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Key Points:

- Bubble plume volume time-integral scales linearly with breaking wave energy dissipation
- Foam evolution can be used to determine the bubble plume volume time-integral
- Remote sensing of evolving foam area could estimate individual breaking wave energy dissipation

Supporting Information:

- Supporting Information S1
- Figure S1
- Figure S2
- Figure S3
- Figure S4
- Figure S5
- Figure S6

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Laboratory air-entraining breaking waves: Imaging visible foam signatures to estimate energy dissipation

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Abstract Oceanic air-entraining breaking waves fundamentally influence weather and climate through bubble-mediated ocean-atmosphere exchanges, and influence marine engineering design by impacting statistics of wave heights, crest heights, and wave loading. However, estimating individual breaking wave energy dissipation in the field remains a fundamental problem. Using laboratory experiments, we introduce a new method to estimate energy dissipation by individual breaking waves using above-water images of evolving foam. The data show the volume of the breaking wave two-phase flow integrated in time during active breaking scales linearly with wave energy dissipated. To determine the volume time-integral, above-water images of surface foam provide the breaking wave timescale and horizontal extent of the submerged bubble plume, and the foam decay time provides an estimate of the bubble plume penetration depth. We anticipate that this novel remote sensing method will improve predictions of air-sea exchanges, validate models of wave energy dissipation, and inform ocean engineering design.

1. Introduction

Breaking waves at the ocean surface dissipate wave energy, and, if sufficiently energetic, also entrain air forming turbulent sub-surface bubble plumes and associated surface whitecap foam patches [Melville, 1996]. Microscale breaking waves also dissipate wave energy but do not entrain air or at least sufficient air to be called whitecaps, and are not the focus of this study [Jessup et al., 1997]. Consequently, air-entraining breaking waves generate underwater bubble plumes and turbulence, mix the upper ocean boundary layer, increase ocean albedo, limit the height of individual waves, and help balance the wind energy input to the oceans [Lamarre and Melville, 1991; Frouin et al., 2001; Deane and Stokes, 2002; deLeeuw et al., 2011; Latheef and Swan, 2013] (hereafter we use the term breaking wave to explicitly mean breaking waves that produce visible foam observable with digital imagery). Despite their importance, estimating energy dissipation by individual oceanic breaking waves remains a fundamental oceanographic problem [Babanin, 2011].

State-of-the-art remote sensing methods for estimating breaking wave energy dissipation rely on measuring the speed of advance of the actively breaking wave crest, c_b . The method is based upon the pioneering laboratory work of Duncan [1981] whose experiments showed the rate of wave energy dissipation in air-entraining breaking waves was proportional to breaking wave speed raised to the fifth power. A non-dimensional constant of proportionality, the so-called breaking strength parameter, b , was defined to link the kinematics of the breaking crest with its energy loss. It has been shown in the laboratory that b can vary by several orders of magnitude for individual breaking waves because of an additional non-linear dependence on wave slope [e.g., Drazen and Melville, 2008; Romero and Melville, 2012]. In the field, however, b has yet to be determined for individual breaking waves and a recent analysis of several field and modelling datasets suggests that averaged bulk values of b vary only weakly with sea state, as defined by wave age [Zappa et al., 2016]. Additionally, field-derived bulk values of b can be sensitive to the image processing methodology adopted [Banner et al., 2014; Zappa et al., 2016]. Complementary methods to estimate energy dissipation by individual oceanic breaking waves are needed.

A new digital image-based remote sensing technique (the volume time-integral method) to estimate the total energy dissipated by individual breaking waves is reported. The volume time-integral method has been developed in the laboratory using images of the two-phase flow generated by breaking waves. Previous laboratory measurements have shown that the maximum volume of air entrained by breaking waves scales with energy dissipation [Lamarre and Melville, 1991]. Recently, the saturation of fluid turbulence within

breaking wave crests has been reported using direct and indirect measurement techniques [Deane *et al.*, 2016]. These observations show that the space and time averaged dissipation rate of turbulent kinetic energy, ϵ , inside actively breaking wave crests is largely independent of breaking wave scale: larger, more energetic breaking waves lead to an increase in air entrainment, but without significant increases in averaged turbulent intensity. Independently, oceanic acoustic data collected at wind speeds up to 50 m s^{-1} suggest that breaking wave turbulence under these extreme conditions is similar in magnitude to that measured in laboratory experiments [Zhao *et al.*, 2014]. Taken together, these laboratory and field results suggest that the total energy dissipated should scale with the volume of the two-phase flow integrated over time. In other words, the available evidence suggests that the volume time-integral of the two-phase flow during breaking may be used as a proxy for total breaking wave energy dissipation in whitecaps.

