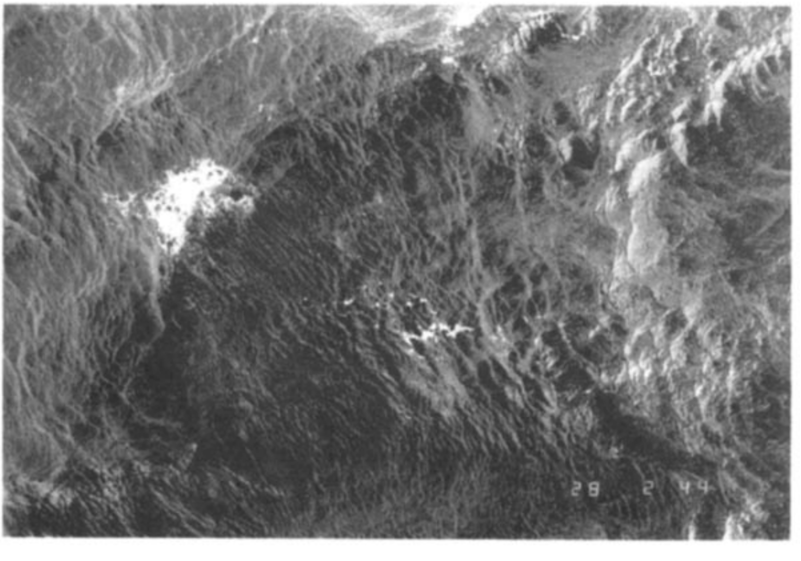

Figure 1 An area of wind blown water surface 4 m × 3 m, showing a small spilling breaker and a lot of microscale breaking. (M. L. Banner)

sea surface to satellite-borne instruments can be used to provide directional data on wave heights and wind speeds. The role of enhanced local radar backscatter from breaking waves is yet to be resolved.

Wind-generated waves are not the only ones that break. Ships generate waves when they move, and it is usual for these waves to be breaking in the vicinity of the ship. In some ways these are simpler than wind waves since in an otherwise calm sea the forcing motion is well-defined, and except for water involved in the breaking process the main part of the water has no vorticity.

The bulk of water-wave theory is for linear waves. This only provides a good approximation for waves with gentle slopes and hence gives little or no insight into breaking. However, the linear wave properties of superposition, energy density, and group velocity are at the core of one range of theoretical approaches. These describe the sea surface with a Fourier spectrum and use theoretical and empirical terms to describe the evolution of the sea state. These often include nonlinear interactions, wind input, and breaking. This last term is, perhaps, the least well known and may simply include all dissipative effects necessary to fit the data used to refine the model.

Direct study of the hydrodynamics of breaking is difficult since it is an unsteady phenomenon. However, weakly nonlinear theory can give an indication of when breaking is likely to occur. Numerical approximations can do better. "Numerically exact" solutions for two-dimensional steadily traveling waves provide the basic flow for stability calculations. Direct numerical modeling of the wave overturning is also possible. In all cases this work is limited to flows with zero or constant vorticity.

Once a wave breaks, splashing, turbulence, and air entrainment make theoretical modeling difficult. Even so, some simple models of spilling breakers do seem to give reasonable results.

MEASUREMENT IN THE FIELD

Detection Methods and Problems of Quantification

It is generally recognized that an individual wave breaking event usually starts when water particles near a wave crest develop a velocity in the wave propagation direction sufficiently large for them to fall down the front of the wave. However, the surface fluid speed is difficult to measure in the field and consequently there have been a number of indirect approaches used to detect and quantify wave breaking. These depend on a surface geometry signature such as a jump in the slope of the water surface at the toe of the breaker, or on locally enhanced properties associated with the breaking such as optical contrast, high frequency energy, radar reflectivity, or acoustic output. While whitecapping provides a familiar visual signature, widespread breaking of very short gravity wind waves occurs without air entrainment in the form of microscale breakers, and their lower visual contrast makes them far more difficult to detect unambiguously using optical methods as is evident in Figure 1. Progress with detection techniques is reviewed below, together with the closely related question of quantification, for which the introduction of more detailed classification criteria such as length scale and directionality further complicates the detection problem.

Phillips (1985, section 6) provides a useful discussion on the statistical quantification of breaking in the wind-wave spectrum, based on the underlying probability distribution $L(\mathbf{c})$, such that $L(\mathbf{c})d\mathbf{c}$ represents the average total length per unit surface area of breaking fronts that have intrinsic velocities in the range $\mathbf{c}$ to $\mathbf{c}+d\mathbf{c}$. Various statistical measures of interest may be derived from this basic distribution, such as the total number of breakers past a fixed point, the fraction of sea surface turned over per unit time, the whitecap cover, and the momentum and energy fluxes associated with breaking events. However, techniques for measuring $L(\mathbf{c})$ are not well-established, and the available data on wave breaking relies on the less direct methods mentioned earlier which are discussed more fully below.

