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Bubbles and breaking waves

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The physical processes which control the transfer of gases between the atmosphere and oceans or lakes are poorly understood. Clouds of micro-bubbles have been detected below the surface of Loch Ness when the wind is strong enough to cause the waves to break. The rate of transfer of gas into solution from these bubbles is estimated to be significant if repeated on a global scale. We present here further evidence that the bubbles are caused by breaking waves, and discuss the relationship between the mean frequency of wave breaking at a fixed point and the average distance between breaking waves, as might be estimated from an aerial photograph.

It has been suggested[1] that there may be a causal relationship between whitecaps, or breaking waves, on the surface of a freshwater lake and the individual clouds or bubbles which have been detected acoustically below the surface. The clouds appear with a typical frequency of about 1 per min in wind speeds of 10 m s^{-1} and penetrate to depths of at least 5–10 m. To investigate the relationship, and other phenomena, we measured breaking waves in Loch Ness using a capacitance wire probe[2] and time-lapse photography.

The capacitance wire probe was placed on a mooring connected to shore[3] in a water depth of ~160 m and 250 m from the shore, where the fetch for north-east or south-west winds is some 10 km. The wind speed was measured by an anemometer on a tripod in the loch. As the slope of the water surface in a breaking wave is large, the electronic circuit used with the probe was designed to detect large gradients in surface height. The signal voltage from the probe, proportional to the wave height, was passed through a differentiator and the output compared with a reference level which could be set according to the wave conditions. When the differentiated signal exceeded the reference, a spike generator was triggered which marked the record.

The slope, $\partial h/\partial x$, of the water surface is related to the time derivative, $\partial h/\partial t$, of the wave height measured at a point, by

$$\frac{\partial h}{\partial t} = c\frac{\partial h}{\partial x} \quad (1)$$

where c is the phase speed of the waves. For small deep-water waves $c = c_0 = gT/2\pi$, where T is the wave period and g the acceleration due to gravity[4]. For large amplitude waves the phase speed is a function of the wave slope. The maximum slope of a regular progressive wave train in deep water[5] is close to 30° when the phase speed[6], $c = 1.0923c_0$, and hence the maximum value of the time derivative is approximately

$$\frac{\partial h}{\partial t} = 0.1004gT \quad (2)$$

(The greatest wave speed is estimated[6] at $c = 1.09295c_0$ and hence equation (1), with $c = c_0$, may be used with an error of <10%).

The capacitance wire probe was used to measure the mean wave period, T, estimated from the zero-crossing interval, and equation (2) used to estimate $\partial h/\partial t$ for a limiting wave. In practice the reference level setting was set empirically to trigger 'spikes' on an ink-plotting pen when a breaking wave could be seen at the probe, and considerably smaller values than the theoretical equation (2) were found to be suitable. Trouble was encountered by spikes being triggered near wave nodes where the wave slope is large but where no breaking or bubble entrainment occurs. Waves tend to break near their crests and these spurious spikes were avoided by incorporating a circuit which passed the signal spike only if the wave height exceeded a certain level, which was set in relation to the observed height of the existing wave field.

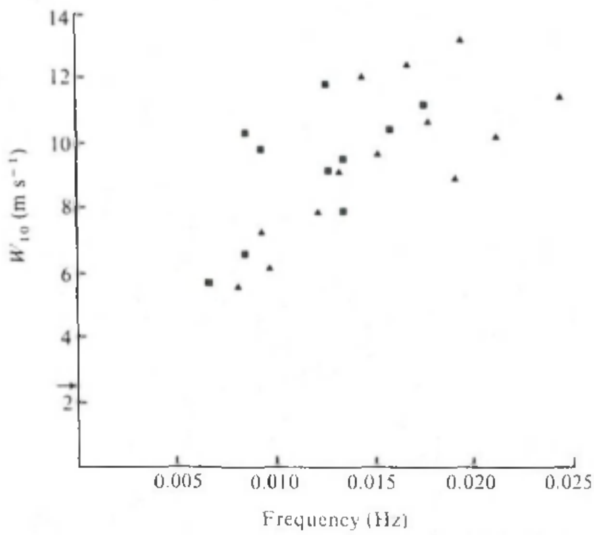

Fig. 1 Wind speed, W_{10} (corrected to 10 m) versus frequency f, of bubble clouds seen on a sonar record[1] (■), or frequency of breaking waves (▲), only one wave being counted when neighbouring waves break as the sonar record cannot resolve a time scale corresponding to individual waves, the bubble clouds from neighbouring waves are expected to merge. Observation periods of at least 20 min were used. The mean standard deviation of the number of waves in a five minute period is ~2.6. The arrow marks the approximate wind speed at which whitecaps and bubbles are first observed.