The data presented here support these findings and show that the volume-time integral of the two-phase flow during the growth of the associated surface foam area is strongly correlated with total breaking wave energy dissipation. To develop a digital image based remote sensing technique around these concepts, the penetration depth of the two-phase flow (which can be measured in the laboratory, but not easily in the field) must be parameterized from above-water imagery. Deeper bubble plumes create a more persistent surface foam expression, or whitecap [Callaghan *et al.*, 2013], and this physical connection is exploited to infer the depth of the bubble plume from the whitecap foam decay time. It is shown that everything required in determining the volume-time integral can therefore be estimated from the growth and decay of surface foam area measured from 2-D images of the sea surface.

The paper proceeds as follows. An overview of the experimental setup is given followed by a description of foam area evolution during breaking. Thereafter, a mathematical model relating whitecap foam variables to energy dissipation is derived for an individual breaking wave. The model is then evaluated with laboratory data for breaking waves ranging from gently spilling to strongly plunging, and the results compared to data from 3 other studies, before final remarks are given.

2. Materials and Methods

Breaking wave experiments were performed in a wave channel (33 m long, 0.5 m wide, 0.6 m deep) located in the Hydraulics Laboratory at Scripps Institution of Oceanography (SIO), which was filled with seawater pumped from La Jolla Shores Beach and passed through a sand filter. Using a dispersive focusing technique, 20 breaking wave packets ranging from gently spilling to strongly plunging were generated. Wave gauges placed upstream and downstream of the breaking region allowed the energy of the wave packet to be calculated before and after breaking; the difference giving the total energy dissipated by breaking. The surface foam generated during breaking was imaged using a one megapixel, downward-looking camera operated at 30 Hz, and the bubble plume was simultaneously recorded through the glass walls of the channel with an identical camera. Examples of foam and plume images are given in Figure 1, and quantitative measures of evolving foam area and bubble plume depth during wave breaking are also shown. Further details on experimental setup, energy dissipation calculations and imaging techniques are given in the Supporting Information.

3. Process Description

The broadband scattering of light by bubbles and surface foam arising during wave breaking, over and above that from unbroken background water, enables time series' of foam area and bubble plume cross-sectional area to be measured from digital images using an intensity threshold technique [e.g., Callaghan and White, 2009; Schwendemann and Thomson, 2015]. For individual breaking waves, the resulting foam area time series, $A(t)$, is well-characterised by a growth-decay function of the form $A(t) = c_0 t^n \exp(-c_1 t)$, where c_0 , c_1 , and n , are suitably-chosen constants, and t is time after the onset of breaking. Similar expressions have been used in other breaking wave studies [e.g., Lamarre and Melville, 1991; Lim *et al.*, 2015]. The temporal evolution of foam area is presented in Figure 1m for a single breaking event, and in Figure 1n, in normalized form, averaged over 20 breaking waves. Least mean square fits of the growth-decay function to individual breaking wave foam area allow the identification of whitecap growth and decay phases that are delineated by a peak foam area, A_0 , which occurs at a time, $t = t_0$. Characteristic whitecap growth and decay timescales are then readily