Optical Detection Methods

Of the above derived statistics, the whitecap cover has received the most attention through systematic measurements of its variation with wind speed and atmospheric stability. Whitecap cover is an important parameter that influences the sea surface microwave brightness temperature and shortwave albedo which are both important in passive remote sensing of the sea surface. It is also a useful measure of the rate at which bubbles are injected into the oceanic mixed layer. Modern video recording and image processing techniques have been particularly useful for whitecap cover measurements. However, interpretation of whitecap cover statistics in terms of active breaking is not straightforward, owing to the persistence of "fossil" foam. Efforts have been made in this direction through visible albedo classification as type A (young) whitecaps and type B (mature) whitecaps (Monahan & Woolf 1989). Interestingly, in fresh water, the onset of whitecapping requires a higher wind speed and the whitecap cover at a given wind speed is lower by a significant margin when compared with ocean data (Monahan 1969). These effects appear to be due to the surface chemistry influence of salt on the formation and coalescence characteristics of air bubbles (Scott 1986), which results in the greater persistence of the smaller bubbles that occur in salt water (Monahan 1969, Scott 1975). In the open ocean, type A whitecap cover is observed to be a little stronger than cubic in the wind speed, with a weak dependence on the atmospheric stability (air-sea temperature difference) and on the sea surface temperature. Type B whitecap coverage is similar, but with a somewhat weaker wind speed and atmospheric stability dependence. Monahan & O'Muircheartaigh (1986) give a useful overview of whitecaps in the context of passive remote sensing of the sea surface and recent research aspects are described in the research symposium monograph edited by Monahan & MacNiocaill (1986).

Wave Gauge Detection Method

Although whitecap cover is accessible with relative convenience, more fundamental parameters associated with breaking are often of interest. Other studies of breaking statistics have involved visual detection of whitecaps passing a fixed location at which wind and wave parameters are monitored. This technique was used by Holthuijsen & Herbers (1986), whose study provided interesting data on the joint breaking probability distribution with respect to wind speed, wave period, and wave height. They demonstrated the inadequacy of using a simple local wave slope criterion to detect breaking and the rather marginal significance of the joint wave height and period distribution as a basis for extracting breaking statistics. An innovative point detection method used by Longuet-Higgins & Smith (1983) and Thorpe & Humphries (1980) relies on the rapid jump in surface elevation at the leading edge of the spilling region of a breaker. This technique used a floating spar with a fine wire wave gauge (called a "jump-meter') to make the detections, but the choice of jump threshold is not known a priori and may be responsible for the relatively low breaking probabilities reported by this method.

Weissman et al (1984) investigated the use of a high frequency analysis of wave height data from a fixed wire gauge at short wind fetches and low wind speeds to detect the passage of breaking events. According to their findings, increased wave energy levels in the high frequency range are associated with breaking events, and a threshold level can be used to detect the passage of a breaking crest past the sensor. Recently, this technique has been refined by Katsaros & Atakturk (1991). However, further field studies are needed to examine the validity of this technique under open ocean conditions, where high frequency wave measurements are more difficult and Doppler distortion of the high frequency elevation spectrum is likely. Figure 7 in Holthuijsen & Herbers (1986), reproduced here as Figure 2, summarizes the observed fraction of breaking waves as a function of wind speed reported by these various detection methods; it is evident that there is considerable scatter among the statistics based on these methods. Thus appropriate care needs to be exercised when interpreting such data and future work will need to reconcile these differences.

Radar Methods

Narrow-beam Doppler radars with footprint dimensions much smaller than the dominant waves have also been used to detect large-scale breaking events. The technique is based on measuring the significant increase in scatterer speed (from about the orbital speed to the phase speed) within breaking events (Keller et al 1986). A significant goal of such research is to estimate the contribution of reflections from breaking waves to the radar backscatter cross section in remote sensing applications. The underlying physical mechanisms and choice of the most suitable threshold to identify breaking events have been examined in a series of recent papers by Jessup and co-workers (1990, 1991a, 1991b). Depending on the spike classification criterion adopted, the contribution from spike events due to large-scale

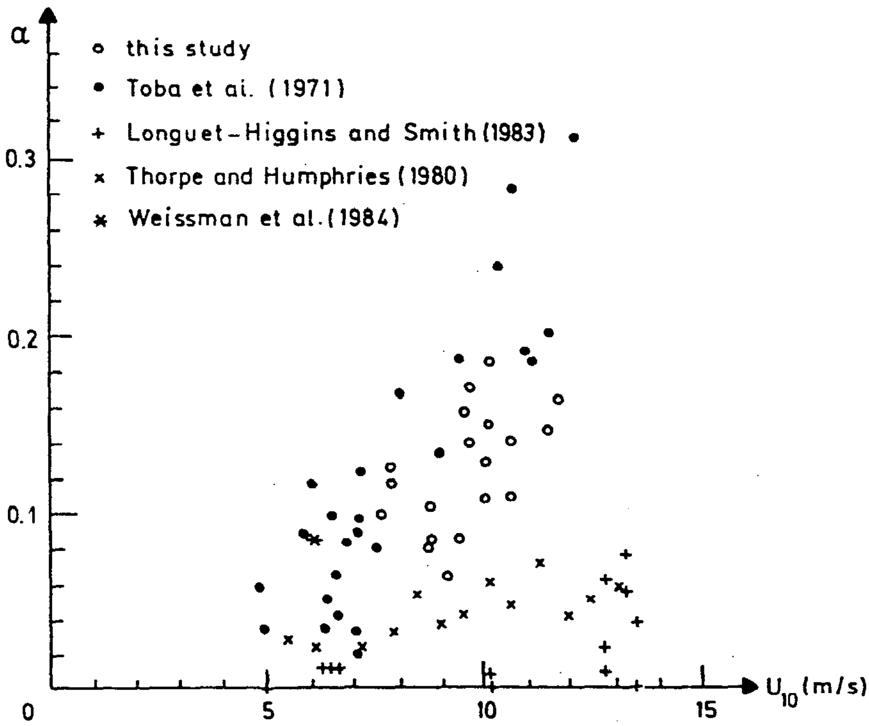

Figure 2 The observed fraction of breaking waves (α) as a function of wind speed (U_{10}) from Holthuijsen & Herbers (1986), with permission of American Meteorological Society.

whitecap events was assessed as 10–20% of the radar cross section. Based on their detailed analysis of radar returns and collocated video images of the sea surface, Jessup et al (1991a) concluded that the increased Doppler bandwidth provided the most consistent signature of sea spikes associated with large-scale wave breaking, but the spatial resolution limitation inherent in the $O(1$ m) scale of the radar footprint precludes a complete understanding of the physical mechanisms involved. Thus while considerable progress has been made, further effort is still needed to refine our understanding of microwave reflectivity associated with breaking waves at sea. In particular, the possible contribution to the backscattered cross section from microscale breaking waves remains to be addressed.

