Cambridge University Press & Assessment
978-1-107-00158-9 — Breaking and Dissipation of Ocean Surface Waves
Alexander Babanin
Excerpt
More Information

1

Introduction

Wind-generated waves are the most prominent feature of the ocean surface. As much as the oceans cover a major part of our planet, the waves cover all of the oceans. If there is any object in oceanography that does not need too much of a general introduction, it is the surface waves generated by the wind.

Being such a conspicuous entity, these waves, however, represent one of the most complex physical phenomena of nature. Three major processes are responsible for wave evolution in general, with many more whose significance varies depending on conditions (such as wave-bottom interaction which is only noticeable in shallow areas). The first process is energy and momentum input from the wind. The waves are generated by turbulent wind, and the turbulence is most important both for their initial creation and for subsequent growth (e.g. Miles', 1957; Miles, 1959, 1960; Phillips', 1957; Janssen, 1994, 2004; Belcher & Hunt, 1993; Belcher & Hunt, 1998; Kudryavtsev *et al.*, 2001, among many others). There is, however, no fixed theory of turbulence to begin with. Experimentalists have to deal with tiny turbulent fluctuations of air which are of the order of 10^{-5}–10^{-6} of the mean atmospheric pressure and which must be measured very close to the water surface, typically below the wave crests (e.g. Donelan *et al.*, 2005). The wind input process is quite slow and it takes hours of wind forcing (thousands of wave periods) and tens and hundreds of kilometres of fetch for waves to grow to a considerable height.

The second process is weak, resonant, nonlinear interactions within the wave system which can only be neglected for infinitesimal waves. For most of its existence, the wind–wave can be regarded as almost sinusoidal (i.e. linear), but its very weak mean nonlinearity (i.e. deviation of its shape from the sinusoid) is generally believed to define the wave's evolution. This is due to such waves, unlike linear sinusoids, exchanging energy when they cross-path. They cross-path because waves of different scales (i.e. different frequencies and wavelengths) propagate with different velocities, and also because waves tend to propagate at a range of angles with respect to the mean wind direction. Such weak interactions appear to be of principal importance. The longer (and higher) the waves are, the faster they move, and therefore the visibly dominant waves move with speeds close to the wind speed. This means that they virtually move in the still air, there is almost no wind for them. If they are still obviously wind generated, how does the wind produce such waves? The answer that is most commonly accepted now, is that the wind pumps energy mostly into shorter

© in this web service Cambridge University Press & Assessment www.cambridge.org

Cambridge University Press & Assessment
978-1-107-00158-9 — Breaking and Dissipation of Ocean Surface Waves
Alexander Babanin
Excerpt
More Information

(high-frequency) and slowly moving waves which then transfer this energy across the continuous spectrum of waves of all scales towards longer (lower-frequency) components thus allowing those to grow – by means of nonlinear interactions. So, this small nonlinearity plays a large role in developing wind–waves as we know them. Analytically, to account for this sort of interaction the theoreticians have to solve relevant equations of hydrodynamics with accuracy down to expansion terms of the third order (e.g. Hasselmann, 1962; Zakharov, 1968; Hasselmann *et al.*, 1994; Badulin *et al.*, 2005). Experimentally, such interactions could not have been studied directly because of a great number of technical difficulties, one of which is the slowness of the process, thousands of wave periods being its time scale. Here, we would also like to mention that there are alternative approaches to explaining the evolution of long wind-generated waves.

The third most important process that drives wave evolution is the wave energy dissipation. Common experience tells us that wind-generated waves, no matter how strong the wind and how long its duration and wave fetch, do not grow beyond a certain limit. In the absence of mainland in the Southern Ocean, high continuous westerly winds are free to run the waves around the globe and thus provide conditions of unlimited wind–wave forcing and growth. Yet, the significant wave height (height of one third of the highest waves) rarely goes beyond 10 m. Individual waves of some 30 m are occasionally reported (e.g. Liu *et al.*, 2007), but these are very seldom and would certainly be the ultimate limit for wind-generated waves on the planet. Therefore, there is a process that controls the wave growth from above, and that is wave dissipation.