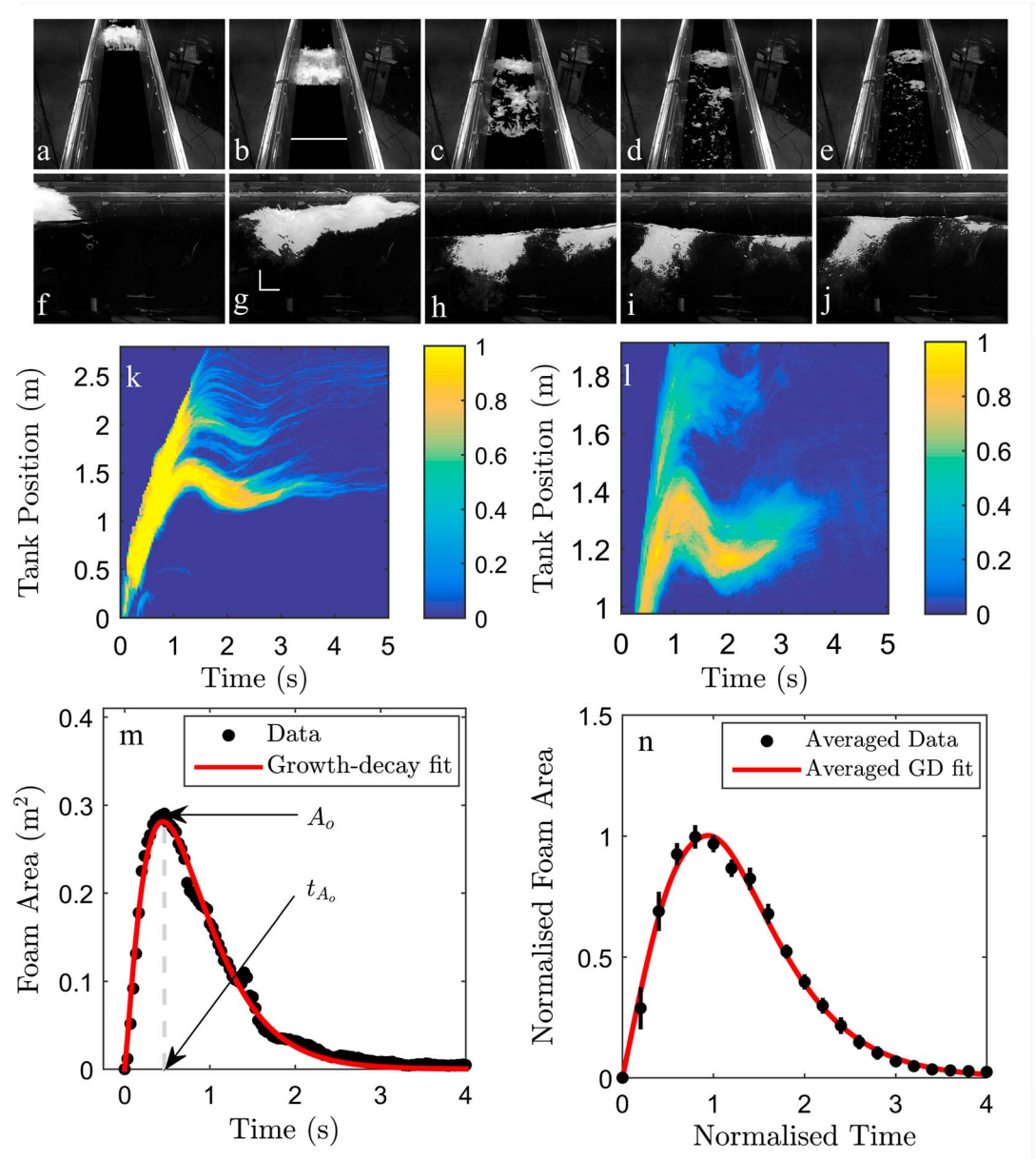


Figure 1. (a–e and f–j) Snapshots in time of the evolving surface foam and subsurface bubble plume during wave breaking, respectively. Adjacent images are separated in time by 1/2 s. The horizontal white line in Figure 1b is 44 cm in scale, the effective width of the channel used. The vertical and horizontal white lines in Figure 1g are 10 cm in scale. (k) The across-channel fractional foam area coverage as a function of time and distance along the wave channel. (l) The normalized maximum bubble plume depth as a function of time and distance along the wave channel. (m) The measured temporal evolution of foam area for a single breaking wave (black dots). The red line is a growth-decay model function, $A(t) = c_0 t^n \exp(-c_1 t)$. The separation of the foam area growth and decay phases is indicated by the vertical dashed grey line which occurs at maximum foam area, A_o , at a time of $t = t_{A_o}$. (n) The normalized foam area evolution averaged over all 20 breaking waves (black dots). The thin vertical black lines correspond to 95% confidence intervals on each averaged data point, and the red line is the normalized averaged growth-decay function fit for all 20 breaking waves.

defined as $\tau_{growth} = A_o^{-1} \int_0^{t_{A_o}} A(t) dt$, and $\tau_{decay} = A_o^{-1} \int_{t_{A_o}}^{\infty} A(t) dt$, respectively. The growth timescale is a function of the duration of breaking and the rate of increase in foam area, and the decay timescale is controlled by bubble plume depth and surfactant activity. Deeper bubble plumes and higher surfactant activity lead to larger values of τ_{decay} . In this analysis, breaking waves generated in filtered seawater with a surface tension

of 73 mN/m are studied. The implied film pressure (~ 1 mN/m) is sufficiently low that the role of surfactant activity on τ_{decay} can be neglected, and foam decay is dominated by bubble plume degassing [Callaghan *et al.*, 2013].

