P4.5 **OCEANIC WHITECAP COVERAGE MEASURED DURING UK-SOLAS CRUISES**

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1. INTRODUCTION

The breaking of wind-generated waves plays a significant role in the exchanges of momentum, heat, water vapour, and gas between the atmosphere and the ocean. Breaking waves entrain air into the surface water forming bubbles, which manifests itself as a whitecap on the ocean surface. Whitecap measurements in the open ocean are sparse and are limited to Monahan and Muircheartaigh, (1980), the warm and moderate seas data sets of Bortovskii, (1987), Stramska and Petelski, (2003), and Callaghan et al. (2008a). During the UK funded SOLAS cruises extensive measurements of the whitecap coverage in the North Atlantic and Norwegian Sea were made. Initial whitecap measurements from these cruises will be presented.

2. PREVIOUS MEASUREMENT METHODS

The fraction of the ocean surface covered by breaking waves has previously been calculated from images of the sea surface taken from still or video cameras mounted on ships (Monahan, 1969 and 1971; Hanson and Phillips, 1992, Asher and Wanninkhof, 1998; Stramska and Petelski, 2003; Lafon et al. 2004; Callaghan et al. 2008a), meteorological towers (Xu et al., 2000; Sugihara et al., 2007; Lafon et al, 2007; Mironov and Dulov, 2008; Callaghan et al. 2008b) and aircraft (Blanchard 1963; Ross and Cardone, 1974; Bondur and Sharkov, 1982; Melville and Matusov, 2002). Cameras were mounted at various heights from 10 m to many 10s of meters. Some are mounted looking straight down whereas others are mounted at an angle which, in the case of ship borne cameras, will vary. Images have been taken at intervals greater than 25 Hz (video) to 20 images every hour (stills). The effects of these different experimental details are not discussed in the literature and due to a lack of published information can not be examined here. Likewise most studies do not go in to detail about analysis methods. For example, the manner in which sunglint and sky reflection are dealt with or avoided, and whether the analysis is on a manual image-by-image basis or automated to some degree is often discussed only briefly if at all.

There is limited use in re-analysing previous data sets since many essential parameters (such environmental and meteorological conditions) were not measured and information detailing methods is often scanty. In addition, many datasets have been re-analysed a number of times by different authors. Recently Zhoa and Toba, (2001) re-analysed all historical data sets that included information on wind-wave properties and reached no overall conclusion.

What is required is a data set with as many sea surface images as possible, plus data for as many of the relevant variables as possible (e.g. atmospheric stability, surface currents, wind fetch, wind duration, sea surface temperature, salinity, rain and surfactants). These should all be analysed in the same fashion so that variations in method can be ruled out as a cause of differences in results. The data set amassed during recent UK-SOLAS cruises in a wide range of conditions will make a significant contribution to understanding how sea-state, wind history and meteorological parameters influence wave breaking and whitecap coverage.

Figure 1 a) Digital image of the sea surface obtained from the bridge-mounted camera on Discovery (taken on March 30 2007), and (b) the same image with a mask derived from AWE image processing (Callaghan and White, 2008) applied to isolate the whitecaps.

3. OBSERVATIONS AND METHOD

The fraction of the sea surface covered by whitecaps was measured by analysis of digital images taken from the *Discovery* during the recent SEASAW and DOGEE cruises (Brooks et al., 2009) in the North Atlantic and during the HiWASE project on the *Polarfront* in the Norwegian Sea. Since 1978 the Norwegian weather ship *Polarfront* has been making meteorological and wave measurements at Station Mike (66^{o}N 2^{o}E). In September 2006, as part of the HiWASE project (Brooks et al. 2009), the ship's existing measurement systems have been complemented by: a digital camera system; the AutoFlux system (Yelland et al., 2009) to measure the transfers of momentum, heat and CO_2; a directional wave radar system. During all campaigns wave measurements were measured using a ship borne wave recorder (SBWR). In addition to the SBWR a WAVEX wave radar system was installed on *Polarfront* to provide additional wave measurements including accurate measurements of the wave direction.

During the SEASAW and DOGEE cruises two Nikon Coolpix 8800 cameras looked directly abeam

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from the ship's bridge. The cameras were located 13 m above the sea surface and images were taken at 30 second intervals in daylight hours. Identical cameras were used on *Polarfront*, but slower sampling rates (between 1 min and 30 minutes) and lower image resolutions were used, since the cameras were serviced only every 2 or 3 months rather than every day. However, an extensive number of images have been recorded in a wide range of conditions during the two year measurement period to date.

