McCormick ME and Murtagh JF (1992) *Large-Scale Experimental Study of the McCabe Wave Pump*. US Naval Academy Report EW-3-92, January.

McCormick M, Murtagh J and McCabe P (1998) *Large-Scale Experimental Study of the McCabe Wave Pump*. European Wave Energy Conference (European Union), Patras, Greece, Paper H1.

Nicholls HB (1999) *Workshop Group on Wave Energy Conversion*. Engineering Committee on Oceanic Resources (ECOR), St Johns, Newfoundland, Canada.

Ross D (1998) *Power from the Waves*. Oxford: Oxford University Press.

Shaw R (1982) *Wave Energy. A Design Challenge*. Chichester, UK: Ellis Horwood.

WAVE GENERATION BY WIND

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Introduction

It is apparent to the most casual observer that waves grow on water surfaces under the action of wind. Except in occasional conditions of very low wind speed, the sea surface is generally covered by 'wind waves', those produced locally by the wind, as well as swell waves which have come from distant storms. The wind waves span a range of frequencies and wavelengths, with dominant periods typically between 1s and 10 s, and they travel mainly in or fairly close to the wind direction. Waves become higher, with longer wavelength and greater periodicity, as the wind increases, and also with greater fetch, the downwind distance from shore; the further from the upwind shore, the larger and longer the waves.

Although the title suggests the idea of waves being formed by the action of wind blowing over the surface of a calm and smooth sea surface, the sea is rarely calm and the meaning of the title is generally taken to include the wind-related processes which lead to the growth of existing waves on the water surface as well as those which lead to their formation in calm weather. Since growth will involve a balance of processes leading to the transfer of energy into and from waves, the subject involves reference to both the way in which wind causes waves to become bigger and to accompanying processes which lead to their loss of energy or 'dissipation.' Ignoring processes affecting waves but which are related only indirectly to wind, such as surface wave interaction with fronts or internal waves, there are three main factors which lead to changes in the the energy of the waves in a given narrow frequency band. These are:

1. growth through the action of wind which is related to the transfer of momentum from the air into the sea and consequently with wind stress (*see* **Heat and Momentum Fluxes at the Sea Surface**);
2. interactions, i.e., waves of a particular frequency may lose or gain energy as a result of nonlinear resonant interactions with other waves, and their propagation may be affected by interaction with currents (*see* **Surface, Gravity and Capillary Waves;**
3. dissipation, i.e., wave dissipation occurs as a result of wave breaking either in deep water or as waves approach shallow water or shore. Dissipation will also occur through their interaction with turbulence or through viscous action, the latter particularly if they are of small wavelength (e.g., capillary waves, *see* **Surface, Gravity and Capillary Waves**. Energy may also be lost when the water surface is covered by a surface film (*see* **Surface Films**).

This article focuses attention on the first point, wind forcing. A little will be said of the observations that have been made to improve understanding and test the theoretical predictions. These are essential ingredients in the advance of knowledge. Because of the complexity of the sea surface and the fact that the wind is not steady, but turbulent in its nature, the theory of wave generation has developed slowly since its beginnings over 130 years ago. Even now, the available theory offers a less than complete or satisfactory explanation of the changing state of the sea surface, in spite of the evident requirement to predict waves. They are an essential ingredient in the interaction of the atmosphere and the ocean (e.g., in the transfer of momentum from the wind to the water (*see* **Breaking Waves and Near-surface Turbulence**, and in the formation of bubbles, foam and aerosols, thereby affecting gas flux (*see* **Bubbles, Whitecaps and Foam** and **Air–Sea Gas Exchange**), and are consequently involved in those exchanges which control climate change. Wave forecasting is used to find the best routes for ships to avoid severe waves, and to predict when it is safe to tow and erect oil platforms or other large off-shore structures. Accurate prediction is essential in such high-cost ventures, and the development of wave prediction models has developed considerably in the last two decades. This article ends with reference to prediction of waves and mention of the aspects of wave generation which appear to require further careful study.

Theories of Wave Generation by Wind

In 1956, Dr Fritz Ursell undertook a review of wave generation which emphasized its very unsatisfactory state and identified the glaring lack of essential understanding of such an important process. Ursell had been a member of a British Admiralty team, Group W, brought together towards the end of World War II under the leadership of Dr George Deacon, to provide predictions of wave conditions for Allied landings on beaches. At the time of writing his review there were two leading theories about how waves were generated. The first, developed as a very idealized model of wind forcing by Lord Kelvin and by H. Helmholtz, independently, in the 1860s, was that in some conditions the flow of air over a flat water surface caused instability, and the consequent growth of infinitesimal disturbances into waves. The theory predicts that the conditions under which waves grow, and the wavelength of the disturbances which grow most rapidly, depend on surface tension and that no waves of any scale will grow if the wind speed is too small. Although such instability may contribute to wave growth, the theory indicates that waves will not be produced on natural water surfaces as a consequence of Kelvin–Helmholtz instability[1] unless the wind speed exceeds about $6.5\,\mathrm{m\,s^{-1}}$, a value far greater than that in which ripples and small waves are actually observed to develop. (The reader is encouraged to watch waves growing at the upwind edge of ponds and lakes.) The second theory of wave generation was by Sir Harold Jeffreys in about 1924, and involved the idea that the air flow over the crests of pre-existing waves would detach or 'separate' from the water surface, creating a sheltered region in the lee of the crest within which air would circulate. The consequence of this 'sheltering hypothesis' was that the air pressure on the back of a wave would be greater than that on the front, so driving the wave forward in the wind direction. Unfortunately, observations provided little support for the hypothesis and the theory was set aside (at least until recent years.)