The success of the system in identifying breaking waves was tested by taking cine film of the probe and water surface from shore and by comparing the record of wave height and spikes with the photographic record. In calm weather tests were also made by artificially creating breaking waves in the wake of a boat which passed close by the probe. The detection system was insensitive to brief spikes of the order of 25 ms or less in which $\partial h/\partial t$ just exceeds the threshold. Waves less than the probe dimensions, ~10 cm, were not resolved either by the probe or by the camera, but larger waves with crest lengths exceeding this dimension were detected.

For wind-waves Loch Ness is effectively an enclosed basin, and swell from distant storms which might, at sea, induce wave breaking[7], is absent. A relationship might therefore be expected between the frequency of wave breaking and the local wind speed. Figure 1 shows the average frequency of wave-breaking

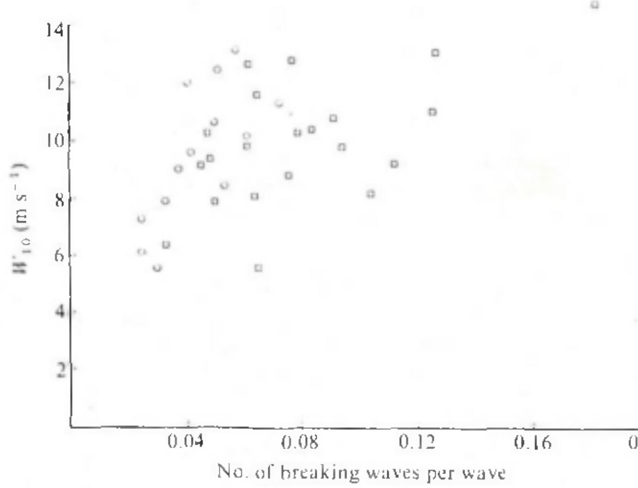

Fig. 2 Wind speed, W_{10} (corrected to 10 m) versus ○, $T/\bar{t}$ or □, $\lambda/\bar{x}$, the number of breaking waves per wave, groups counting once only (see text). $\lambda/\bar{x}$ was calculated over an effective horizontal length of at least 2,280 m.

events and individual bubble clouds seen in the sonar records[1], plotted against wind speed. There is considerable scatter, arising partly from the uncertainty in identifying individual bubble clouds in the sonar records and partly from the unsteadiness of the wind. There is an upward trend in both sets of points, commensurate with a zero value at a wind speed of $\sim 2.5 \text{ m s}^{-1}$ when whitecaps and bubble clouds are first observed. Whilst the frequencies are similar, the number of wave-breaking events exceeds that of the bubble clouds. A contributing factor may be that some waves, breaking 'gently', do not produce bubbles which penetrate below the depth of the pre-existing cloud.

The average period between the occurrence of breaking waves at the probe was compared with the mean distance between breaking waves approaching the probe. The latter was derived from time-lapse photographs of the water surface taken from the hillside above the loch. The width of the camera frame was established by taking photographs of a rubber boat of known dimensions. The time interval between frames was such that groups of waves would travel a distance well exceeding the frame width during the time interval, and thus be filmed only once. With the assumption that their statistics were uniform, the mean distance between whitecaps, $\bar{x}$, was found by dividing the number of breaking waves observed to intersect a line along the loch axis (approximately the mean direction of wave advance) into the total effective frame length.

The large and steep waves which break, forming whitecaps, occur in groups. It was very rare to see two neighbouring waves break simultaneously and when this happened only one wave was included in the count. Figure 2 shows estimates of $\lambda/\bar{x}$, where λ is the mean wavelength estimated from using the relation[4] $\lambda = gT^2/2\pi$. Also shown are estimates of $\bar{t}/T$, where $\bar{t}$ is the average time interval, measured by the capacitance wire probe, between successive groups which contained breaking waves. About 58% of the groups which passed the probe with breaking waves contained more than one (none more than three). There is again much scatter in the observations (again variation in wind conditions may have contributed) but evidence of an increase in both $\lambda/\bar{x}$ and $T/\bar{t}$ with wind speed. This is partly due to an increase in T (and hence λ) with wind speed from an average of 2.58 s at wind speeds of 6.17 m s^{-1} to 3.05 s at winds of 12.4 m s^{-1}. On average the values of $\lambda/\bar{x}$ are significantly greater than those of $T/\bar{t}$ at the same wind speeds. (Mean values are 0.076 and 0.056 respectively at a mean wind speed of 9.9 m s^{-1}).