Figure 1 shows an image taken during the SEASAW experiment on the *Discovery*. Ship wake and brightness effects close to the horizon were eliminated from the analysis by selecting a rectangular region in the centre of the image. The automated whitecap extraction (AWE) method of Callaghan and White, (2008) was used to analyze the results. AWE analyzes images and determines a suitable threshold intensity value for each image with which whitecaps can be separated from the background water. Each image (Figure 1b) was manually checked after analysis to determine its suitability. Images are rejected if there contamination from sunglint, sky reflection, birds or uneven illumination in the image.

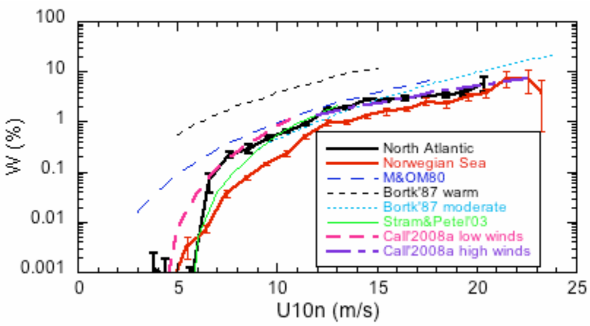

Figure 2 Total whitecap fraction as a function of wind speed for measurements made from *Discovery* (North Atlantic) and *Polarfront* (Norwegian Sea). The other open ocean relationships are shown. The error bars indicate the standard error.

To date 4 days (6,810 measurements) of images from *Discovery* have been processed out of a possible 54. Data were selected during periods of high winds (DOGEE) and during deployments of the University of Leed's aerosol buoy (SEASAW). The cameras located on *Polarfront* are autonomous and will be recording images until September 2012. At present this data set includes 8,023 whitecaps measurements (~100 days of data out of 470 days available). Concurrent measurements of the sea surface temperature (SST) ranged from 5 to 15 °C at station Mike and 8 to 12 °C in the North Atlantic. Possible effects of SST (Monahan and O'Muircheartaigh, 1986) on whitecap coverage will be investigated when a larger whitecap data set has been collected. A subset of the *Polarfront* whitecap measurements was used to validate satellite estimates of whitecap coverage (Anguelova et al., 2009).

4. RESULTS

4.1 Wind speed relationship

All currently processed data from the *Discovery* (North Atlantic) and the *Polarfront* (Norwegian Sea) are shown in Figure 2. The wind speed has been adjusted to a height of 10 m and the effects of atmospheric stability have been accounted for.

Measurements made on the *Discovery* in the North Atlantic compare well with the previous North Atlantic relationships of Callaghan et al. (2008a) and the moderate water relationships of Bortovskii, (1987). With the exception of wind speeds below 7 ms^{-1} the *Discovery* data and the Callaghan et al. (2008a) relationships are similar. This is encouraging as both sets of measurements were analysed using the AWE method, but made using different systems on different ships. The drop off in the *Discovery* data below 7 ms^{-1} is due to little data currently processed at low wind speeds.

The warm water relationship of Bortovskii, (1987) was measured in the tropical Pacific and Indian Oceans and overestimates the other open ocean results. This may be due to either the high SST or possibly a fully developed sea (Monahan and O'Muircheartaigh, 1986; Stramska and Petelski, 2003) associated with the measurement region.

The measurements of Monahan and O'Muircheartaigh, (1980) [hereafter MOM80] made in the Atlantic and Pacific oceans overestimate the latest findings using the AWE method. This may be due to the analysis method used (Callaghan et al. 2008a).

The Stramska and Petelski, (2003) wind speed relationship agrees well with the North Atlantic relationships above a wind speed of 10 ms^{-1}. At low wind speeds Stramska and Petelski, (2003) underestimate the other relationships. However, the difference is small (range of 0.06 % to 0.2% at 7ms^{-1}).

Except at high winds greater than 20ms^{-1}, the whitecap measurements made on the *Polarfront* in the Norwegian Sea are significantly lower than the measurements made from the *Discovery*. Experimental bias such as camera viewing direction (Section 4.2) will be examined before any difference is attributed to environmental conditions.

