ACOUSTIC AND OPTICAL MEASUREMENT OF BUBBLE POPULATIONS IN THE ATLANTIC OCEAN AND THE MODELING OF GAS TRANSFER THROUGH THESE BUBBLE CLOUDS

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Abstract: *Bubbles, formed by breaking waves, play an important role in the transfer of gases between the Earth's oceans and atmosphere and have been shown to increase the flux of gases during periods of heightened sea state. Having been formed, these bubble clouds evolve through the effects of buoyancy, gas exsolution and dissolution, and the fragmentation and coalescence of bubbles. A number of experimenters have successfully measured sub-surface bubble clouds using a variety of acoustic and optical techniques, although data over a wider range of bubble radii are required for fuller comparison with models of how these clouds evolve and contribute to air/sea transfers of mass, momentum and energy. This paper presents data measured in the Atlantic Ocean, using an 11 metre spar buoy, between 16th June and 18th July 2007. An acoustic system measured the additional attenuation due to bubbles to infer the bubble size distribution whilst an optical system exploited the change in refraction caused by a bubble at the tip of an optical fibre probe. The measured bubble populations are then used as an input to a gas transfer model and the resulting fluxes and their significance will be calculated.*

Keywords: *Bubbles, atmosphere/ocean gas flux, underwater acoustics, ocean waves*

1. INTRODUCTION

With the current high profile of the global climate systems, greater understanding of the factors affecting these systems is required. In response to this, the Natural Environment Research Council set up a programme called SOLAS, Surface-Ocean Lower-Atmosphere Study. The research presented here was carried out as part of this programme.

It has been shown that in areas of increased breaking wave activity, the flux of atmospheric gases into the ocean is increased [1]. This increase has now been shown to be caused by bubbles dissolving atmospheric gas into the ocean [2] and produce a slight supersaturation of these gases in the upper ocean [3].

Bubble populations under breaking waves can number millions per cubic metre, and contain bubbles ranging in radius from microns to centimetres. Of the available techniques for measuring such populations, acoustic methods are the most applicable [4, 5]. However any such acoustic technique contains ambiguities, and so it is best to check the results against an independent measurement (preferably a non-acoustic one) [6, 7].

This paper presents results from experiments carried out in June/July 2007, using acoustic and optical systems mounted on a free-floating, autonomous spar buoy. These data will then be applied to the issue of air/sea gas transfer.

2. EQUIPMENT

The bubble sensing equipment designed by the authors was attached to an 11 metre spar buoy (Figure 1) that was built by the authors' collaborators at the National Oceanography Centre, Southampton, UK (NOC). To this buoy the NOC collaborators also attached wave wires and downward-looking cameras to image the sea surface. The buoy was designed to be free floating and fully autonomous. When deployed in the ocean, approximately 80% of the buoy is underwater, with just 2 metres protruding above the surface. The buoy had an Argos beacon situated in the dome, which sent position data to the ship allowing the buoy to be recovered at the end of a deployment.

2.1. Acoustic system

The acoustic system for bubble counting measures the increased attenuation caused by the presence of bubbles. The acoustic setup consisted of transmit transducers, power amplifiers, an array of hydrophones and an onboard computer to control the equipment. The computer (a MagnumX 1000 low-wattage single-board computer) had a National Instruments 6110 data acquisition card installed to allow high frequency sampling of the incoming data. The power amplifiers and matching circuits used to drive the transmit transducers were custom designed and built by Paul Doust, at the time working for Blacknor Technology. The amplifiers were designed to run off batteries and yet produce a high sound pressure level in the water (approximately 190 dB re 1 μPa). For each measurement, three transducers repeatedly emitted a train of 14 pulses ranging in centre frequency from 3 kHz to 197 kHz. This allowed bubbles with radii ranging from 17 to 1107 microns to be measured. The pulses were then received by an array of three D/140 hydrophones, positioned between approximately 0.8 and 2.6 metres below the sea surface. The received waveforms were then digitised by the data acquisition card and stored on a hard drive for analysis once the buoy had been recovered.

