Response to Referee #1
"Ocean bubbles under high wind conditions. Part 1: Bubble distribution and development" by Helen Czerski et al., Ocean Sci. Discuss.
https://doi.org/10.5194/os-2021-103-RC1, 2021
27th January 2022

We are grateful to the reviewer for their comments and have prepared a revised manuscript which addresses their concerns. Our response to each point and a description of the changes made are given below (reviewer comment in blue, author response in black).

Scientific issues:

Lin 334, Figure 4: Splitting the data into 3 cases seems very arbitrary. Give more detail on how the data were assigned to a particular case. For example, why are the Case 2 data with 2m void fraction < 7 x 10 -7 not part of Case 3. If there is no objective way to stratify the data, then present them as one case and a fit through all data – or best to remove this figure.

The previous separation was based on data points either both meeting or both falling below numerical criteria. We agree that this appears arbitrary and in the revised manuscript we have removed the case distinction. However have left the figure in because we think it makes an important point. We have noticed a general assumption in the scientific community that bubble plumes vary reasonably smoothly with depth (which is the impression given by sonar backscatter data in other papers) and we think that it is important to show the extent of the heterogeneity at small local scales.

Ln352: What is the area of the camera FOV? Please quantify “very few “. How does the observed number of breaking waves compare to the breaking rate reported in the literature? (E.g. there are several studies that quantify the active breaking rate from breaking crest length distributions obtained from video imagery). If the observed breaking rate is much lower than expected, it might indicate that the freely drifting buoy somehow avoids breaking waves., similar to wave buoys often missing the peak of a steep crest, or by the buoy being located preferentially in the convergence region of Langmuir circulations. If so, the bubble statistics would be biased.

The camera had a fisheye lens but was only 2m above the ocean surface, and so the effective imaging footprint only extended 3-4 metres upwind of the buoy. The camera position was chosen to see the detail of waves breaking just in front of the buoy to correlate with the subsurface measurements, and was not designed to provide data on breaking statistics. The field of view was too small, given the low probability of waves breaking directly within a specific 4m x 4m patch of ocean. “Very few” here is less than ten over the whole campaign, and so we cannot compare breaking statistics. We have added text to the manuscript to clarify this point, and a reference to a paper that has some description of the setup and and example pictures. The buoy behaviour was observed carefully while it was within sight of the ship, and we saw no evidence that the buoy position was biased.

Ln405: Can you exclude the possibility of measurement saturation at high void fractions? Turbulence models assume TKE injection in breaking waves to a depth comparable to the

significant wave height. It is surprising that bubbles would not get injected to 2m depth when Hs is 3 to 5m. Does this imply that void fractions in breaking waves are <10-4? Or does it mean that the breaking layer is << Hs?

The bubble camera and resonator have both been extensively tested and were designed for void fractions of 10^{-4} and above. The companion paper discusses the bubble size distributions at these high void fractions and there is no evidence of bias. We are confident that there is no saturation of the measurement, and we have added text to clarify this point in the manuscript. We have GoPro footage of breaking waves (not shown in this paper, but from this expedition at ~15 m/s) does not show visible bubbles from a breaking wave mixing down below the top half metre or so – they stay in a very shallow layer. We also note that the bubble size distributions that reach 2 m depth (discussed in the companion paper) show that bubble populations that reach 2m depth are already highly processed within the top metre and are much smaller than turbulence arguments alone would suggest.
Although turbulence models assume a depth of TKE injection comparable to the significant wave height, we are not aware of any experimental data collected at sea to support the idea that bubbles are injected to this depth. The breakers on the open ocean are spilling rather than plunging and bubbles are formed on the front wave face with forward rather than downward momentum.
Our conclusion is that the breaking layer is << Hs, and we discuss this in more detail in the companion paper.

Section 3.3.2: Your analysis shows that void fraction does only poorly stratify with wind history. In almost all cases the median void fraction for rising/falling winds is within 1 standard deviation of the opposite situation. Similarly, wave age does not affect void fraction. Both results are not surprising. Void fraction is ultimately determined by wave breaking, which in turn is not directly linked to wave age or wind history. But is well correlated with the saturation of the wave field (see work by M. Banner and colleagues).

The literature has relatively few direct bubble measurements in high winds close to the sea surface to constrain detailed mechanisms for bubble distribution and gas flux. Our aim here was to examine the possible influence of wind history on void fraction patterns at 2m depth, since the mechanism of deep plume formation by Langmuir circulation (which we discuss further in the companion paper) does not necessarily correlate directly with the bubble population details in the top metre of the ocean. As we set out in the companion paper, we think that there are several linked mechanisms influencing bubble distribution, but some of these mechanisms may have a stronger influence on gas fluxes than others. Recent papers (for example Liang 2017) suggest that rising and falling winds have different effects on bubble distribution and gas fluxes, and think that the direct observations are useful even if they do not show strong separation between cases.

Ln 517: Can the (relative) age of a bubble plume be determined from the bubble size distribution? If this is done in the companion paper it should be mentioned here. If not, the analysis should be included here.

We have maintained the separation of material in these papers (void fractions in this first paper, bubble size distributions in the second) because there is too much material to fit into one paper and because both data types have their own nuances which need significant discussion in context. One major finding in the second paper is that the bubble size distribution at 2m for void fractions above 10^{-6} is highly conserved, varying in void fraction due to dilution but with the same relative numbers of bubbles of different sizes. There is no evidence at 2m depth of either buoyancy sorting the bubbles over time (with the exception of a small number of very large bubbles) or size-dependent dissolution. Our conclusion is that these fixed populations are formed within the top metre and are only redistributed through advection or destroyed through size-independent collapse after that. So the relative age of bubble plumes can not be determined by the bubble size distribution at 2m, but we do not think it appropriate to include that analysis here because this is a nuanced point and the details of the bubble size distributions are the subject of considerable discussion in the second paper.

Ln594-619: The explanation of higher void fractions during decreasing wind speeds being the result of higher gas saturation is plausible. Another explanation is similarly plausible: during falling wind speeds the wave field is not equilibrated, resulting in a higher breaking rate (bubble production) associated with wave saturation at a prior time.

We have added this hypothesis to the manuscript (lines 464-467).

Technical issues:

Ln 24: define R_{Hw}

We have added the definition in the revised version, with text but not an equation, so it now states "… or a wind-wave Reynolds number of $R_{Hw} = 2 \times 10^6$,…".

Ln 159: change to: "Studies by Salter et al (2014) and Slauenwhite & Johnson (1999) observed…."

This change has been made in the revised manuscript.

Ln294: The standard deviation of the measurement depth is not dimensionless (add units to both instances).

Extra text has been added to clarify the units.

Figure 3: Change y-axis label to "Void fraction" on panel b and c

This has been changed in the revised manuscript.

Figure 7: Specify in caption "….split by wind speed (bottom row) and wind-wave Reynolds number (top row)."

This change has been made in the revised manuscript.

Figure9, caption Ln123: "There were no bubble camera data…"

This change has been made in the revised manuscript.