When an individual wave breaks, it may entrain multiple vortices of air with associated surface whitecap foam strips (see Figure 1). The temporal evolution of total foam area forming an isolated individual breaking wave is therefore a function of the growth and decay of the combined set of individual whitecap foam strips, and A_o simply marks the point at which whitecap growth and decay phases are in equilibrium. Importantly, A_o , τ_{growth} and τ_{decay} are easily measured for individual whitecaps using digital imagery of the water surface [Callaghan, 2013], and are parameters well-suited for automated measurement with digital image processing.

The whitecap growth phase is accompanied by vigorous air entrainment, intense fluid shear stress and sound generation, and has been termed the acoustically active phase [Deane and Stokes, 2002]. Air fraction and turbulent kinetic energy are largest in this phase of evolution. By contrast, during the whitecap decay phase air entrainment ceases, turbulent motions decay, bubbles are no longer fragmented, and the two-phase flow becomes acoustically quiescent. The interdependence between the surface whitecap foam and sub-surface bubble plume forms an important physical link between what is observed at the water surface and the physical processes occurring within the water column (see Figure 1).

4. Results

4.1. Model Development

To accomplish the task of developing the remote sensing technique, the breaking wave energy dissipation must first be described mathematically, and then linked to the surface foam variables A_o , τ_{growth} and τ_{decay} . It is assumed that the dominant mechanisms for the dissipation of wave energy include loss of energy due to fluid turbulence, E_e , and potential energy of the submerged bubble plume, E_{PE} [Rapp and Melville, 1990; Blenkinsopp and Chaplin, 2007], and other dissipative mechanisms, such as the generation of currents, are ignored. A glossary of all mathematical terms is included in the Supporting Information.

The energy loss associated with the i th bubble plume and associated whitecap foam strip ($\Delta E_{T,i}$) in an individual breaking wave may be approximated as

$$\Delta E_{T,i} = E_{e,growth,i} + E_{e,decay,i} + E_{PE,i}. \quad (1)$$

Here E_e has been separated into a growth-phase component, $E_{e,growth,i}$ and a decay-phase component, $E_{e,decay,i}$ [see also equation (7) in Deane *et al.*, 2016]. To clarify the relative importance of the terms in equation (1), the scaling factors $\beta_i = E_{e,decay,i}/E_{e,growth,i}$ and $\gamma_i = E_{PE,i}/\Delta E_{T,i}$ are introduced. We do not have direct estimates of β , but it may be reasonably assumed to be equal to or less than 1, and, based on previous laboratory experiments, may be relatively constant for spilling and plunging breakers [e.g., Rapp and Melville, 1990]. Estimates of $E_{PE,i}$ from prior studies [e.g. Deane and Stokes, 2002] show γ_i to lie in the range of 0.03 and 0.15, but higher values have also been reported [Lamarre and Melville, 1991].

Using β_i and γ_i , equation (1) is rewritten as

$$\Delta E_{T,i} = E_{e,growth,i} \left[\frac{1 + \beta_i}{1 - \gamma_i} \right]. \quad (2)$$

The turbulent kinetic energy dissipation, $E_{e,growth,i}$ can be cast in terms of the turbulent dissipation rate of turbulent kinetic energy, ε , water density, ρ , and two-phase flow volume, V ,

$$E_{e,growth,i} = \rho \bar{V}_i \bar{\varepsilon}_i \tau_{A,i} (1 - \overline{\alpha_{e,i}}) \quad (3)$$

where a single overbar represents a time-average, a double overbar a time and space average. The term $\tau_{A,i}$ is

the timescale of the acoustically active period of the i th bubble plume, $\bar{V}_i$ is an average plume volume defined to be $\bar{V}_i = \frac{1}{\tau_{A,i}} \int_0^{\tau_{A,i}} V_i(t) dt$, and the variables $\bar{\epsilon}_i$ and $\bar{\alpha}_{e,i}$ are the space and time averaged turbulent kinetic energy dissipation rate and air fraction [see equations (12) and 14 in *Deane et al.*, 2016, and Supporting Information]. The total energy dissipated by a breaking wave can be estimated across all N plumes:

$$\Delta E_T = \sum_{i=1}^N \Delta E_{T,i} = \sum_{i=1}^N \rho \bar{V}_i \tau_{A,i} \bar{\epsilon}_i (1 + \beta_i) \left[\frac{1 - \bar{\alpha}_{e,i}}{1 - \gamma_i} \right]. \quad (4)$$