4.2 Camera viewing direction

The field of view of the *Polarfront* cameras are 90 degrees apart: one camera points directly over the bow and the other directly abeam. For the majority of the time the *Polarfront* drifts with the wind over the starboard beam until the weather deteriorates and the ship goes hove-to (heads directly into the wind). Whitecap fraction from each camera has been split by camera viewing direction relative to the true wind direction, either across the true wind direction, along looking upstream or along looking downstream. However, up to an order of magnitude difference exists between the measurements. One would assume that the forward camera looking upwind would give the same results as the beam camera looking upwind, and similarly for the other directions. However, Figure 3 shows that this is not the case (e.g. compare the black lines). Figure 3 shows an apparent bias related to the ship's orientation to the relative wind direction. When the ship is beam-on to the wind the measured whitecap fraction is biased low (i.e. black and cyan dashed lines and red solid line are lower than the other three).

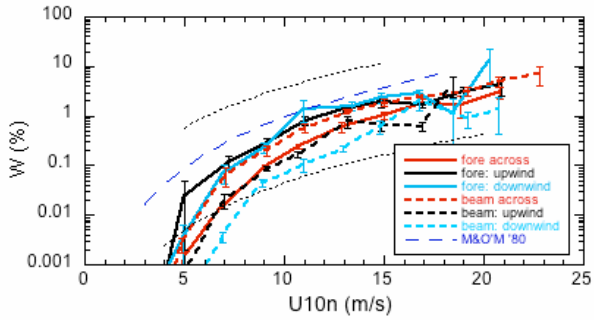

Figure 3 Total whitecap fraction as a function of wind speed for measurements made from the cameras on the *Polarfront*. The data were split by either looking across or along (up- or down-wind) the true wind direction. The thin dashed lines represent the extremes of the previous relationships (Figure 1 - Anguelova and Webster, 2006). The error bars indicate the standard error.

In particular, when the ship is beam-on to the wind the data from the beam camera looking downwind is biased low (cyan dashed line Figure 3) in comparison to the other cameras and viewing directions. It is currently unknown why, but it may be a sheltering effect of the ship or an increase in ship motion when the ship is beam-on. There are similar numbers of measurements made from this camera at this direction (Table 1), compared with the other camera/directions. To try and understand this effect a gimballed camera will be installed on the ship in an attempt to consistently measure the whitecap fraction from a fixed area of the ocean.

Except on passage the *Discovery* rarely collects any data when the wind is over the beam, so a direct comparison with Figure 3 cannot be made. Nevertheless, the beam camera measurements from both ships when hove-to are compared in Figure 4 and there is now a good agreement between the measurements (c.f. Figure 2).

camera	direction	Sample size
fore	across	2844
	upwind	615
	downwind	422
beam	across	1195
	upwind	1163
	downwind	1784

Table 1 Number of whitecap measurements by viewing direction made from each camera on the *Polarfront*.

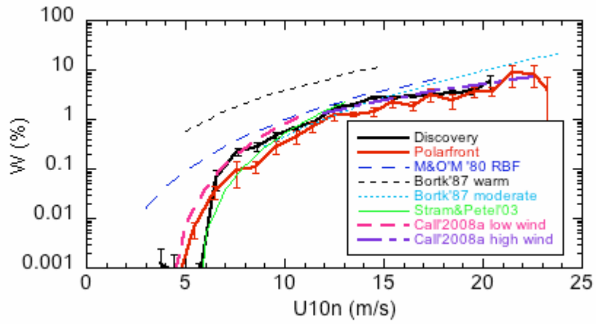

Figure 4 Total whitecap fraction as a function of wind speed for measurements made from the beam cameras when the *Discovery* and *Polarfront* are hove-to. The error bars indicate the standard error.

The effects of wave slope and sea-state on the whitecap coverage measured are briefly examined in Section 4.3 and 4.4 respectively.

4.3 Significant slope

The slope of the surface waves may be a better basis for a whitecap parameterization as it is directly linked to wave breaking, i.e. assuming steeper waves break more readily than long period swell. The significant slope was calculated using:

$$significant\ slope = \frac{2\pi Hs}{g(T_z)^2} \qquad (1)$$

were g is the acceleration due to gravity, Hs is the significant wave height, Tz is the zero upcross wave period from the ship borne wave recorder (SBWR). The whitecap verses significant slope relationship for the *Polarfront* is shown in Figure 5. The relationship between whitecap fraction and ship orientation is not as clear as that shown in Figure 3, but there is still a difference in the measured whitecap fraction when the ship was beam-on compared to hove-to. Accurate measurements of wave period from the SBWR are only obtained when the ship was moving at speeds of 1 m/s or less. This only reduced our data set by 644 measurements (<8%).