1.1 Wave breaking: the process that controls wave energy dissipation

There are a number of physical mechanisms in the oceanic and atmospheric boundary layers, other than breaking, that contribute to wave energy dissipation (e.g. Babanin, 2006; Ardhuin *et al.*, 2009a), but once wave breaking occurs it is the most significant sink for energy. In well-developed deep-water wind-forced waves, it is believed that breaking accounts for more than 80% of dissipation. Wave energy is proportional to the wave height squared, and therefore a sudden reduction of wave height during breaking by, for example, two times, signifies a four-times' reduction in energy. Obviously, provided there is a sufficient number of waves breaking, such a dissipation mechanism is much more efficient compared to viscosity, to the interaction of waves with winds, currents, background turbulence and to other ways of gradual decline. The energy lost to breaking is spent on injecting turbulence and bubbles under the ocean interface, emitting spray into the air, and thus wave breaking, and wind-generated waves in general, play a very significant role in negotiating the exchange of momentum, heat and gases between the atmosphere and the ocean.

Breaking happens very rapidly, it only lasts a fraction of the wave period (Bonmarin, 1989; Rapp & Melville, 1990; Babanin *et al.*, 2010a), but the wave may indeed lose more than half of its height (Liu & Babanin, 2004). Thus, the wave energy slowly accumulated under wind action and through nonlinear transfer over thousands of wave periods is suddenly released in the space of less than one period. Obviously, this process,

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE
Cambridge University Press & Assessment
978-1-107-00158-9 — Breaking and Dissipation of Ocean Surface Waves
Alexander Babanin
Excerpt
More Information

the breaking-in-progress process of wave collapse, is a highly nonlinear mechanism of very rapid transfer of wave energy and momentum to other motions. So far, there are no adequate mathematical and physical descriptions of such a process.

Conceptually, however, the physics of wave collapse is completely different from the physics leading to breaking onset. While collapse is driven, to a greater extent, by gravity and inertia of the moving water mass and, to a lesser extent, by hydrodynamic forces, breaking onset occurs mostly due to the dynamics of wave motion in the water. Approaching breaking onset by a background wave is also very rapid, and also happens in the space of one wave period (e.g. Bonmarin, 1989; Babanin *et al.*, 2007a, 2009a, 2010a), but it should be considered separately from the following wave collapse. Essentially, the breaking process consists of two different sets of physics – one leading to breaking and another driving the wave breaking once it has started. These are not entirely disconnected, however, and the outcome of breaking collapse appears to 'remember' the 'input' that made a wave break. This will be discussed in more detail in Section 7.3.2.

The distinct difference between whitecapping dissipation and other processes involved in wave evolution is also determined by the fact that not every wave breaks whereas every wave experiences continuous energy input from the wind and continuous nonlinear energy exchange with other components of a continuous wave spectrum. A typical picture of a wavy surface under moderately strong wind conditions is shown in Figure 1.1. Waves of all scales, forming a continuous spectrum in terms of wave periods and lengths, exist simultaneously and run concurrently with different phase speeds, riding on top of each other or intercepting momentarily in different directions. All of these waves are subject to wind input and nonlinear exchange, but as is seen in Figure 1.1 just a small fraction of them break. Only under very strong winds does the rate of breaking crests reach 50% or more, but normally it is well below 10% (Babanin *et al.*, 2001). This means that, on average, it is every 20th or even every 50th wave that breaks, and this is sufficient to hold the energy balance in the wave system where every single wave gains energy one way or another. In the continuous time-space environment of a continuous wave spectrum and continuous physical processes, random breaking, which is intermittent in time and does not cover the surface uniformly, appears to control the equilibrium and ultimately wave growth. There is evidence that coverage of the ocean surface with breaking has a fractal dimension rather than being a two-dimensional surface (Zaslavskii & Sharkov, 1987), and this fact provides further mathematical complications if a description of this phenomenon is attempted by means of hydrodynamics or statistics.

It is important to mention at this stage that the three major processes, wind energy input, energy redistribution due to nonlinear interactions and energy dissipation, are closely coupled, affect each other and are equally important in wave evolution. Obviously, there would be no waves if they were not generated by the wind, but the wind input mechanism alone cannot explain evolution to any extent. As soon as the waves grow beyond the infinitesimal stage, nonlinear interactions begin to play an important role, and soon after, once individual steeper waves start to break, whitecapping dissipation assumes its responsibility as the balance holder.