Summing over all bubble plumes within a single breaking wave, equation (4) becomes

$$\Delta E_T = \left[\frac{1 - \bar{\alpha}_e}{1 - \gamma} \right] (1 + \beta) \bar{\epsilon} \bar{V} \tau_A, \quad (5)$$

where $\bar{V} = \sum_{i=1}^N \tau_{A,i}^{-1} \int_0^{\tau_{A,i}} V_i(t) dt$ and $\tau_A = \sum_{i=1}^N \tau_{A,i}$.

The task now is to develop the necessary steps to estimate $\bar{V} \tau_A$ using digital images of evolving surface foam. Firstly, it is noted that $\bar{V} \tau_A$ is $\bar{V} \tau_A = \tau_A \tau_A^{-1} \int_0^{\tau_A} V(t) dt$, and represents the time integral of the two-phase flow volume when air is entrained and large bubbles are fragmented due to fluid shear stresses. Next, $V(t)$ is written in terms of the surface foam area, $A(t)$, and bubble plume penetration depth, $z_p(t)$, such that $V(t) = A(t) z_p(t)$, noting that $A(t)$ can be measured from digital imagery of the surface foam. It is further assumed that the time to maximum foam area is proportional to the acoustic timescale such that $t_{A_0} \propto \tau_A$. This is a reasonable assumption since the foam area expands in its growth phase as air is entrained during active wave breaking. Now $\bar{V} \tau_A$ in equation (5) can be approximated as the integrated volume of the two-phase flow during the growth period of the foam area written as

$$\bar{V} \tau_A \propto \int_0^{t_{A_0}} A(t) z_p(t) dt, \quad (6)$$

where t_{A_0} is the time of peak foam area. To express the integral in equation (6) in terms of variables easily quantified through digital image remote sensing, namely A_0 and τ_{growth} defined above, the second mean value theorem for integrals is used. By doing so, the whitcap area-weighted mean bubble plume depth, $\hat{z}_{p,t_{A_0}}$, is defined as $\hat{z}_{p,t_{A_0}} = \int_0^{t_{A_0}} A(t) z_p(t) dt / \int_0^{t_{A_0}} A(t) dt$. Equation (6) can now be written in terms of A_0 , τ_{growth} and bubble plume depth, $\hat{z}_{p,t_{A_0}}$, following

$$\bar{V} \tau_A \propto \hat{z}_{p,t_{A_0}} A_0 \tau_{growth}. \quad (7)$$

As a final approximation, the asymptotic value of the area-weighted mean bubble plume depth, $\hat{z}_{p,\infty}$, is used in place of $\hat{z}_{p,t_{A_0}}$ (see Supporting Information), and $\bar{V} \tau_A$ is approximated in terms of three variables, two of which can be easily estimated from images from surface foam. The final task is therefore to develop a method of estimating $\hat{z}_{p,\infty}$ from images of surface foam, and this is explored in more detail in the following section. Total wave energy lost by an individual breaking wave is now written as

$$\Delta E_T \propto \underbrace{\rho \left[\frac{1 - \bar{\alpha}_e}{1 - \gamma} \right] (1 + \beta) \bar{\epsilon}}_a \underbrace{A_0 \hat{z}_{p,\infty} \tau_{growth}}_b. \quad (8)$$

By definition, the terms $\bar{\epsilon}$, β , γ and $\bar{\alpha}_e$ are constant for an individual breaking wave, and equation (8) shows that the energy dissipated by an individual breaking wave is proportional to the two-phase flow volume during the foam area growth phase. Furthermore, because bubble plume potential energy ($E_{PE} = \gamma \Delta E_T$) is dependent on the volume of air inside the two-phase flow, the terms $\bar{\alpha}_e$ and γ are inter-dependent. Accordingly, equation (8) is re-written as

$$\Delta E_T = \underbrace{\rho \Omega (\bar{\epsilon}, \bar{\alpha}_e, \beta, \gamma, t^*)}_a \underbrace{A_0 \hat{z}_{p,\infty} \tau_{growth}}_b, \quad (9)$$

where the terms in part a of equation (8) are represented by a single variable, Ω , which is referred to as a turbulence strength parameter with dimensions $W \text{ kg}^{-1}$. The value of Ω is dependent on the dissipation rate of