Acoustic Methods

It is a familiar experience that whitecaps produce noise associated with the dynamics of the entrained air bubbles. A detailed field study from a tower in the Bight of Abaco was reported by Snyder et al (1983) in which the acoustic output from large-scale whitecaps was used to trigger a rapid sequence of photographs, covering an area of 10 m x 10 m. A wave gauge array in the field of view monitored the directional wave spectrum. This study allowed a detailed examination of the correlation between the onset of whitecapping with a threshold based on the local vertical acceleration threshold, providing qualified support for this concept. It also provided very useful statistics of low order temporal and geometrical whitecap statistics. Breaking also contributes significantly to the ambient underwater noise spectrum which can be measured with a hydrophone. This provides a potentially useful method for remotely sensing the wind speed since whitecapping is strongly dependent on wind speed (e.g. Lemon et al 1984). The ambient noise produced by whitecaps has been exploited to extend our present knowledge of their basic properties. Farmer & Vagle (1988) deployed a vertical hydrophone array to investigate the properties and distribution of whitecap events and the influence of their bubble clouds on the ambient noise field generated by the whitecaps. More recently, within the SWAPP (Surface Waves Processes Program, Weller et al 1991), Farmer has deployed an acoustic drifter instrument package with the capability of monitoring bubble cloud distributions and directional ambient sound characteristics. Such studies are providing substantial new information on the fundamental properties of ocean whitecaps and their associated acoustic properties.

Present Status

Field results on breaking statistics for whitecaps from the various observational techniques show well-defined trends with wind speed, but are characterized by very considerable scatter. Some of this is undoubtedly due to the breaking detection criterion adopted, while some is likely to be due to environmental influences. Insufficient field data are available on the distribution of whitecapping with wavelength and none appear to exist on the directionality properties of whitecaps or on any aspect of microscale breaking. However, more data on such breaking wave statistics will follow with the presently increasing interest and attention of air-sea interaction investigators.

LABORATORY EXPERIMENTS

To circumvent the difficulties of field measurement, several investigators have reported laboratory studies of fundamental properties of breaking waves. Some studies have been concerned primarily with breaking detection and statistics, while other studies have focused on investigating basic properties of breaking waves.

Detection

While some authors have exploited the "jump-meter" approach (e.g. Xu et al 1986, Banner 1990), other authors have investigated the use of local wavetrain properties derived from the Hilbert transform of the wave elevation signal (Melville 1982, 1983; Hwang et al 1989). Visual detection techniques have been reported as well, using wave-by-wave flow visualization, (e.g. Koga 1984) and optical backscatter (Ebuchi et al 1987) to detect and describe characteristics of breaking wind waves. More directly, Melville & Rapp (1988) used horizontal surface particle velocity—detected by a novel use of laser anemometry—to register breaking occurrences in modulating wave groups. They investigated a range of fundamental aspects, including surface current enhancement and the validity of linking breaking events with necessarily large associated wave slopes. While highly desirable, extension of this direct detection scheme to the field is not yet feasible. Microwave backscatter signatures of breaking waves have also been investigated in laboratory studies (e.g. Kwoh & Lake 1984, Banner & Fooks 1985, Melville et al 1988, Loewen & Melville 1991) to assist with the interpretation of microwave backscatter from wind waves at sea. Such studies have motivated and guided investigation of sea spike returns in the ocean remote sensing context described earlier in this article.

A complementary goal of the laboratory approach has been to isolate and study the influence of wave breaking on a range of fundamental air-sea interfacial properties. Two modes—propagating and quasi-stationary—have been used. The use of the latter allows for considerable simplification in the instrumentation, avoiding the need for a surface-following servo-mechanism in certain classes of investigations.

Steady Flows

Steady breakers usually occur in the form of spilling breakers. In the laboratory, Banner & Melville (1976), Banner & Fooks (1985), Banner & Cato (1988), and Banner (1990) used a subsurface hydrofoil in an otherwise steady, uniform current to create such breakers as shown in Figure 3. These authors investigated, respectively, the existence of separation of the overlying air flow, the properties of the fluctuating flow in the spilling crest region and consequent increased radar reflectivity, mechanisms of underwater noise generation from breaking waves, and the augmented form drag associated with breaking waves when compared with unbroken waves. Battjes & Sakai (1981) used a similar configuration to investigate the mean velocity field and turbulence structure of the trailing wake from a spilling breaker, noting its similarity to a self-preserving turbulent wake.

In two comprehensive studies, Duncan (1981, 1983) towed a submerged hydrofoil at constant speed, examining in detail the relative contributions to the wave resistance from the breaking and nonbreaking trailing surface waves generated by the obstacle. Duncan found that the breaking wave contribution could exceed the latter by a significant margin. He also investigated detailed geometric and hydrodynamic properties of the break-