© in this web service Cambridge University Press & Assessment www.cambridge.org

Cambridge University Press & Assessment
978-1-107-00158-9 — Breaking and Dissipation of Ocean Surface Waves
Alexander Babanin
Excerpt
More Information

Figure 1.1 Wind–wave pattern at a moderate wind. Waves of all scales are present simultaneously, representing a continuous wave spectrum. Only a small fraction of them are breaking at each scale. Gulf of St Vincent, Indian Ocean, August 2010

So-called whitecapping dissipation is the dissipation due to wave breaking, but it is not always that waves form whitecaps when they break (i.e. so-called micro-breaking discussed in Section 2.8 below). Since such a notion contradicts the general intuitive perception of wave breaking, we first have to answer a question: what do we call wave breaking?

1.2 Concept of wave breaking

Definitions pertaining to different physical and mathematical aspects of the wave breaking process will be formulated in Chapter 2. Here, we would like to discuss a common concept of breaking – that is what is a wave-breaking event and how is it generally perceived?

In Figure 1.2, a linear harmonic sinusoidal wave (sometimes called Airy wave), a Stokes wave, and an incipient breaker of the same height and length, i.e. all waves of the same average steepness, are compared graphically. This figure tests our ability to describe nonlinear behaviour of waves theoretically. The Stokes wave is a perturbation solution of hydrodynamic equations, assuming that the steepness of the waves is small. Obviously, although this traditional approach does produce a nonlinear wave shape, it does not look like anything close to a breaking wave as we perceive it (dash-dotted line). Needless to say the steepness of a breaking wave can hardly be expected to be small.

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE

Cambridge University Press & Assessment
978-1-107-00158-9 — Breaking and Dissipation of Ocean Surface Waves
Alexander Babanin
Excerpt
More Information

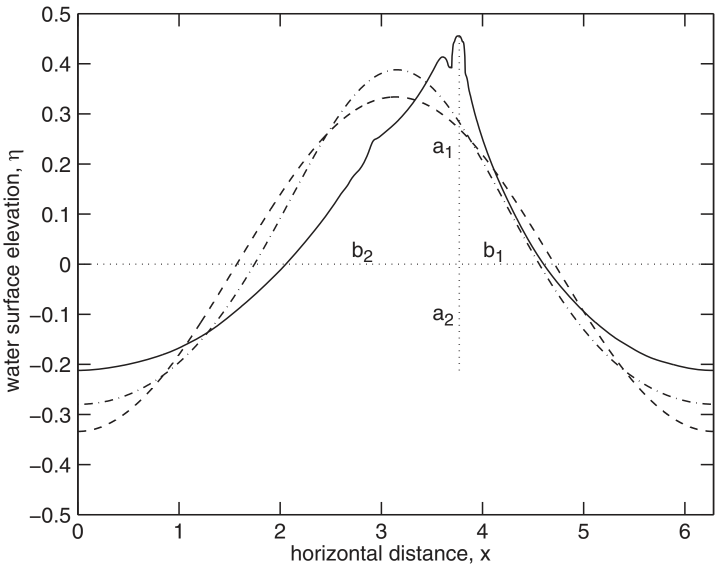

Figure 1.2 Geometric definition of wave skewness and asymmetry. The wave propagates from left to right. b_1 and b_2 are horizontal distances from the breaker crests to the zero-upcrossing and -downcrossing respectively. a_1 and a_2 are the breaker crest height and trough depth respectively. Solid line – numerically simulated incipient breaker (skewness is $S_k = 1.15$, asymmetry is $A_s = -0.51$). Dashed line – harmonic wave of the same wavelength and wave height ($S_k = A_s = 0$). Dash-dotted line – nonlinear wave of the same length and height obtained by means of perturbation theory ($S_k = 0.39$, $A_s = 0$). Dotted lines – mean (zero) water level (horizontal) and line drawn from the breaker crest down to the level of its trough (vertical). Figure is reproduced from Babanin *et al.* (2010a) with permission

An incipient breaker shown in Figure 1.2 (solid line) is produced numerically by means of the Chalikov–Sheinin model (hereinafter CS model (Chalikov & Sheinin, 1998; Chalikov & Sheinin, 2005)) which can simulate propagation of two-dimensional waves by means of solving nonlinear equations of hydrodynamics explicitly. The shape of such a wave is very asymmetric, with respect to both vertical and horizontal axes, and even visually the wave looks unstable.

