See also

Abyssal Currents. Antarctic Circumpolar Current. Current Systems in the Atlantic Ocean. Current Systems in the Southern Ocean. Elemental Distribution: Overview. Intrusions. Mesoscale Eddies. Ocean Circulation. Regional and Shelf Sea Models. Satellite Altimetry. Satellite Remote Sensing of Sea Surface Temperatures. Upper Ocean Time and Space Variability. Water Types and Water Masses.

Further Reading

Gordon AL (1981) South Atlantic thermocline ventilation. *Deep-Sea Research* 28A(11): 1239–1264.

Peterson RG and Stramma L (1991) Upper-level circulation in the South Atlantic Ocean. *Progress in Oceanography* 26(1): 1–73.

Reid JL, Nowlin WD Jr and Patzert WC (1977) On the characteristics and circulation of the southwestern Atlantic Ocean. *Journal of Physical Oceanography* 7(1): 62–91.

Reid JL (1989) On the total geostrophic transport of the South Atlantic Ocean: flow patterns, tracers and transports. *Progress in Oceanography* 23(3): 149–244.

Stramma L and England M (1999) On the water masses and mean circulation of the South Atlantic Ocean. *Journal of Geophysical Research* 104(C9): 20 863–20 883.

Tomczak M and Godfrey JS (1994) *Regional Oceanography: An Introduction.* London: Pergamon.

BREAKING WAVES AND NEAR-SURFACE TURBULENCE

S. A. Thorpe, School of Ocean and Earth Science, Southampton, UK

doi:10.1006/rwos.2001.0071

Introduction

The breaking of waves on the sea surface creates turbulence in the water. This article is about wave breaking in deep water where the waves and turbulence are not affected by the presence of the sea bed; it does not describe turbulence generated by waves breaking on beaches or by the bores within the surf zone at the edge of the sea (*see* **Beaches, Physical Processes Affecting**).

The processes of wave breaking and turbulence generation are very important in the transfer of momentum and exchange of heat and gases between the atmosphere and the oceans, in generating and dispersing bubbles, oil droplets or surface films into the body of the 'mixed' layer, and in renewing the sea surface with subsurface water; breakers disrupt the cold surface skin of the ocean (e.g. *see* **IR Radiometers**). Nevertheless, the state of knowledge of wave breaking and its consequent turbulence is profoundly unsatisfactory. The present incomplete knowledge of breaking and turbulence hinders progress in understanding vitally important processes, such as those of gas transfer and the dispersion of pollutants from the water surface. The subject is, however, presently one of some activity, made possible only in the last two decades of the last century by the development of suitable sensors and methods of mounting them in the often violent and hostile environment of the sea surface, and future progress can be expected.

The turbulence generated by breaking waves will coexist with, and interact with turbulence generated in other ways in the upper ocean, such as Langmuir circulation (which, in view of its instability, may have turbulent characteristics; *see* **Langmuir Circulation and Instability**) and that produced by shear or convection in the mixed layer. These interactions are not presently understood and will not be discussed further in this article.

Breaking Waves

Three related kinds of wave breaking occur in deep water and lead to turbulence in the water. These are:

1. a spilling breaker in which water near a wave crest entrains air leading to a white cap on or slightly forward of a wave crest;
2. a plunging breaker, the more dramatic form of breaking observed commonly on the sea shore, in which a jet of water moves forward from near the top of a wave and falls, trapping and entraining into the water a volume of air;
3. the formation of capillary ripples on the forward face of a steep, short (typically 0.1 m wavelength) surface-gravity wave. In their most extreme form the ripples may lead to entrainment of air into the water. (*see* **Surface, Gravity and Capillary Waves**).

The severe irregularity of the sea surface in the conditions where breaking occurs, which is often characterized by presence of waves of different often frequencies and amplitudes traveling in different directions, makes it impossible to identify precise threshold conditions for the onset of breaking. However, two are commonly believed to be separately important:

1. a vertical acceleration of the water particles at the sea surface comparable to the acceleration due to gravity, g;
2. horizontal motion of particles at or near the wave crest at a speed which exceeds the phase speed of the wave, so that the wave steepens and begins to overturn. (The particle motion consists of two components, one wave-induced and the other caused by a mean shear. Banner and Phillips have shown how the latter will enhance breaking.)