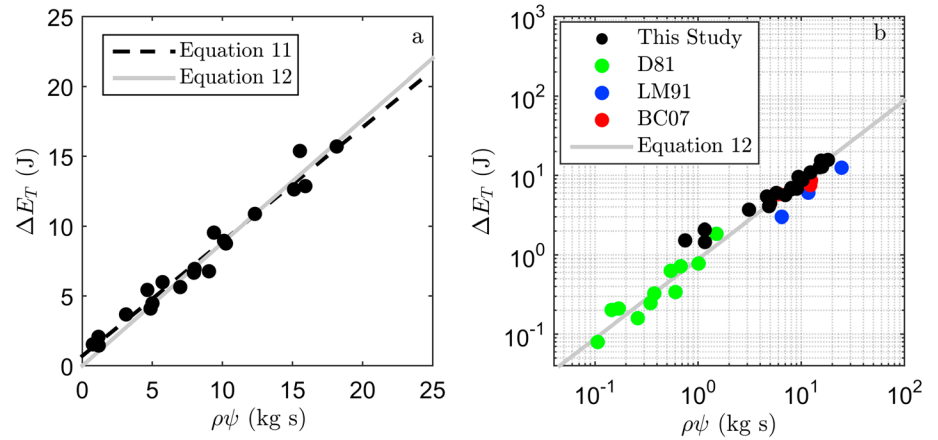


Figure 2. (a) The relationship between the volume-time integral (ψ) and the measured energy dissipation (ΔE_T) calculated from water surface elevation measurements. The dashed black line and the solid grey line depict equations (11) and (12), respectively. (b) The relationship between ψ and measured energy dissipation for this study (black dots), and the studies of Duncan [1981] (D81, green dots), Lamarre and Melville [1991] (LM91, blue dots), and Blenkinsopp and Chaplin [2007] (BC07, red dots). The solid grey line depicts equation (12).

turbulent kinetic energy and air fraction inside the breaking wave crest, the values of the scaling coefficients β and γ , as well as t^* which is a constant of proportionality that relates the acoustic and optical estimates of the two-phase flow volume time-integral (see equation (6)). Deane *et al.* [2016] report $\bar{\epsilon}$ to fall between 0.4 and 1.2 W kg^{-1} , and Ω is expected to lie close to this range. Part b of equations (8) and (9) is the volume time-integral (ψ) of the sub-surface two-phase flow during the whitecap growth phase defined to be

$$\psi = A_o \bar{z}_{p,\infty} \tau_{\text{growth}}, \quad (10)$$

with units $\text{m}^3 \cdot \text{s}$. Equation (9) states that total wave energy dissipation for a single breaking wave is proportional to the time-integrated two-phase flow volume beneath a whitecap during its growth phase. Since ΔE_T and ψ can be measured in the laboratory, values of Ω can be determined for individual breaking waves of varying slope, scale and bandwidth.

Having established a simplified model for breaking wave energy dissipation, the development of a remote sensing technique to estimate ΔE_T for individual breaking waves is dependent on two primary factors. Firstly, the value of Ω should remain relatively invariant for all breaking waves, and secondly, a measure of bubble plume depth must be obtained from images of surface foam. The results presented below suggest that Ω is largely constant across 20 breaking waves ranging from gently spilling to strongly plunging, and more generally, good agreement is found between this study and the results from three other laboratory studies [Duncan, 1981; Lamarre and Melville, 1991; Blenkinsopp and Chaplin, 2007; hereafter these studies are referred to as D81, LM91, and BC07 respectively]. In the following section the model is evaluated and the link between whitecap and bubble plume decay time is exploited to estimate bubble plume depth from whitecap decay times.

4.2. Model Evaluation

Measurements and calculations from this study and D81, LM91 and BC07 allow the volume time-integral method derived above to be evaluated (Full details on how the volume time-integral was evaluated for the additional studies are given in the Supporting Information). Beginning with this study, digital images of the foam and subsurface bubble plumes are used to estimate ψ , and surface elevation records from wire wave gauges are used to estimate ΔE_T (see Supporting Information).