Instability is a key word in the breaking process. The wave that we interpret as the incipient breaker in Figure 1.2 cannot keep propagating as it is: it will either relax back to a less steep, skewed and asymmetric shape, or collapse. We will define the steepness, skewness and asymmetry (with respect to the vertical axis) as

$$\epsilon = ak = \pi \frac{H}{\lambda}, \tag{1.1}$$

$$S_k = \frac{a_1}{a_2} - 1, \tag{1.2}$$

$$A_s = \frac{b_1}{b_2} - 1, \tag{1.3}$$

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE
Cambridge University Press & Assessment
978-1-107-00158-9 — Breaking and Dissipation of Ocean Surface Waves
Alexander Babanin
Excerpt
More Information

respectively (see Figure 1.2 and its caption). Here, a is wave amplitude, H is wave height ($a = H/2$ in the linear case), $k = 2\pi/\lambda$ is wavenumber and λ is wavelength, a_1 and a_2 are the wave crest height and trough depth, and b_1 and b_2 are horizontal distances from the breaker crests to the zero-upcrossing and -downcrossing, respectively. Thus, the steepness ϵ is an average steepness over the wave length, and obviously, local steepness is much higher near the crest and is less than average at the trough. Positive skewness $S_k > 0$ represents a wave with a crest height greater than the trough depth (a typical surface wave outside the capillary range), and negative asymmetry $A_s < 0$ corresponds to a wave tilted forward in the direction of propagation. Importantly here, experimentally observed negative asymmetry A_s has been broadly associated with wave breaking (e.g. Caulliez, 2002; Young & Babanin, 2006a).

Intrinsically, both the asymmetry and the skewness are natural features of steep deep-water waves regardless of their size, crest length, forcing or generation source (see e.g. Soares *et al.*, 2004). In Figure 1.3, examples of real waves are demonstrated which exhibit both these properties. The left panel shows a wind-generated and wind-forced wave of

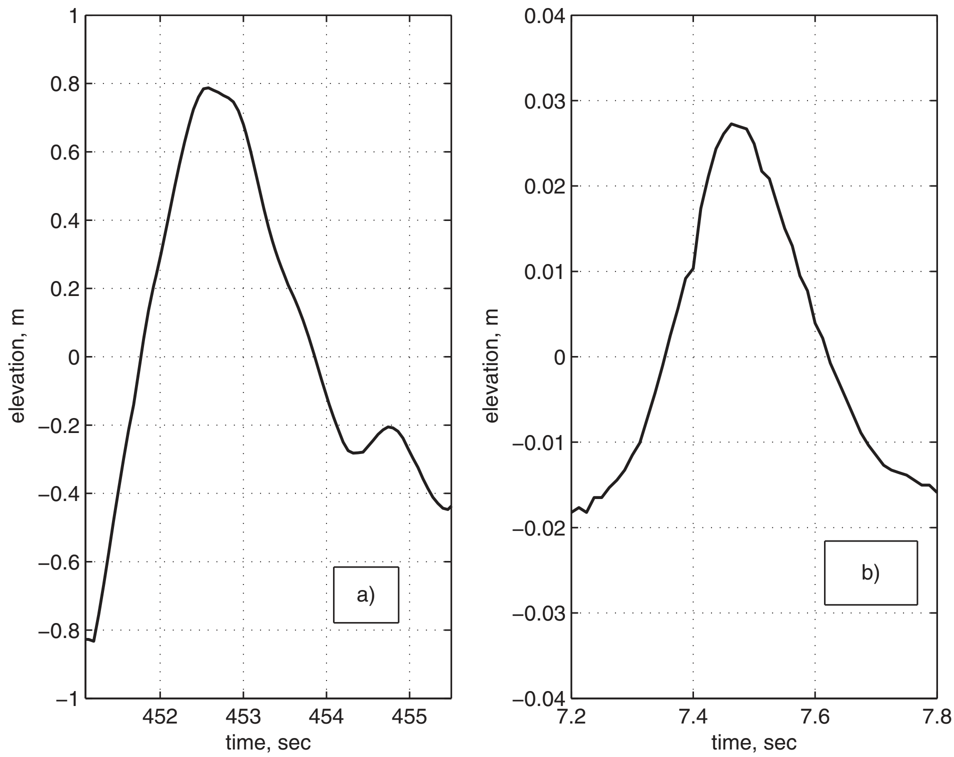

Figure 1.3 Real waves exhibiting both skewness and asymmetry. The waves propagate from right to left. a) Field wave measured in the Black Sea; b) laboratory (two-dimensional) wave measured in ASIST