Wave breaking, enough to produce acoustically observed, subsurface bubble clouds, generally occurs in winds exceeding $3\,\mathrm{m}^{-1}\,\mathrm{s}$, although no absolute threshold wind speed has been established. (Indeed breaking can be induced in the laboratory in the absence of wind.) A measure of the amount of wave breaking is given by the fraction, f, of waves which are breaking as they pass a given location. This is given, very approximately, by

$$f = (4.0 \pm 2.0) \times 10^{-3}(W_{10}/c_{\mathrm{m}})$$

where W_{10} is the wind speed at a height of 10 m above the water surface and c_{m} is the speed of the dominant waves, i.e., those at the peak of the wave frequency spectrum. (The ratio W_{10}/c_{m} is inversely proportional to the 'wave age', *see* **Wave Generation by Wind**.) This implies that there is relatively frequent breaking when the wind speed is much greater than the wave phase speed (e.g., at short fetches), and relatively little when the wind speed is less that the phase speed. (Recent work of Gemmrich and Farmer (see Further Reading) suggest that a scaling of f with wave age is too simplistic.) Breaking generally persists for less than a wave period after breaking commences. However, the most frequent breaking appears to be associated with waves which have a frequency which is higher than the frequency at the spectral peak, although which frequency band contributes most to, say, bubble formation or gas transfer is not certain.

It is apparent on careful observation of the sea surface in windy conditions that waves are not regular but travel in groups of six to eight waves, those near the center of the groups being higher than others and more likely to be breaking. (This explains why, at time intervals of typically six to eight wave periods, larger waves arrive on a beach.) Such packets of waves carry wave energy and propagate at the group velocity, which is $c/2$ in deep water, half the phase speed, c, of the waves, i.e., half the speed at which a wave crest propagates (*see* **Surface, Gravity and Capillary Waves**). Consequently waves advance through a group at a relative speed of $c/2$; they appear from the back of a group and disappear at the front, the front being in the direction in which the group and individual waves are advancing. Waves in a group break when they reach a certain location in the group where they are sufficiently large. Only the highest waves in a group, possibly two but more often only one, may break at any one time. The time interval between wave breaking in a group is approximately the time taken for a following wave to reach the position in a group at which its predecessor had begun to break. This is equal to the distance in the group through which the following wave must advance to reach the breaking location of the one in front of it (i.e., one wavelength, λ), divided by the wave speed, $c/2$, relative to the group. Since, however, $c = \lambda/T$, where T is the wave period, this time interval between breaking is $2T$, i.e., twice the wave period. This means that when the wave period is about 5 s, waves will break successively in a group at intervals of about 10 s. Although estimation of wave period is difficult at a distance, a careful observer at a high vantage point on shore or in an aeroplane flying over the sea will see waves moving downwind in groups and breaking repetitively in this way. It is often possible to see such repetitive breaking occurring three to five times, presumably until a wave group loses so much energy that breaking ceases.

Turbulence Generated by Breaking Waves

Breaking waves appear to be very important in the process of momentum transfer from the wind into the water. Little excess momentum is carried by waves from a region of wave generation by wind and this implies that the wind stress on the water is approximately equal to the Reynolds stress within the water. The magnitude of currents in the turbulent velocity field of the upper ocean is characterized by the friction velocity, $u*_{\mathrm{w}}$, in the water. Because the stresses in the air and the water are approximately equal, this is approximately equal to $u*(\rho_{\mathrm{a}}/\rho_{\mathrm{w}})^{1/2}$, where $u*$ is the friction velocity in the air (*see* **Wave Generation by Wind**) and ρ_{a} and

ρ_w are the densities of air and water, respectively. Since the wind stress, τ, equal to $\rho_a u*^2$, can be written as $\tau = C_D \rho_a W_{10}^2$, where C_D is the drag coefficient (about 1.2×10^{-3}; *see* **Heat and Momentum Fluxes at the Sea Surface**) and ρ_a/ρ_w is about 1.2×10^{-3}, $u*_w$ is roughly equal to $1.2 \times 10^{-3}\ W_{10}$; a wind speed of $8\,\mathrm{ms}^{-1}$ leads to a characteristic turbulent velocity speed in the water of about $1\,\mathrm{cm\,s}^{-1}$. In these conditions, typical waves of height, $2a$, of 1 m and period of 4 s will have particle speeds at the wave crests of about $2\pi a/T$, or about $80\,\mathrm{cm\,s}^{-1}$, much greater than the turbulent velocities. The measurement and resolution of turbulent motions within the velocity field of motion produced by the waves are consequently nontrivial.