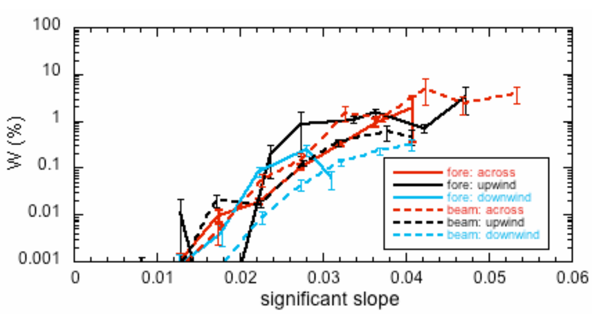

Figure 5. As Figure 3, but as a function of significant slope. The error bars indicate the standard error.

4.4 Sea-state

The *Polarfront* whitecap data were split into swell-dominated, developing and fully developed sea by comparing the ship borne wave recorder wave period with that expected from a fully developed sea (using the Pierson Moskowitz relationship Tpm=0.785*U10n [Pierson and Moscowitz, 1964]).

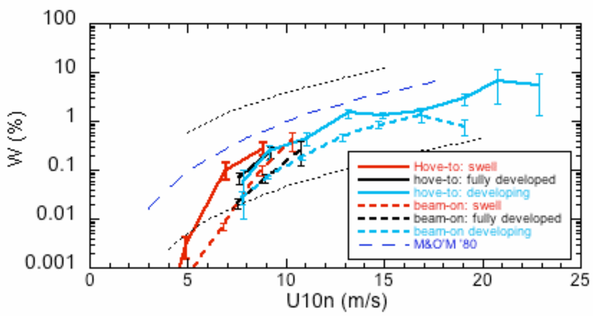

Figure 6 Total whitecap fraction measured from *Polarfront* as a function of wind speed for different sea-states. The error bars indicate the standard error.

The sea-state during periods when the ship was hove-to and beam-on are shown in Figure 6. It is clear that sea-state does not reconcile the differences in the whitecap measurements made at different ship orientations. As the SBWR does not give directional information on the wave field, a combined data set of SBWR and WAVEX wave radar data will be created to further examine the effect of sea state on whitecap measurements.

5. SUMMARY

Digital cameras have been installed on two ships to measure the whitecap fraction of breaking waves. The *Discovery* has undertaken three dedicated research cruises in the North Atlantic. The Norwegian weather ship *Polarfront* located at station Mike (66°N 2°E) has been collecting images of the sea surface since September 2006. Both *Discovery* and *Polarfront* data sets have coincident wave and meteorological measurements.

The various open ocean relationships shown here agree reasonably well, except for low winds were the whitecap signal is very small.

There is good agreement between whitecap measured in the North Atlantic and in the Norwegian Sea when the ships are head to wind.

The orientation of the ship relative to the wind direction has a significant influence on the whitecap measurements. In particular, the whitecap fraction measured on the *Polarfront* is lower for beam on winds when the camera is looking down-wind. It is not yet known whether this is due to sheltering by the ship or some effect of increased ship motion.

Initial results show that neither wind speed, wave slope or a basic measure of sea state alone account for the difference in whitecap coverage measured at different ship orientations to the wind.

More data are to be processed which will allow the combined dependence on sea-state and meteorological parameters to be studied.

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REFERENCES

Anguelova M. D. and F. Webster, 2006: Whitecap coverage from Satellite measurements: A first step towards modelling the variability of oceanic whitecaps, *J. Geophys. Res.,* **111**, C03017.

Anguelova M. D., J. P. Bobak, W. E. Asher, D. J. Dowgiallo, B. I. Moat, R. W. Pascal and M. J. Yelland, 2009: Validation of satellite-based estimates of whitecap coverage: approaches and initial results, *AMS 16th Conference on Air-sea interaction*, January 12-15, Phoenix, Arizona.

Asher W. E. and R. Wanninkhof, 1998: The effect of bubble-mediated gas transfer on purposeful dual-gaseous tracer experiments, *J. Geophys. Res.,* **103**, 10555-10560.