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE
Cambridge University Press & Assessment
978-1-107-00158-9 — Breaking and Dissipation of Ocean Surface Waves
Alexander Babanin
Excerpt
More Information

height 1.6 m measured in a natural directional wave field in the Black Sea. The right panel shows a freely propagating (very small) two-dimensional wave of height 4 cm without wind forcing. This wave was mechanically generated in the Air Sea Interaction Salt water Tank (ASIST) of the University of Miami.

Once the skewness is non-zero and the amplitude a is not clearly determined, a definition of the wave steepness in terms of ak becomes ambiguous. Therefore, unless otherwise specified, the steepness will be expressed in terms of wave height $H = a_1 + a_2$ rather than wave amplitude a, as $\epsilon = Hk/2$. In these terms, steepness $\epsilon = 0.335$ of the wave shown in the figure far exceeds the limits of a perturbation analysis.

The dashed line in Figure 1.2 represents a steep sinusoidal wave ($S_k = A_s = 0$). Such a wave will immediately transform itself into a Stokes wave (e.g. Chalikov & Sheinin, 2005). The steep Stokes wave in the figure (dash-dotted line) is highly skewed ($S_k = 0.39$), but remains symmetric (i.e. $A_s = 0$). The incipient breaker in Figure 1.2 ($S_k = 1.15$, $A_s = -0.51$) was produced by the CS model, in a simulation which commenced with a monochromatic wave of $\epsilon = 0.25$. Such a wave profile looks visually realistic for a breaker and corresponds to, or even exceeds, experimental values of skewness and asymmetry for breaking waves previously observed (e.g. up to $A_s = -0.5$ instantaneously in Caulliez (2002) or $A_s = -0.2$ on average in Young & Babanin (2006a)). It is worth noting that the steepness of the individual wave has grown very significantly at the point of breaking: from $\epsilon = 0.25$ initially to $\epsilon = 0.335$.

When collapsing, the wave shape becomes singular at least at some points along the wave profile (i.e. space derivatives of the surface profile have discontinuities). This stage of wave subsistence is called breaking. Breaking of large waves produces a substantial amount of whitecapping, but smaller waves, the micro-breakers, do not generate whitecaps or bubbles and lose their energy directly to the turbulence.

Examples of various breaking and non-breaking waves are shown in Figures 1.4–1.8. Figures 1.4–1.5 show deep-water waves. The swell in Figure 1.4 are former wind–waves which have left the storm region where they were generated. They most closely conform to our intuitive concept of what the ideal wave should look like: uniform and long-crested, with crests marching parallel to each other. Their steepness is low and they do not break until they reach a shore.

Wind-forced waves hardly resemble this ideal picture. They look random and chaotic, they are multi-scale and directional, and they break. In Figure 1.5 a deep-water breaker is shown whose height is in excess of 20 m.

In Figure 1.6 (see also the cover image), waves approaching finite depths and, ultimately, the surf zone are pictured. In finite depths, waves break more frequently. Possible reasons are two-fold. Mainly, the waves break for the same inherent reason as in deep water, but they do it more often because the bottom-limited waves are steeper on average. Another fraction of waves break due to direct interaction with the bottom; this fraction grows as the waters become shallower (see Babanin *et al.*, 2001, for more details).

If deep-water waves enter very shallow environments, as shown in Figure 1.7, all of them will break and ultimately lose their entire energy to interaction with the bottom, to

© in this web service Cambridge University Press & Assessment www.cambridge.org

Cambridge University Press & Assessment
978-1-107-00158-9 — Breaking and Dissipation of Ocean Surface Waves
Alexander Babanin
Excerpt
More Information

Figure 1.4 Ocean swells are gently sloped former wind–waves propagated outside the storm area. They have low steepness and do not break. Image © iStockphoto.com/Jason Ganser

Figure 1.5 Large wave breaking in deep water. Distance from the mean water level to the lowest deck of the Fulmar Platform in the North Sea is 21 m. The photo is courtesy of George Forristal