Laboratory experiments in the absence of wind show that turbulence generated by a breaking wave spreads downwards to a depth which increases linearly with time for the first two wave periods after breaking and reaches a depth of about twice the wave height in some four wave periods after breaking. By this time 90% of the energy lost from the wave has been dissipated. As much as 50% of the energy lost from the breaking wave may be used in generating bubbles, although part of this may be transferred to the water in the wakes of bubbles rising back to the surface. Further deepening of the turbulent region produced by a breaker occurs after four wave periods after breaking, but the downward spread is very slow, with a power law of $(\mathrm{time})^{1/4}$ in previously undisturbed water. A breaker generates a rotor, a circulating motion, below the water surface reaching a depth roughly equal to the wave height and within which small, slowly rising bubbles may be temporarily trapped. Bursting motions, perhaps akin to those in turbulent flow over a solid boundary, have also been reported in laboratory experiments. What is most evident from these laboratory studies is that turbulence near the sea surface will be very patchy and intermittent, depending on how long it has been since a wave broke in a particular water mass. This again places high demands on observations which must be sufficient to sample sufficient breakers to provide good estimates of their high rates of dissipation.

Early observations at sea suggested that the mean turbulent dissipation of kinetic energy per unit mass, ε, below the water surface varies with depth in a way similar to the 'Law of the Wall' near a rigid wall, i.e. as $\varepsilon = u*_w^3/kz$, where z is the depth and k is von Karman's constant, approximately 0.4. This suggested that waves play a minor role in dictating the turbulence of the near-surface boundary layer. However in 1992, it was shown that although data were very scattered, the ratio $\varepsilon kz/u*_w^3$ (which would be unity if the Law of the Wall relation holds) increases as the free water surface is approached, from a value of approximately unity well below the surface. These data show that the enhanced region of dissipation extends to a depth, z, of about $10^5 u*_w^2/g$ (about 2.6 m in winds of $10\,\mathrm{m\,s}^{-1}$). It appears likely that a depth scaling with the significant wave height, H_s, and wave age is appropriate, as suggested in 1996, but further measurements are needed of the depth of active turbulence penetration to establish its dependence on waves and wind. It should, however, be noticed that bubbles are diffused by near-surface turbulence to mean depths of $4H_s$ and that plumes extend to $6H_s$. This is possible evidence of the significant effect of Langmuir circulation in vertical transport processes from the water surface.

Some important progress has been made in modeling turbulence near the sea surface, but the state of knowledge is not yet sufficient to fully test its validity.

Conclusion

The study of breaking waves and of the turbulence they produce is a topic of active research. It appears possible that more subtle effects than scaling with H_s are important. One is that the speed of the breaking crests appears to be related to dissipation. This has opened the possibility of gaining useful quantitative information using aerial studies of the movement and number of breakers. It is also evident from the patterns observed in foam sheets produced as, and shortly after, waves break that the subsurface turbulent field of motion contains some regular features or coherent structures, and these deserve further study. Little is presently known about the three-dimensional form of breakers; the along-slope length of the wave crest along which breaking occurs is generally less than one wavelength, so that breakers are not two-dimensional; breaking is 'patchy'. Vortices are known to have properties of amalgamation and strong three-dimensional interaction, and the three-dimensional nature of breakers may have implications, yet unknown, for the way in which the subsurface rotors, generated in breaking, roll-up or transport material away from the sea surface. A further, and yet inadequately understood, but intriguing problem is how rain 'knocks-down' a sea, reducing the frequency of wave breaking.

See also

Air–Sea Gas Exchange. Beaches, Physical Processes affecting. Bubbles. Heat and Momentum

Fluxes at the Sea Surface. IR Radiometers. Langmuir Circulation and Instability. Surface, Gravity and Capillary Waves. Wave Generation by Wind. Whitecaps and Foam.