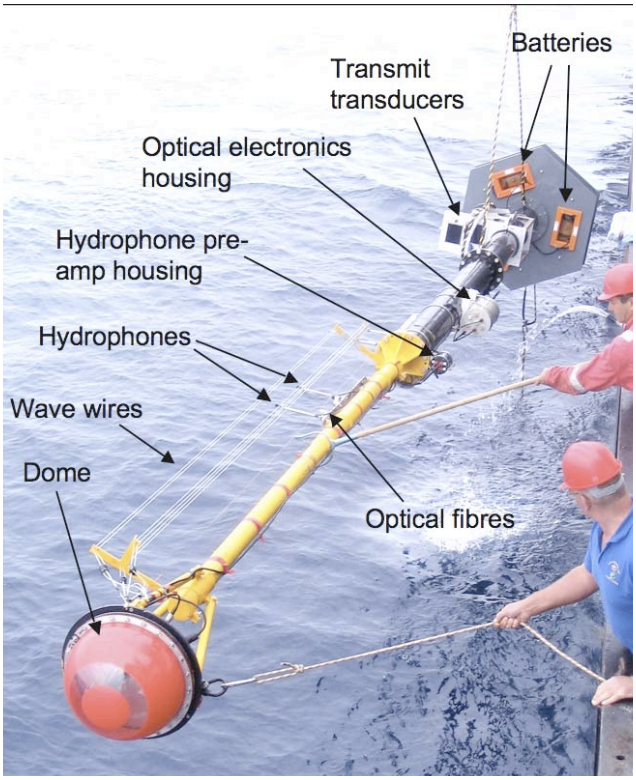

Figure 1. A labeled photograph of the buoy as it is deployed.

2.2. Optical system

The optical system used three fibre-optic tips mounted along the buoy. As bubbles pass over these tips, a change in light intensity is measured and bubble populations can be inferred [8, 9]. The optical system therefore monitors the scattering of light transmitted down an optical fibre: the backscattered scattering changes depending on whether there is water or gas at the end of the tip. As such, the passage of a bubble over the fibre tip generates a transient, one per bubble, and the magnitude, duration, and rise-times of each transient can be used to estimate the bubble size.

3. EXPERIMENTS

As part of the SOLAS programme, the buoy was taken on two sea trials on *RRS Discovery* in the Atlantic Ocean. The first cruise, D313 in November/December 2006, was primarily a proof-of-concept sea-trial for the buoy [10], which enabled the authors to optimise the equipment and prepare for the second sea-trial. The second cruise, D320, took place in June/July 2007. The area of operation was in the North Atlantic, 400 miles west of Portugal.

The buoy was deployed 4 times during D320, with each deployment being 3 or 4 days in duration. During the first deployment, useful data was acquired by the optical system but the bubbles clouds did not penetrate deep enough for the hydrophones to record any meaningful attenuation. The acoustic system did however acquire useful data on the second deployment, whilst a leak in the optical amplifier housing caused a failure of the optical system. The third and fourth deployments did not return any useful data owing to damage to the equipment.

Therefore optical data from the first deployment and acoustic data from the second deployment are presented in the following section.

Meteorological conditions for the deployments can be seen in table 1.

Deployment	**Measurement**	**Mean wave height [m]**	**Mean wind speed [m/s]**	**Mean water temperature [°C]**
1	Optical	1.9	7	17
2	Acoustic	2.7	13	17

Table 1. Meteorological conditions for the two deployments in which data were measured.

4. RESULTS

Bubble size distributions were measured using both acoustic and optical techniques.