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE

Cambridge University Press & Assessment
978-1-107-00158-9 — Breaking and Dissipation of Ocean Surface Waves
Alexander Babanin
Excerpt
More Information

Figure 1.6 Deep-water waves approach finite depths, grow steep and break. Hallett Cove, South Australia. Photo from Anna Babanina

Figure 1.7 Shallow water breaking. 100% of waves coming into the shallows break and lose all of their energy. This photo was purchased from http://www.istockphoto.com/

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE
Cambridge University Press & Assessment
978-1-107-00158-9 — Breaking and Dissipation of Ocean Surface Waves
Alexander Babanin
Excerpt
More Information

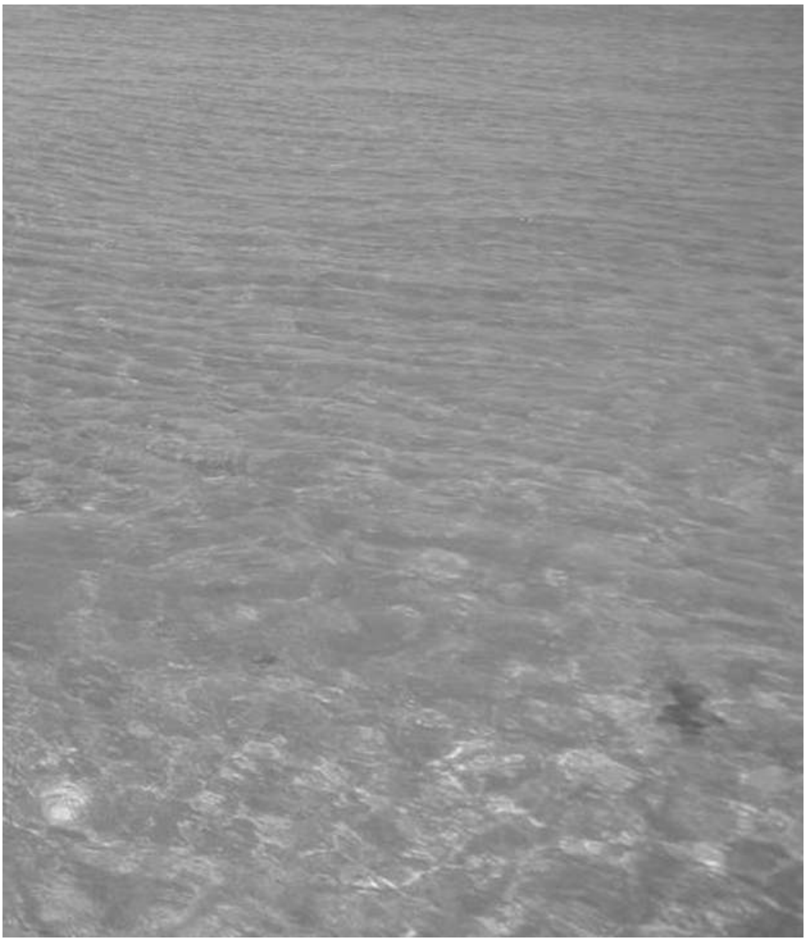

Figure 1.8 Wave ripples. Such waves are steep and break frequently, but do not form whitecapping. Port Phillip Bay, Victoria. Photo from Anna Babanina

sediment transport, to production of turbulence, bubbles and droplets, to mean currents and to generation of a small amount of waves reflected back into the ocean.

In the close-up picture in Figure 1.8, the waves can still be breaking even though it is now not possible to spot them visually. Short (in terms of wavelength) and small (in terms of wave height) ripples can nevertheless be quite steep. Such micro-breakers do not generate whitecapping, but demonstrate all the other singular surface features and irreversibly lose a significant part of their height and dissipate their energy (see e.g. Jessup *et al.*, 1997a).

At very strong wind-forcing conditions, wave-breaking behaviour is different yet again, and even the definition of breaking needs to be adjusted. As seen in Figure 1.9, taken from an aeroplane in Hurricane Isabel, the air–water interface is now smeared, the atmospheric boundary layer being full of droplets (spray) and the water-side boundary layer is filled

© in this web service Cambridge University Press & Assessment www.cambridge.org