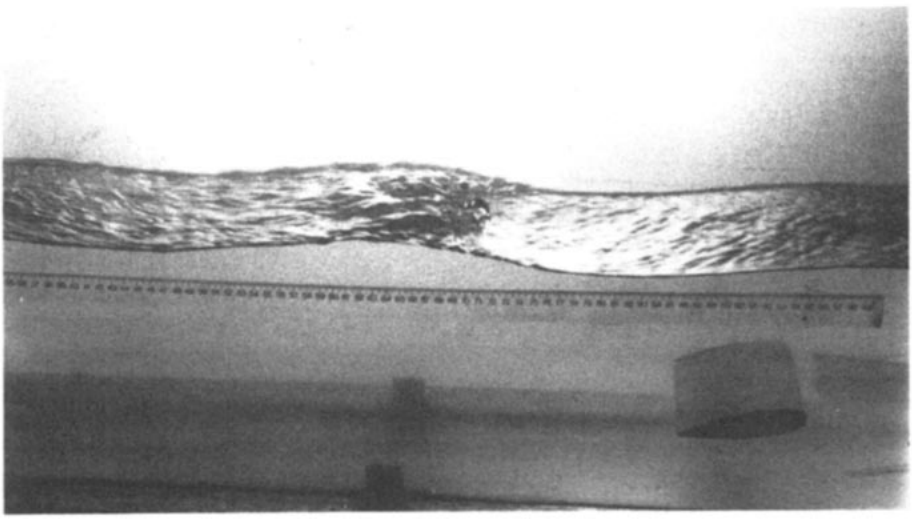

Figure 3 Quasi-steady spilling breaker generated in a laboratory flume by the submerged hydrofoil seen at the lower right side. (M. L. Banner)

ing region, observing that the drag associated with the breaking region was proportional to the downslope component of its weight. He also noted a persistent low frequency oscillation in the length of the breaking region, at about four times the intrinsic wave period. Banner (1987) also noted this surging characteristic in a laboratory investigation of the perturbation response of a quasi-steady breaking wave. Models that describe the steady state and such transient response properties of quasi-steady breaking waves are described later in this review. Based on the detailed measurements of Duncan (1981, 1983), Cointe (1987) published a more detailed and comprehensive theory of the dynamics of steady breaking waves, together with an analysis of their stability properties, and also described a numerical model for calculating unsteady breaker motion.

Unsteady Flows

Experimental studies of the details of unsteady breaking waves fall into various categories. The first are those where kinematic information that might be useful in predicting or estimating wave breaking occurrences is sought. The work of Kjeldsen & Myrhaug (1978), Bonmarin & Ramamonjiarsoa (1985), and Bonmarin (1989) fall into this category. Perhaps Bonmarin (1989) gives the most detail of how wave steepness and speed change as a deep-water wave approaches breaking. These studies define steepness in terms such as (wave height)/(crest to trough distance) and thus do not necessarily relate directly to wave overturning, or to portions of wave surface exceeding the maximum theoretical slope for steady waves of just over 30 degrees to the horizontal.

Descriptive studies of three-dimensional breaking waves have been made by Kjeldsen (1984) for a spectral distribution and by She et al (1992) where breaking of waves was caused by wave focusing in a wide tank.

Experimental studies that include comparisons between experiments and equivalent potential flow computations have been made by Kjeldsen & Myrhaug (1980), Dommermuth et al (1987), Skyner et al (1990), and Skyner & Greated (1992). In each case wave breaking was induced by focusing two-dimensional waves in space-time. That is, the frequency of the wave generated was smoothly reduced in such a manner that, if linear theory for slowly-varying waves were to hold, all wave energy would arrive at the same place at the same time. Agreement with computation is fairly good, though Dommermuth et al only computed one example and Kjeldsen & Myrhaug (1980) made only a general comparison. Skyner and co-workers measure velocity fields with Particle Image Velocimetry, and compute many examples, though with a linear time-to-space transformation of the initial waves. They find that the details of wave breaking are very sensitive to initial conditions, but in Skyner & Greated (1992) they report a remarkably good agreement between theory and measurement, even in the jet.

The most fundamental studies have been made by Rapp & Melville (1990). They have used the two-dimensional focused waves approach to examine in detail a range of isolated breaking wave events. From many viewpoints the most significant dynamical aspect of wave breaking is its efficacy in transferring momentum and energy from the surface wave motion into the underlying water motion. For example in wind-driven currents, the major transfer of stress is from wind to waves and waves to current; wave breaking is significant and dominant in the two transfers respectively. Rapp & Melville give measurements of the surface motion, momentum flux, energy changes, breaking induced currents, turbulent fluctuations, and surface mixing. For example, Figure 4 shows the ensemble mean velocity field generated by 10 repeats of a plunging breaker at 1, 4, 6, 10, 20, and 50 periods after the breaking event. Although it is too early to assess the full impact of this work, it should prove valuable for many purposes.

THEORY

Almost all theoretical studies of wave hydrodynamics relevant to breaking are for irrotational flow. For a long time there was little more than Stokes' (1880; see Lamb 1932, section 250) hypothesis that the steepest steadily traveling wave train would have a 120 degree angle at its crests. We now know that regular two-dimensional wave trains in deep water are liable to a number of hydrodynamic instabilities. All of these instabilities can lead to wave breaking if the initial wave train is steep enough.

Instabilities of Uniform Wave Trains

Tanaka's (1983, 1985) instability is more closely related to wave breaking than any other. Uniform wave trains have an energy density that does not increase monotonically with wave steepness (Longuet-Higgins 1975). At a steepness of $ak = 0.43$ ($H/L = 0.137$), the energy density has a maximum, and Tanaka showed steeper waves are unstable. Jillians (1989) showed how the unstable eigenfunctions are concentrated near the wave crest and used numerical methods to show how the instability eventually leads to the wave breaking.