Further Reading

Agarwal YC, Terray EA, Donelan MA *et al.* (1992) Enhanced dissipation of kinetic energy beneath surface waves. *Nature* 359: 219–220.

Banner ML and Phillips OM (1974) On the incipient breaking of small scale waves. *Journal of Fluid Mechanics* 77: 825–842.

Banner ML and Peregrine DH (1993) Wave breaking in deep water. *Annual Review of Fluid Mechanics* 25: 373–397.

Craig PD and Banner ML (1994) Modelling wave-enhanced turbulence in the ocean surface layer. *Journal of Physical Oceanography* 24: 2546–2559.

Gemmrich JR and Farmer DM (1999) Observations of the scale and occurrence of breaking surface waves. *Journal of Physical Oceanography* 29: 2596–2606.

Kantha LH and Clayson CA (2000) *Small Scale Processes in Geophysical Flows*. San Diego: Academic Press.

Melville WK (1996) The role of surface-wave breaking in air–sea interaction. *Annual Review of Fluid Mechanics* 28: 279–321.

Rapp RJ and Melville WK (1990) Laboratory experiments of deep-water breaking waves. *Philosophical Transactions of the Royal Society of London, A* 331: 731–800.

Terray EA, Donelan MA, Agarwal YC *et al.* (1996) Estimates of kinetic energy dissipation under breaking waves. *Journal of Physical Oceanography* 26: 792–807.

Thorpe SA (1995) Dynamical processes of transfer at the sea surface. *Progress in Oceanography* 35: 315–352.

Tsimplis M (1992) The effect of rain in calming the sea. *Journal of Physical Oceanography* 22: 404–412.

Van Dyke M (1982) *An Album of Fluid Motion*, pp. 112–114. Stanford, CA: The Parabolic Press.

BUBBLES

D. K. Woolf, Southampton Oceanography Centre, Southampton, UK

doi:10.1006/rwos.2001.0062

Introduction

Air–sea interaction does not solely occur directly across the sea surface, but also occurs across the surface of bubbles suspended in the upper ocean, and across the surface of droplets in the lower atmosphere. This article describes the role of bubbles in air–sea interaction.

There are three quite different types of bubbles in the oceans that can be distinguished by their sources (atmospheric, benthic, and cavitation). Benthic sources of bubbles include vents and seeps and consist of gases escaping from the seafloor. Common gases from benthic sources include methane and carbondioxide. Cavitation is largely an unintentional by-product of man's activities; typically occurring in the wake of ship propellors. It consists of the rapid growth and then collapse of small bubbles composed almost entirely of water vapor. Cavitation may be thought of as localized boiling, where the pressure of the water falls briefly below the local vapor pressure. Cavitation is important in ocean engineering due to the damage inflicted on man-made structures by collapsing bubbles. Both cavitation bubbles and bubbles rising from the seafloor are encountered in the upper ocean, but are peripheral to air–sea interaction. Atmospheric sources of bubbles are a product of air–sea interaction and, once generated, the bubbles are themselves a peculiar feature of air–sea interaction. The major sources of bubbles in the upper ocean are the entrapment of air within the flow associated with breaking waves and with rain impacting on the sea surface.

Once air is entrapped at the sea surface, there is a rapid development stage resulting in a cloud of bubbles. Some bubbles will be several millimeters in diameter, but the majority will be < 0.1 mm in size. Each bubble is buoyant and will tend to rise towards the sea surface, but the upper ocean is highly turbulent and bubbles may be dispersed to depths of several meters. Small particles and dissolved organic compounds very often collect on the surface of a bubble while it is submerged. Gas will also be slowly exchanged across the surface of bubbles, resulting in a continual evolution of the size and composition of each bubble. The additional pressure at depth in the ocean will compress bubbles and will tend to force the enclosed gases into solution. Some bubbles will be forced entirely into solution, but generally the majority of the bubbles will eventually surface carrying their coating and altered contents. At the surface, a bubble will burst, generating droplets that form most of the sea salt aerosol suspended in the lower marine atmosphere.

The measurement of bubbles in the upper ocean depends largely on their acoustical and optical