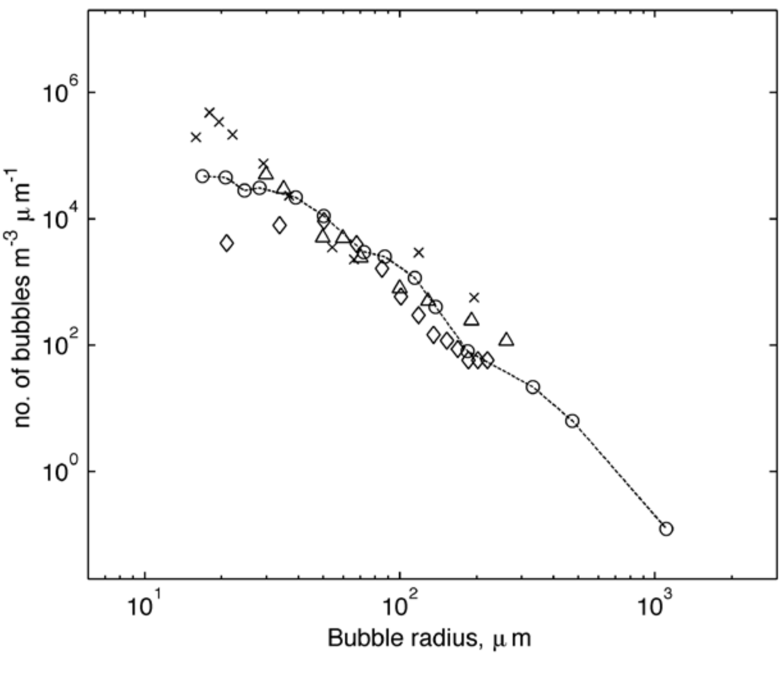

Figure 2. Plot of the acoustically measured bubble size distribution (black circles with dashed line). This population estimate represents the spatially averaged bubble density between two hydrophones, at mean depths of 0.8 m and 2.54 m. Historical measurements are also shown. The diamonds are those of Johnson and Cooke [11], the triangles are those of Breitz and Medwin [12] and the crosses are those of Phelps and Leighton [13].

The acoustic techniques give the population for bubbles ranging from 17 to 1107 microns in radius. The optical techniques could potentially increase this range to larger bubble radii with a working range of approximately 167 to 3500 microns in radius, though the methods have not yet been reliably verified and therefore the results are not shown here. There is very good agreement between the acoustic dataset and the historic measurements. Coupled with the optical measurements, the range of bubble radii measured would exceed any historic measurement. Although these measurements demonstrate the principal that this range is achievable, equipment failure meant that they were not taken under identical sea conditions.

In order to calculate the gas flux associated with these populations, a model of the sub surface bubble cloud evolution can be used and this is described in more detail in the next section.

5. APPLICATION

Woolf and Thorpe [3] show how the traditional equation for air-sea gas transfer can be split into bubble mediated transfer and direct transfer, given by

$$F = K_o(C_w - C_a) + K_b[C_w - C_a(1+\delta)] \quad [5.2]$$

where F is the net transfer of gas across of the sea surface, C_a is the concentration of the gas in air, C_w is the concentration of the gas in water, K_o is the direct contribution to the transfer velocity, K_b is the contribution of bubbles to the transfer velocity and δ is the equilibrium fractional supersaturation of the gas.

The contribution of bubbles to the transfer velocity can be calculated using a model of the evolution of sub-surface bubble clouds and the associated gas transfer through these bubbles presented by Woolf & Thorpe [3]. The results produced by Woolf & Thorpe [3] were based on estimates of oceanic conditions. More accurate results can be obtained if the model is run with parameters taken from the meteorological conditions of D320 and adapted to produce a best fit with the measured bubble size distributions. This technique will be applied in future papers for the data of this paper, and will produce estimates of bubble mediated gas transfer based upon real data and would be an important assessment of the viability of the estimates made by Woolf & Thorpe [3]. This will also enable the variation in the bubble size distribution with depth to be determined and a comparison made of the optical and acoustic measurements.

6. CONCLUSIONS

Bubble measurements were made from a free-floating, fully autonomous spar buoy using both acoustic and optical techniques. These measurements were taken in open ocean, with a depth of approximately 4 km. A range of bubble radii potentially broader than ever before has been measured and a method has been outlined for applying these data to the calculation of bubble mediated gas transfer between the atmosphere and the ocean.

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