Another instability which occurs for a wide range of wave steepnesses was found by Benjamin & Feir (1967) and Benjamin (1967): Infinitesimal long modulations of a wave train grow in amplitude until strongly modulated wave groups occur. Lake et al (1977) found further that, in a narrow wave flume the wave groups "demodulate" and a uniform wave train

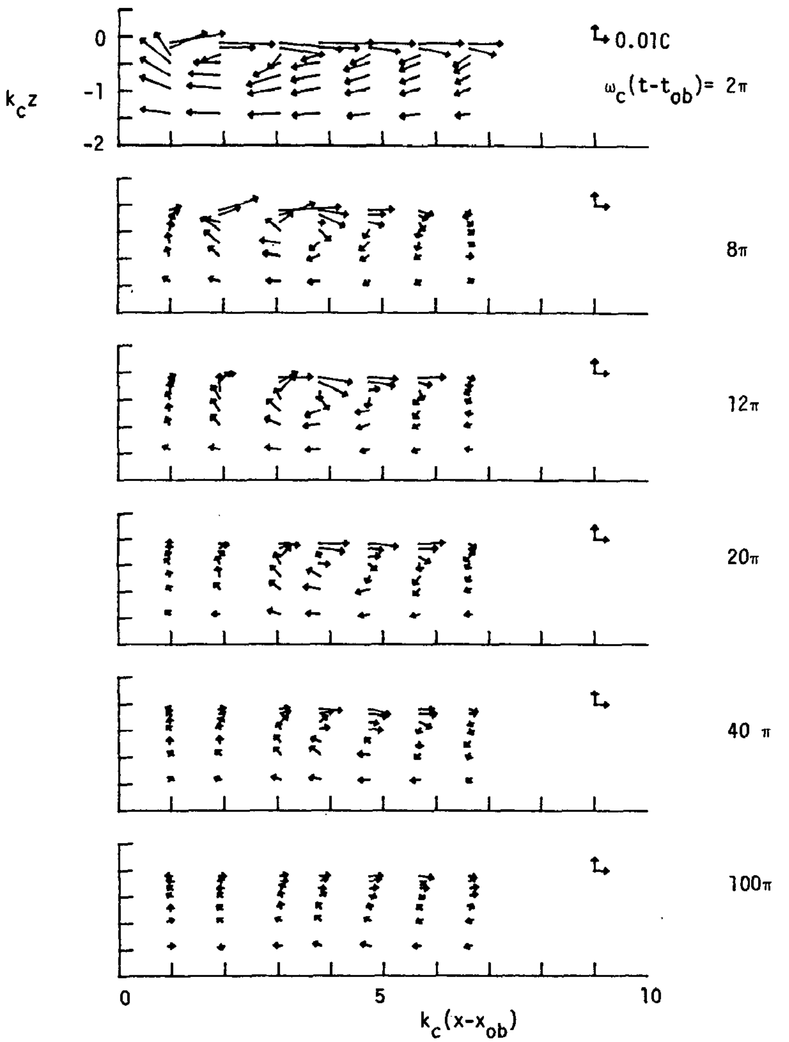

Figure 4 The mean velocity field at the following times after a plunging breaker occurs (from top to bottom at 1, 4, 6, 10, 20, and 50 periods); from Rapp & Melville (1990) with permission of The Royal Society, London.

recurs. For sufficiently steep waves the new wave train has a longer period than the original one, i.e. the waves experience a "frequency downshifting." This appeared to occur only when the waves at maximum modulation were breaking or close to breaking. Further experiments have been conducted by Su (1982), Su et al (1982), Melville (1982, 1983), and Chereskin & Mollo-Christensen (1985).

Computations for fully nonlinear irrotational examples of gently modulated waves show wave breaking occurring for wave trains of moderately gentle steepness—for example at a steepness which is one-quarter the maximum, which corresponds to an energy density of only one sixteenth of the steepest wave train of that period. A preliminary account of this work is given in Dold & Peregrine (1986). Interestingly, except for the increasing magnitude of the modulation most of the wave development is as one would expect from linear theory. The wave groups travel at half the phase velocity. Individual wave crests pass through the modulation and breaking first occurs when the modulation has grown "too big" and a crest passes through the maximum of the modulation. The details of wave breaking depend on the growth of the modulation and the precise timing of crests passing through the maximum so that details vary from example to example. In one case Dold & Peregrine obtained a wave with a crest very close indeed to the 120 degree angle which Stokes (1880) found for the limiting traveling wave.

Steeper deep-water wave trains also suffer an instability in which alternate crests grow at the expense of those in between. This instability was found by Longuet-Higgins (1978) and later shown to be a special case of a three-dimensional instability investigated by McLean (1982) and called Class II. Benjamin-Feir instability is a special case of McLean's Class I instability. The further evolution of the alternate crest instability, beyond the exponential growth of the linear hydrodynamic instability analysis, was computed by Longuet-Higgins & Cokelet (1978) who also found that the waves broke. Su (1982, figure 10) shows experimentally generated waves which are breaking after developing a three-dimensional instability which appears to be an example of Class II instability.

Rayleigh-Taylor instability of an interface has often been cited as a possible cause of wave breaking. This instability occurs if pressure in the denser fluid is less than in the lighter fluid, as when water is at rest over air. Numerous computational studies (P. McIver & D. H. Peregrine, unpublished) revealed no examples for irrotational waves, other than very weak, poorly defined, small regions at the tip of jets. On the other hand, study of steady waves on flows with vorticity shows that with sufficiently strong vertical shear, waves are unstable. See Teles da Silva & Peregrine (1988).

The instabilities which clearly contribute to the variable amplitude and short crests of many deep-water waves make it difficult to advance a "breaking criterion" such as is often used for the rather different circumstance of waves on beaches.