The regions of large waves, and hence whitecaps, advance at the group velocity[8], which, in deep water, is half the phase speed of the waves. Figure 3*a*,*b*,*c* shows the waves in space–time coordinates. The individual breaking waves, advancing at the phase speed, are shown as solid lines of slope $c = \lambda/T$. The groups containing breaking waves advance at the group velocity and are indicated by a succession of these lines, forming a patch outlined by dotted lines with slope $c/2$. If the duration of persistance of a whitecap, D, is more than double the wave period (Fig. 3*a*) each group with breaking waves will contain at least one breaking wave when it is observed at constant time (by a photograph) or as it passes a constant position (the wave probe). If only one breaking wave in each group is counted, the ratio r of the mean distance between such successive observations at constant time and their mean period will be the group velocity, $c/2$. Hence the ratio

$$\chi = (\lambda/\bar{x})/(T/\bar{t}) = \frac{c}{r} = 2 \qquad (3)$$

If, however, $2T > D > T$ (Fig. 3*b*), whilst each group containing breakers will be recorded by at least one breaking wave at the probe (constant x), there are times when no waves at all will be breaking in a particular group, and hence $\chi < 2$. Moreover at most one wave at a time will be breaking in a group. If, as is often observed, $D < T$, then groups containing breaking waves may pass the probe with no breaking event registering. Groups containing multiple breaking waves are more likely to be recorded at a fixed location than to be seen in a photograph, as is indeed observed. The occurrence of multiple breaking waves at the probe suggests that D frequently exceeds T, whilst their

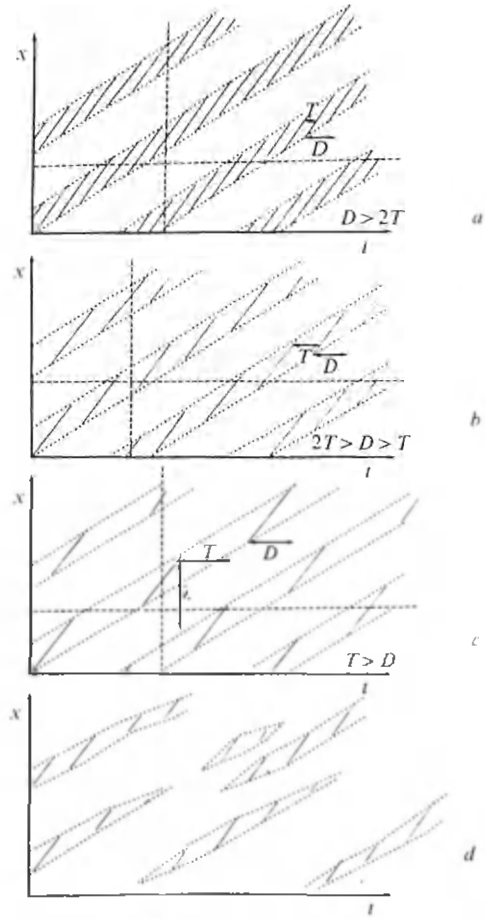

Fig. 3 Space (x)–time (t) diagram of the movement of breaking waves and groups. The heavy lines are breaking waves and the dotted lines are groups. Idealised diagrams when: *a*, $D > 2T$; *b*, $2T > D > T$; *c*, $T > D$; *d* is a sketch of a more realistic situation in which the groups break intermittently. The groups of breaking waves have been drawn closer together than they are in reality. The dashed lines x, constant; and t, constant indicate the way in which the breaking waves are sampled by the probe and by photographs respectively. In *a* these lines cut at least one breaking wave in each group. In *b*, t, constant misses, but x, constant always intersects, one or two of the breaking wave tracks, whilst in *c* both lines occasionally miss and more than one breaking wave in the same group is never sampled.

absence in photographs implies that D is usually less than $2T$.

The observed mean value, $\chi = 1.65$, is consistent with this argument. Because the breaking waves are unlike the idealised model (but resemble Fig. 3*d*) there seems at present no obvious way in which χ may be related to the simple statistics of the wave field. A working value of χ would, however, be useful as it would then be possible, by finding $\bar{x}$ and T (or λ)[8] from aerial photographs, to estimate $\bar{t}$ and hence to determine how often a stationary structure, for example, an oil rig or wave power device, would be subject to groups of breaking waves.

Whilst there is at least circumstantial evidence for a causal relationship between breaking waves and bubbles, more research is needed. Progress might be made by using narrow-beam upward-pointing sonar which could resolve details of the wave surface during wave breaking.

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