Ursell's review served as a strong stimulus for further research and prompted the development of two very different theories, one by Dr Owen Phillips and the other by Dr John Miles, which formed the corner stones of subsequent work. Phillips' theory, first published in 1957, boldly embraced the notion that the air flow over waves is turbulent. It supposed that turbulent pressure-producing eddies are advected by the wind over the water surface in the wind direction and, under suitable conditions, force surface waves. Free surface waves are those which have speeds and wavenumbers which satisfy the dispersion relation of surface gravity waves (*see* **Surface, Gravity and Capillary Waves**, eqn 12). Phillips showed that pressure fluctuations in the turbulent eddies which have the same downwind speed and wavelength as free surface waves may transfer energy to them; a resonant coupling can exist between the waves and the turbulent wind field which leads to linear growth of waves. However, since the downwind component of the speed of the waves depends on their direction on the water surface relative to that of the wind, resonance may and does occur for waves which do not travel directly downwind. The theory appears to provide useful predictions for small amplitude waves with a bimodal distribution of directions symmetrical about the wind direction in the early stages of wave formation.

In contrast, Miles' theory applies to waves which already exist. He ignored the fact that the wind was turbulent in nature but included the vertical variation in mean wind speed, drawing attention to the fact that there is a level above the water surface where the mean wind speed is equal to the speed of sufficiently short waves. At this critical level or layer, the waves produce motions which result in energy transfer from the mean wind field into the wave-correlated motion, so providing a mechanism for the extraction of energy from the mean wind field and into the waves. In 1960 Miles combined his 'boundary layer' theory with that of Phillips, allowing for some aspects of airflow turbulence.

Observations and Wave Forecasting

Measurements by Snyder and Cox and others, soon demonstrated however that even the revised theory underestimated the observed growth rates. One aspect not properly accounted for in the early theories is the co-presence of waves forming a spectrum

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[1] The term Kelvin–Helmholtz instability (sometimes KHI) is now more usually used to denote the instability of shear flows in which the density increases smoothly with depth.

which is broad in frequency and wavenumber, including in particular waves of relatively small wavelength which 'ride' on the longer.

As well as being the subject of further theory, this and other aspects of wave generation have been subjected to experimental study in laboratory wind-wave tunnels in which air is blown over a water surface. In some tunnels, artificially generated waves are produced as well as waves by driven air flow. These facilities have been very useful in guiding theoretical advances under controlled and well-measured conditions. Their ability to simulate natural waves is however limited, e.g., the tunnel length, usually less than 30 m, precludes the development of large waves and limits the time available for wave interactions to occur as a wave travels down the tunnel. The side walls delimit the directional spectra and phase relations.

Dr Klaus Hasselmann was one of those who, with Dr Walter Munk in the early 1960s, measured the propagation of waves right across the Pacific Ocean from storms near New Zealand to their eventual demise on the shores of Alaska. He has been particularly instrumental in encouraging the development of a practical understanding of wave growth. He led the Joint North Sea Waves Project experiment in the early 1970s which, among other things, measured the rate at which the peak of the wave frequency spectrum grows and moves to lower frequencies with increasing fetch, and made estimates of the relative contributions to these changes of wave interactions, wind forced growth, and dissipation.

These and other observations have been essential in devising and testing predictive models of waves. Dr Hasselmann was also active in the development of what has been termed a Third Generation Wave Model which is currently in general use for wave prediction. The prediction of waves at sea is now more advanced and well tested than any other kind of modeling and prediction of oceanic properties except that of tides. Wave models now allow, for example, for the 'state' of wave development in relation to the wind. This is characterized by the nondimensional parameter called the 'wave age', defined as $cu*^{-1}$, where c is the speed of the dominant surface waves, those at the peak of the frequency spectrum, and $u*$ is the friction velocity in the air, equal to the square root of the wind stress divided by the density of air (*see* **Breaking Waves and Near-surface Turbulence**). The friction velocity is proportional to wind speed. Strong wind forcing or large wave growth occurs when the wave age is small.

Conclusion

This article about wave generation is too brief to enter into the complexities of the theory of wave generation or to do justice to the many recent contributions to the subject. The interested reader is encouraged to refer to the Further Reading and references to which this leads.

The subject is by no means closed. Fundamental advances are still being made, for example on the effects of swell on wind-wave generation. Observation shows that the wave field is by no means uniform, but that it is dominated by the presence of groups of higher waves, often apparent because of their associated breaking (*see* **Breaking Waves and Near-surface Turbulence**). What perhaps is still required is a model of wave generation by wind which takes full account of this important property of waves on the sea surface.

See also

Breaking Waves and Near-surface Turbulence. Bubbles. Fish Ecophysiology. Heat and Momentum Fluxes at the Sea Surface. Surface Films. Surface, Gravity and Capillary Waves. Waves on Beaches. Whitecaps and Foam.

Further Reading

Belcher SE and Hunt JCR (1998) Turbulent flow over hills and waves. *Annual Review of Fluid Mechanics* 251: 109–148.

Donelan M (1990) Air–sea interaction. In: *The Sea*, part 7, vol. 9: *Ocean Engineering Science*, pp. 239–292, New York: Wiley Interscience.

Hasselmann K *et al.* (1973) Measurements of wind-wave growth and swell decay during the joint North Sea wave project (JONSWAP). *Deutsche Hydrographigsche Zeitschrift* Suppl. A, 8(12).

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

Komen GJ, Cavaleri L, Donelan M *et al.* (1994) *Dynamics and Modelling of Ocean Waves*. Cambridge: Cambridge University Press.

LeBlond PH and Mysak LA (1978) *Waves in the Ocean*. New York: Elsevier.

Ursell F (1956) Wave generation by wind. In Batchelor GK (ed.) *Surveys in Mechanics*, pp. 216–249. Cambridge: Cambridge University Press.