Unsteady Flow

Despite the fact that overturning waves are unsteady two-dimensional flows with a free surface, some progress has been made towards an analytical description. Longuet-Higgins (1980) suggests that a solution for a rotating hyperbola falling under gravity could represent the motion at the tip of the jet. New (1983) found that the curve of the face of waves underneath a jet is often well described by an ellipse, and found unsteady solutions for flow around an elliptical free surface. More comprehensive, but approximate solutions have been described by Greenhow (1983) and Jillians (1988). One feature of all these analytical solutions is that they have several free parameters. In addition, details of computed solutions show that the similarity of breaking waves apparent to the eye does not survive close inspection. The initial size, direction, and velocity of the jet can vary substantially as well as its size relative to the rest of the wave.

Full details of the wave profile, velocity field, and pressure fields in waves as they overturn and form jets are obtainable from detailed unsteady numerical computations. These all follow Longuet-Higgins & Cokelet (1976) in using boundary integral methods, but more robust, more accurate, and more efficient integration schemes have been developed. The most striking feature discovered from those computations (Peregrine et al 1980) is that the water rising up the front of the wave into the jet is subject to large accelerations. Typical computed maxima are around $5g$, where g is the gravitational acceleration. New et al (1985) give details of profiles, velocities, and accelerations of a few waves.

The traditional criterion for wave breaking is that horizontal water velocities in the crest must exceed the speed of the crest. This appears self-evident, but from detailed flow fields it is found that since the crest shape is changing there is often no precisely relevant crest velocity. Rather, there is a range of velocities which roughly correspond to crest speed, and water velocities usually exceed these by appreciable margins.

Much work has been done with deterministic two-dimensional computation of waves, especially for the case where waves are caused to break by focusing of components with differing frequencies (Dommermuth et al 1987, Skyner et al 1990, Skyner & Greated 1992). Despite this type of activity, surprisingly little progress has been made in developing quantitative descriptions of wave breaking. The simple descriptions: "plunging breaker" and "spilling breaker" cannot yet be quantified. In part this is due to difficulty of modeling the splashing phase of a breaker after an overturning jet plunges into the water.

Spilling Breakers

Spilling breakers are more amenable to modeling since steady examples can be generated, and other spilling breakers are sometimes quasi-steady. Models are mostly at a very elementary level simply representing the spilling breaker as a "roller" riding passively on the water. (See Figure 5*a* which shows mean streamlines.) However, after study of a range of experiments, Peregrine & Svendsen (1978) suggest that these flows may be best modeled by considering the whole region of turbulence, as in Figure 5*b*. In a reference frame moving with the wave, the turbulent velocities are of the same order of magnitude as the wave velocity. The fluid content of the "roller" is continually mixing with the rest of the turbulent fluid in the wave.

In considering the source of the turbulence, we note that the water falling/spilling down the front of the wave is clearly contributing to the turbulence by losing its potential energy. On the other hand Peregrine & Svendsen come to the conclusion that this is relatively unimportant in quasi-steady waves and the falling water is more important when it con-

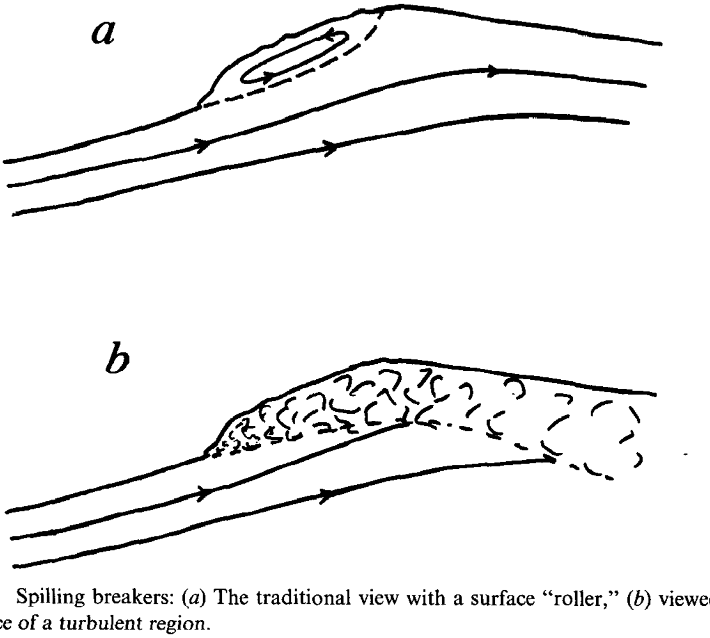

Figure 5 Spilling breakers: (*a*) The traditional view with a surface "roller," (*b*) viewed as the source of a turbulent region.

tacts previously undisturbed water. Between the water masses there is a large velocity difference tangential to the smooth surface in front of the breaker, which suggests an analogy to the well-studied shear layer between two streams of different velocities, i. e. the turbulent mixing layer. Such measurements as are available from hydraulic jumps supported this view, e.g. Hoyt & Sellin (1989). The structure of quasi-steady waves is thus an initial mixing-layer region, followed by the region beneath the crest of the wave where gravity influences and restrains the turbulent motions near the surface. Finally trailing behind the breaker is a turbulent wake which has a momentum deficit relative to the breaking wave. When viewed in a frame of reference where the wave is propagating this wake contains the momentum lost from the wave during the breaking process. This same momentum is of importance in setting up currents, especially wind-driven currents.

The main application of these ideas to practical modeling has been for shallow-water waves (Madsen & Svendsen 1982, Svendsen & Madsen 1984). For deep-water waves the "roller" concept has been used by Banner (1987) in a "lumped mass" approximation to obtain ordinary differential equations which give a reasonable simulation of his measurements of the unsteady response of a steady breaker to a disturbance. The work that has been carried furthest at present (Tulin & Cointe 1986 and Cointe 1987) uses a modeling scheme intermediate between the above mentioned. Here, linear wave theory is combined with a passive hydrostatic model of the roller, and results compare favorably with experiments. All these models require refinement, but constitute a promising start to understanding a complex flow.