Blanchard, D., 1963: The electricification of the atmosphere by particles from bubbles in the sea, *Prog. Oceanogr.,* **1**, 71-2002.

Bondur, V., and E. Sharkov, 1982: Statistical properties of whitecaps on a rough sea, *Oceanology*, **22**, 274–279.

Bortkovskii, R. S., 1987: Air-sea exchange of heat and moisture during storms, Springer, New York. 193pp

Brooks, I. M. and 50 co-authors, 2009: Physical exchanges at the air-sea interface: field measurements from UK-SOLAS, *Bull Amer. Meteorol. Soc*., *(accepted).*

Callaghan, A. H., G. Leeuw, L. Cohen and C. D. O'Dowd, 2008a: Relationship of oceanic whitecap coverage to wind speed and wind history. *Geophys. Res. Lett.*, **35**, L23609,doi: 10.1029/2008GL036165.

Callaghan, A. H., G. B. Deane and M. D. Stokes, 2008b: Observed physical and environmental causes of scatter in whitecap coverage values in a fetch limited coastal zone, *J. Geophys. Res.,* ***113****,* CO5022.

Callaghan, A. H. and M. White, 2008: Automated processing of sea surface images for the determination of whitecap coverage, *J. Atmos. and Ocean. Tech*., (in press).

Hanson, J. L. and O. M. Phillips, 1992: Wind sea growth and dissipation in the open ocean, *J. Phys. Oceanogr.,* **29**, 1633-1648.

Lafon, C., J. Piazzola, P. Forget, O. LE Calve and S. Despiau, 2004: Analysis of the variations of the whitecap fraction as measured in a coastal zone, *Boundary layer Meteorology*, **111**, 339-360.

Lafon, C., J. Piazzola, P. Forget, and S. Despiau, 2007: whitecap coverage in coastal environment for steady and unsteady wave field conditions, *J. of Marine Systems*, **66**, 38-46.

Melville, W. K. and P. Matusov, 2002: Distribution of breaking waves at the ocean surface, *Nature*, **417**, 58-63.

Mironov, A. S. and V. A. Dulov, 2008: Detection of wave breaking using sea surface video records, *Measurement Science and Technology*, **19**, 1-10.

Monahan, E. C., 1969: Fresh water whitecaps, *J. of the Atmospheric Sciences*, **26**, 1026-1029.

Monahan, E. C., 1971: Oceanic whitecaps, *J. Phys. Oceanogr.,* **1**, 139-144.

Monahan E. C. and I. O. Muircheartaigh, 1980: Optimal Power law Description of Oceanic whitecap coverage dependence on wind speed, *J. Physical Ocean.,* **10**, 2094-2099.

Monahan, E. C. and I. O'Muircheartaigh, 1986: Whitecaps and the passive remote sensing of the ocean surface, *Int. J. of Remote Sens*., **7**, 627-642.

Pierson, W. J. and L. Moscowitz, 1964: A proposed spectral form for fully developed wind seas based on the similarity theory of S A Kitaigorodskii, *J. Geophys. Res.,* **69**, 5181-5190.

Ross, D. B. and V. Cardone, 1974: Observations of oceanic whitecaps and their relation to remote measurements of surface wind speed, *J. Geophys. Res.,* **79**, 444-452.

Stramska, M. and T. Petelski, 2003: Observations of oceanic whitecaps in the north polar waters of the Atlantic, *J. Geophys. Res.,* **108C3**, 3086. doi: 10.1029/2002JC001321

Sugihara, Y., H. Tsumori, T. Ohga, H. Yoshioka and S. Serizawa, 2007: Variation of whitecap coverage with wave-field conditions, *J. of Marine Systems*, **66(1-4),** 47-60.

Xu.D., X. Liu and D. Yu, 2000: Probability of wave breaking and whitecap coverage in a fetch-limited sea, *J. Geophys. Res.,* 105, 14253-14259.

Yelland, M. J., Pascal, R. W., Taylor, P. K. and Moat, B. I., 2009: AutoFlux: an Autonomous System for the Direct Measurement of the Air-Sea Fluxes of CO_2, Heat and Momentum. *Journal of Operational Oceanography, (accepted)*

Zhao D and Y Toba, 2001: Dependence of whitecap coverage on wind and wind wave properties, *J. of Oceanography*, **57**, 603-616.