Evolution of bubble statistics in intermediate breaking wave groups

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The bubbles generated by breaking waves in the open ocean are an important feature of the ocean surface. They affect optical and acoustical properties of the top few meters of the ocean, influence surfactant scavenging, aerosol production and air-sea gas transfer. Short-lived larger bubbles which re-surface and burst dominate the transfer of less soluble gases such as carbon dioxide. A single wave crest approaching breaking deforms rapidly and in a storm sea the most common breaker is the spilling type. Detailed observations in space and time connecting the shape of the spilling breaker to subsequent bubble populations are limited, and the effect on the bubble penetration depth and residence time underwater is particularly important. In this study, we carried out a series of experiments to track the formation and evolution of large bubbles for different local crest geometries.

A breaking wave in a wave flume was generated with dispersive focusing of a wave group. The group has a pre-defined amplitude spectrum. Running experiments with different phase shifts of the same amplitude spectrum showed that when a peak-focussed wave (zero phase shift) breaks, then wave groups with other added phase shifts break as well. To investigate possible differences in the deformation of those breakers a laser imaging technique was used. An algorithm identified the 2D shape of the breaker in successive images. It also separated the crests from bulges based on geometric criteria. We showed that, despite wave groups having same spectra, the extracted bulges differed locally in shape, volume and velocity for each phase shift at the location of breaking. Therefore, breakers ranging from the more traditional spilling type, which has a bulge that collapses on the front face of the wave, to the micro-plunging type, which has a pronounced overturning tip, were observed depending on the phase shift.

The evolution of bubbles for each phase shifted bulge was captured by a high speed camera and measured by a feature extraction algorithm. We generally found that spilling bulges created fewer bubbles in total than micro-plungers. They also created fewer larger bubbles, i.e. with radius r>1 mm, at all measured flume areas. In contrast, micro-plungers that trap air within a small cavity as they break had less steep size distributions for r>1 mm. The maximum volume of air per radius
showed a gradual shift from $r>1$ mm to $r=1$ mm moving away from the breaking location for all breakers. It is interesting, finally, that the maximum volume per radius did not shift to smaller radii as time passes. This is an indication that the largest bubbles, i.e. $r>4$ mm, rise to the surface and burst instead of splitting into smaller ones, irrespectively of the local breaker properties.