The process of initiation of spilling breakers on deep water is not entirely clear. A small plunging event at the wave crest does sometimes occur but other effects may be more important. This is particularly so in the presence of wind or previous breaking waves, where the flow is rotational and may well have current which is greatest at the surface in the direction of wave propagation, e.g. if the wind is generating the waves and a wind drift layer has formed, then, as indicated by Phillips & Banner (1974), the surface shear leads to a substantial reduction in the maximum height that a steady wave can have. However, the strongest shear under wind is at the surface and has a small length scale, which makes it seem unlikely that such a thin layer will strongly influence the dynamics of a large wave. However spilling might start as a small breaking event with capillary action inhibiting white water formation (i. e. no bubbles are created), but the breaker could then grow rapidly in intensity so that the more readily visible "whitecap" breaker appears to be spilling ab initio. This is not the only case where spilling may start without plunging. If a wind is blowing small capillary ripples are always present. Large wave crests are continually catching them up. The effect of the flow field in the large wave is to shorten and steepen those ripples it overtakes, and analysis shows (Popat 1989) that for a wide range of large gravity waves, the small ripples steepen up to breaking. This breaking may then trigger larger scale spilling on suitably steep waves as described above. Limiting capillary waves are thought to break in an entirely different manner from gravity waves. The trough steepens until it overhangs and a bubble may pinch off, with strong shears and circulation as in the gravity wave case (Crapper 1957, Longuet-Higgins 1992).

For wind blowing against the direction of wave propagation, the effects of wind-drift surface shear are different. Breaking waves become higher and more likely to plunge, as any surfer knows. Kjeldsen & Myrhaug (1980) show a laboratory example of this effect. Teles da Silva & Peregrine (1988) give theoretical examples of steep steady waves with constant vorticity.

Occurrence of Deep Water Breaking

A popular approach to predicting deep-water breaking for a directional wave spectrum has evolved from studies of modulating wave trains and narrow-band random waves, as described in a previous section. The actual threshold for breaking in a random wave spectrum is not well understood. In the spectral context, Longuet-Higgins (1969) presented a simple statistical model for the loss of energy by wave breaking in a random sea, based on a crest downward acceleration threshold of $0.5\,g$ for the sharp-crested limiting Stokes wave. More recently, Longuet-Higgins (1985, 1986) pointed out that careful distinction between Lagrangian and Eulerian acceleration is necessary, and Lagrangian accelerations calculated for steep, irrotational wave trains may be used as a basis for a breaking threshold. Investigation of this class of threshold forms the basis of theoretical papers by Snyder & Kennedy (1983) and Kennedy & Snyder (1983) for ocean waves near the spectral peak; they describe a theoretical framework and numerical simulations for various moments of the whitecap geometry, including the whitecap cover. Qualified support is given for the use of an acceleration threshold for the statistics of whitecapping of waves near the spectral peak. Ochi & Tsai (1983) also proposed a model for breaking statistics based on the joint wave amplitude-frequency distribution, examining one-dimensional, non-narrow band deep-water waves with various frequency spectra. This class of model was developed further in studies by Srokosz (1986), Yuan et al (1986), and Huang (1986). Papadimitrakis et al (1988) extended these previous analyses to embrace broader spectral bandwidths. By relating their findings to previous models and observations, they provide insight on the implications for wave energy dissipation. These studies point out the underlying importance of the fourth moment of the spectrum, which is strongly dependent on the high wavenumber tail of the spectrum. Although the form of the latter is not well established, it is presently an area of active concern and ongoing investigation. Attention to this issue is also drawn by the work of Glazman (1986), who examined the relation between the geometry of the sea surface, higher order moments of the wave spectrum, and the theory of random fields. This study examines two-dimensional wave groups, considering the wave envelope and wave slope statistics in modeling breaking wave occurrence.

Future theoretical progress will need to address mechanisms related to breaking that have been documented in laboratory and field observations. In addition to saturation from direct wind input, modulation of very short wind waves by longer waves is a mechanism contributing to the breaking of short wind waves. Several laboratory investigations have reported the marked attenuation of the short wave spectrum as the modulating wave steepens (e.g. Phillips & Banner 1974, Donelan 1987). Phillips & Banner (1974) modeled this effect as enhanced breaking due to wind drift layer influence, but this mechanism was questioned by Wright (1976). Donelan (1987) suggested that modification of the nonlinear wave-wave interactions was responsible for the observed behavior. Longuet-Higgins (1987) proposed a two-scale model which considered randomness in both long and short waves and examined the effects of breaking of the short waves under conditions where the short waves were regenerated by the wind, and reported predictions in qualitative agreement with observations. When the large-scale wind wave is itself involved in breaking, it produces a marked local attenuation of the entire short wind-wave spectrum in its wake (Banner et al 1989, figure 5).

In summary, there has been considerable progress with regular wave trains and narrow-band random waves. However, theoretical modeling of breaking statistics in broad-band directional wind seas embracing major whitecaps down to the ubiquitous microscale breakers is not well-established and remains a challenging and elusive goal. In turn, this compromises our ability to provide a reliable model for the spectral dissipation through wave breaking in sea state prediction, as discussed below.

Wind-Wave Modeling

The capability of making reliable sea state predictions for a prescribed wind field has been a long standing oceanographic goal with significant scientific, engineering, and economic benefits. While earlier wind-wave generation models focused on the behavior of the significant wave height, more recent models have pursued the prediction of the full directional spectrum of the wave height, based on the numerical solution of the radiative transfer equation (e.g. the WAMDI Group 1988). According to this formulation, the rate of evolution of the spectrum at a given wavenumber results from the net influence of source terms due to wind input $S_{in}(\mathbf{k})$, nonlinear wave-wave interactions $S_{nl}(\mathbf{k})$, and wave dissipation processes $S_{diss}(\mathbf{k})$. While the wind input source term is reasonably well modeled from measurements and the nonlinear spectral transfer term is known theoretically for homogeneous seas (Hasselmann 1962, 1963a, 1963b), the form of $S_{diss}(\mathbf{k})$ which includes wave breaking, is not well-understood, either observationally or theoretically.