Figure 2a depicts the relationship between ΔE_T and ψ for the breaking waves examined here. A least-squares fit to the laboratory data gives the linear relationship

$$\Delta E_T = 0.82(\pm 0.07)\rho\psi + 0.70(\pm 0.72)[J], \quad (11)$$

with $r^2 = 0.97$ (values in parentheses represent 95% confidence intervals). The slope of equation (11) is related to the turbulent intensity inside the actively breaking crest, and has the value $0.82(\pm 0.07) \text{ W kg}^{-1}$. The non-

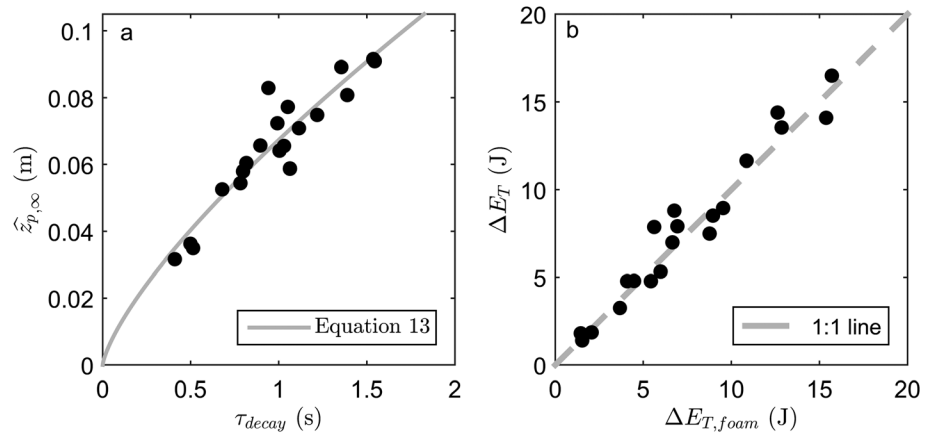


Figure 3. (a) The relationship between foam decay time and asymptotic value of the area-weighted mean bubble plume depth, $\hat{z}_{p,\infty}$. The grey line is equation (13). (b) A scatterplot of breaking wave energy dissipation calculated from in situ measurements of the water surface elevation (ΔE_T) and the breaking wave energy dissipation inferred from remotely sensed measurements of surface foam ($\Delta E_{T,foam}$). Values of $\Delta E_{T,foam}$ are calculated by using equations (10), (11), and (13). The dashed grey line represents perfect agreement.

zero y-intercept may indicate that processes such as the generation of vorticity in the steep wave crest just prior to breaking also contributed to wave energy loss but not directly to air-entrainment. Measurement errors, residual motions in the wave channel between breaking events, and simplifications regarding the relative magnitude of energy sinks other than fluid turbulence and bubble plume potential energy, may also have contributed to the offset. Nevertheless, Figure 2a suggests that for the breaking waves generated in this study, ψ is a good indicator of total energy dissipated due to breaking. The lack of considerable scatter demonstrates the relative invariance of Ω across the range of breaking waves studied lending support for the model derivation above and to the hypothesis of fluid turbulence saturation [Deane *et al.*, 2016]. Forcing the fit to pass through the origin results in the relationship

$$\Delta E_T = 0.88(\pm 0.04)\rho\psi [J], \quad (12)$$

with $r^2 = 0.96$, which is only marginally different from equation (11).

For comparison to other studies, Figure 2b shows the relationship between energy dissipation and ψ from D81, LM91, BC07, and this study. The combined datasets from these four studies demonstrate an encouraging level of agreement across 2.5 decades of energy dissipation. The majority of data points lie close to equation (12), and the lack of significant scatter within the amassed dataset lends support to the hypothesis that the volume time-integral of the two-phase flow is linearly related to total energy dissipated. The probability density function of Ω for the data in Figure 2b is given in the Supporting Information, and shows a distinct peak in the range $0.5 < \Omega < 1$ [W kg⁻¹].

4.3. Digital Image Remote Sensing Technique

The data presented in Figure 2 demonstrates that the ability to remotely sense ψ using images of foam, coupled with an estimate of Ω , could provide a reasonable estimate of energy dissipation by individual breaking waves. From an above-water remote sensing viewpoint, the terms A_o and τ_{growth} are easily determined from images of evolving foam. However, $\hat{z}_{p,\infty}$ is a subsurface measurement, and thus needs to be determined from the evolving surface foam. It has been shown that surface foam area decay follows a 1:1 relationship with the bubble plume decay when surfactants do not significantly affect foam evolution [Callaghan *et al.*, 2013]. In other words, optically discernible foam persists as long as there is a sufficient flux of bubbles to the water surface (see Figure 1). We exploit the physical link between bubble plume depth and foam area decay time to infer $\hat{z}_{p,\infty}$ using 2-D surface foam imagery.