The paucity of knowledge of dissipative processes occurring within the wave spectrum, particularly the inherent complexity of representing wave breaking, has resulted in very few models for $S_{diss}(\mathbf{k})$. The form proposed by Hasselmann (1974) treats the breaking events as an ensemble of pressure impulses which are weak-in-the-mean. The resulting form for $S_{diss}(\mathbf{k})$ is quasi-linear in the wave spectral density, with the coefficient a functional of the whole wave spectrum, weighted towards higher wave numbers. Other approaches to represent $S_{diss}(\mathbf{k})$ have also been proposed (e.g. Duffy 1991), but the Hasselmann form appears to have been most widely adopted in operational wave models.

These terms have been incorporated in the radiation transfer equation and solved numerically for simplified situations such as homogeneous wind and wave fields with fetch-limited growth, for which a reasonable observational base exists. Such cases have served to tune the level of the dissipation source term (e.g. see Komen et al 1985). However, with the advent of more detailed information on the shape of the directional wave number spectrum both near the spectral peak (e.g. Donelan et al 1985) and in the high wavenumber tail region (e.g. Banner et al 1989), it is becoming possible to subject the wave model predictions to closer scrutiny and possible refinement of the form of $S_{diss}(\mathbf{k})$.

Wind-wave models have been extended to handle more complex situations such as turning winds and refraction by horizontally sheared currents, although observational support for such calculations is not widely available. Large-scale ocean experiments are required with well-defined wind fields. While this is difficult to realize, the recent Surface Waves Dynamics Experiment (SWADE) conducted off the U.S. East Coast during 1990–1991 (Weller et al 1991) will provide such data and serve as a very valuable basis for testing wave models in complex wind fields and currents, particularly the validity of the adopted forms for $S_{diss}(\mathbf{k})$.

Most present wind-sea models use a prescribed wind field and a standard drag coefficient relationship which depends only on the wind speed to infer the wind stress. Recent observational investigations (e.g. Donelan 1982, Smith et al 1992) reveal a sea state dependence in the wind stress, in addition to the dependence on wind speed. These studies found that young wind seas are associated with significantly higher drag coefficients than old wind seas. Interest in this problem has heightened in recent years, motivated by the need to provide the best estimate for the wind stress in models for sea state and wind-driven circulation. In this context, with the observed large augmentation of the local wind stress and wave form drag over breaking waves (Banner 1990), it is of interest to estimate the incremental impact of wave breaking in the spectrum on the wind stress. This is difficult to answer at present because of a lack of knowledge of the spectral distribution of breaking probability, but some initial efforts have been made in this direction by Phillips (1985, 1988) for the equilibrium range of wave numbers. When combined with detailed knowledge of the local energy dissipation and momentum flux associated with individual breakers, which is becoming available from laboratory studies (e.g. Melville & Rapp 1985, Rapp & Melville 1990), knowledge of this distribution will also provide a refinement of $S_{\mathrm{diss}}(\mathbf{k})$ as well as the momentum flux from breaking waves to the ocean currents.

SECONDARY ASPECTS

Air Entrainment, Bubble Clouds

Whitecapping produces clouds of air bubbles which are advected downwards by the surface layer turbulence. The formation and interaction of the air bubbles in the upper ocean mixed layer provides vertical and horizontal distributions of bubbles. The bubble cloud shapes are detectable using various sonar techniques (e.g. Thorpe 1986) and serve to label the surface layer turbulence, play a role in the exchange of gases between the atmosphere and the ocean, and influence the ambient noise spectrum. Progress in these areas is reflected in recent research symposium proceedings by Monahan & MacNiocaill (1986) and Kerman (1988).

More locally, a better understanding of the physical role played by the air bubbles entrained by breaking waves in basic processes such as wave energy dissipation and ambient underwater noise generation is becoming available through detailed laboratory investigations (e.g. Melville et al 1988, Loewen & Melville 1991a, Lamarre & Melville 1991) and modeling (e.g. see Loewen & Melville 1991b).

Spray

Associated with high winds, breaking waves cast off clouds of spray into the atmosphere, and it has been proposed in model studies (e.g. Ling et al 1980, Bortkovskii 1987) that this mechanism greatly enhances the net water vapor flux into the atmosphere. However, using data from the recent HEXOS experiment, DeCosmo (1991) found no such increase in the water vapor transfer coefficient with increasing wind speeds up to 18 m/s, despite the attendant increase in whitecapping, and suggested that while sea spray production and evaporation might increase at low levels, the enhanced moistening and cooling of the air near the interface would act to reduce the interfacial moisture flux and possibly the net flux, due to the reduction in the near-surface saturation vapor pressure. So even if the vertical turbulent transport is enhanced by the increased breaking activity, the net effect might be insignificant at the measurement elevation of several meters.

Influence on Remote Sensing of the Ocean

Satellite-borne active and passive microwave instruments presently in use (or scheduled for imminent deployment) have been shown to have the potential to provide routine, cost-effective monitoring of basic air-sea interfacial variables such as the global distribution of ocean wind stress, dominant wave height and direction, and sea surface temperature. As described above, breaking waves may well have an impact on the interpretation of ocean data from these remote sensing instruments, and their influence needs to be understood and quantified in order to improve the reliability of the algorithms used to interpret the microwave returns. Research in this direction is continuing.

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