Figure 3a shows that the relationship between foam area decay time, τ_{decay} , and $\hat{z}_{p,\infty}$. The resulting best fit power law relationship is written as

$$\hat{z}_{p,\infty} = 0.07(\pm 0.01)\tau_{decay}^{0.74(\pm 0.15)}. \quad (13)$$

with $r^2 = 0.88$. The power law relationship between τ_{decay} and $\hat{z}_{p,\infty}$ allows subsurface plume properties to be determined from surface foam evolution. Additional power law and linear relationships between the foam decay time and several measures of bubble plume penetration depth are presented in the Supporting Information.

The final observation demonstrating a link between the sub-surface bubble plume and foam decay time completes the remote sensing technique. Using data from this study, Figure 3b shows the comparison between the measured breaking wave energy dissipation and that estimated using foam properties, $\Delta E_{T,foam}$, calculated using equations (10), (11) and (13). By adopting a practical way to estimate bubble plume depth, foam properties can be used to determine the volume time-integral for individual breaking waves, and the associated energy dissipation can be determined in combination with the turbulence strength parameter, Ω .

5. Discussion and Conclusions

A simplified mathematical model relating energy dissipation to the breaking wave two-phase flow volume time-integral has been presented, and evaluated with data from 4 different laboratory studies. Moreover, it is shown that the volume time-integral and energy dissipation can be determined from measurements of evolving surface foam area. Key to this process is exploiting the physical link between the foam decay time and bubble plume depth.

As stated in the Introduction, current optical remote sensing techniques to estimate breaking wave energy dissipation require measuring the breaking wave speed and choosing a value for the wave-slope dependent breaking strength parameter, b . However, estimating b in the field on a whitecap-by-whitecap basis has not yet been achieved. The plume volume time-integral method presented here allows the possibility to determine b for individual oceanic breaking waves, for comparison with laboratory measurements.

The analysis presented here is explicitly applicable to air-entraining breaking waves, or whitecaps. It is acknowledged, however, that recent field studies have demonstrated the importance of dissipation by microscale breaking waves, which may support 10% to 90% of total wave energy dissipation depending on wave field development [Sutherland and Melville, 2013, 2015]. Employing a bottom-up accounting system for energy dissipation by whitecaps, coupled with independent estimates of total wave field energy dissipation, could provide an indirect means to estimate the fraction of energy dissipated by microscale breaking waves. Doing so accurately would have important implications for evaluating how bubble-mediated air-sea interaction processes vary depending on the relative magnitude of dissipation by micro-breakers and whitecaps.

These laboratory data are the first to quantify the relationship between individual evolving foam area signatures and energy dissipation, and show that foam evolution in both whitecap growth and decay phases depends on the energy dissipated during breaking. Taking the whitecap area growth phase to be analogous to the Stage A whitecap definition of Monahan and Lu [1990], these results imply that Stage A whitecap coverage is not uniquely related to breaking wave energy dissipation. Such a relationship would only strictly be valid if bubble plume penetration depths were constant across all oceanic breaking waves, which is contrary to laboratory observations, and unlikely to be true in the field.

It has been shown that the total energy dissipated by laboratory air-entraining breaking waves is strongly correlated to the volume time-integral of the two-phase flow generated during active breaking and can be estimated using digital images of time-evolving whitecap foam. Further laboratory work should apply the concepts outlined above to breaking arising from modulational instability, as well as breaking in 3-dimensions and in random seas in the presence of wind. Indeed, Galchenko *et al.* [2012] demonstrate that direct wind forcing can shorten the time to breaking for a wave group and decrease the dissipation in a single breaking event. It remains to be tested if this decrease in dissipation would also be reflected in the evolution of the two-phase flow, which is of particular relevance to the method presented here. Data collected in wind-forced conditions should be added to those in Figure 2b which were obtained in the absence of wind-forcing.

Furthermore, the relationship between plume penetration depth and foam decay time should also be explored for wind-forced breakers since this forms an integral part of the remote sensing technique. Finally, surfactants in the open ocean have the potential to prolong the decay time of whitecap foam over-and-above that expected from bubble plume degassing. Therefore the imprint, nature, and magnitude of any surfactant effect on foam evolution should also be quantified so that plume penetration depths are not overestimated in any field application of the volume time-integral technique.

Acknowledgments

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