Characteristics of Whitecaps Estimated from Image Processing of The Ocean Surface

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Introduction

Whitecaps generated by wave breaking on the ocean surface play an important role in the local interaction between the atmosphere and the ocean. Figure 1 shows image of whitecaps. Whitecap coverage is defined by the area of whitecaps per the unit ocean surface. It has been recognized as one of important physical quantities for describing the ocean surface fluxes such as the momentum, heat and carbon dioxide, so that the quantitative evaluation of whitecap coverage becomes significant from viewpoints of environmental hydraulics and ocean engineering. Figure 2 shows whitecap coverage extracted by different threshold.

In this study, in order to validate typical estimation methods for whitecap coverage, the AWE algorithm proposed by Callaghan and White (2008) was compared with the threshold method adopted usually in previous studies. The agreement between both was examined on the basis of the influence of solar radiation. Previous studies have suggested that the depth of bubble penetration generated by wave breaking may be proportional to the significant wave height. Based on this assumption, we proposed a new index for expressing characteristics of whitecaps, i.e., whitecap depth, indicating the product of whitecap coverage and the bubble penetration depth. This quantity denotes the averaged depth of the bubbly layer per the unit ocean area, and can be expected to become a more significant quantity than whitecap coverage. In addition, for the data of whitecap coverage obtained from the AWE method, we investigated the relation of whitecap depth with 10-m wind speed or the windsea Reynolds number.

Fig. 1 Image of whitecaps

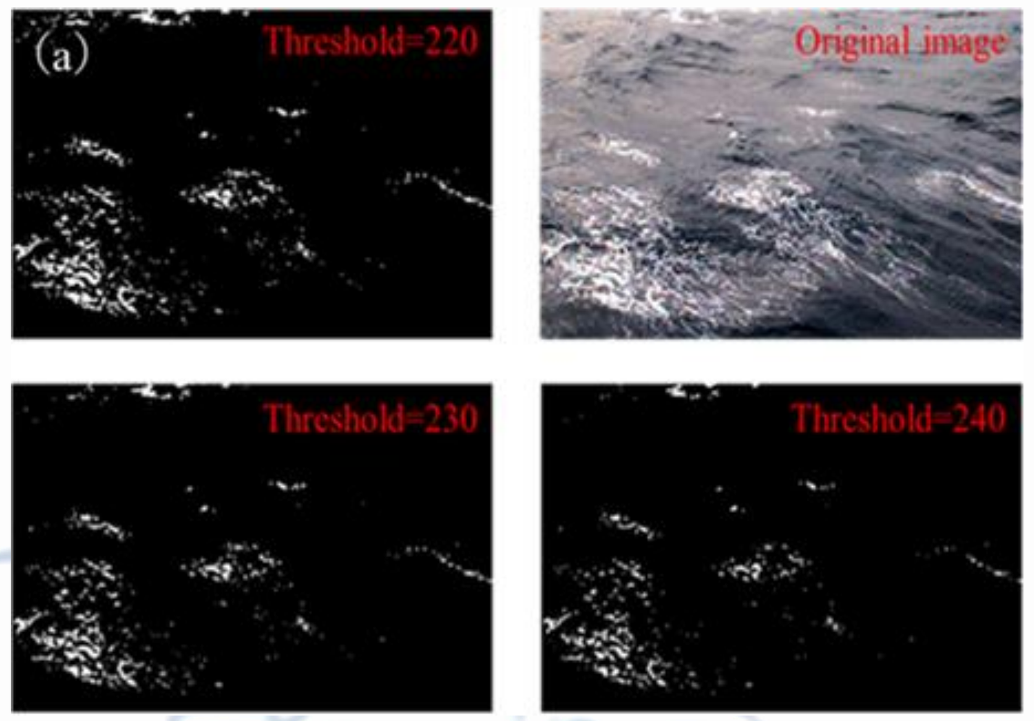

Fig. 2 Comparison between original and binary images

Analysis method

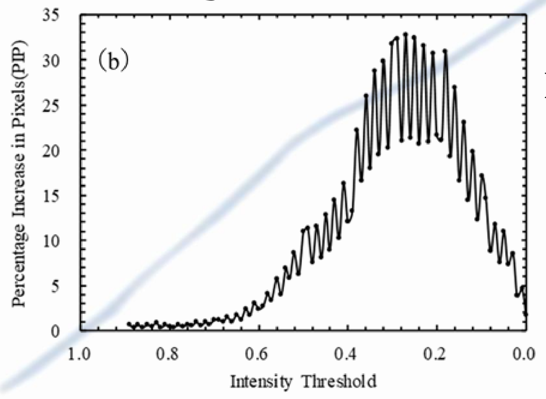

Fig. 3 Change of PIP for each intensity threshold

$$\mathrm{PIP}(i) = \frac{P(i) - P(i+0.01)}{P(i)} \times 100 \quad (1)$$

$$\frac{d[\Phi(i)]}{di} = \frac{\Phi(i) - \Phi(i+\Delta i)}{\Delta i} \quad (2)$$

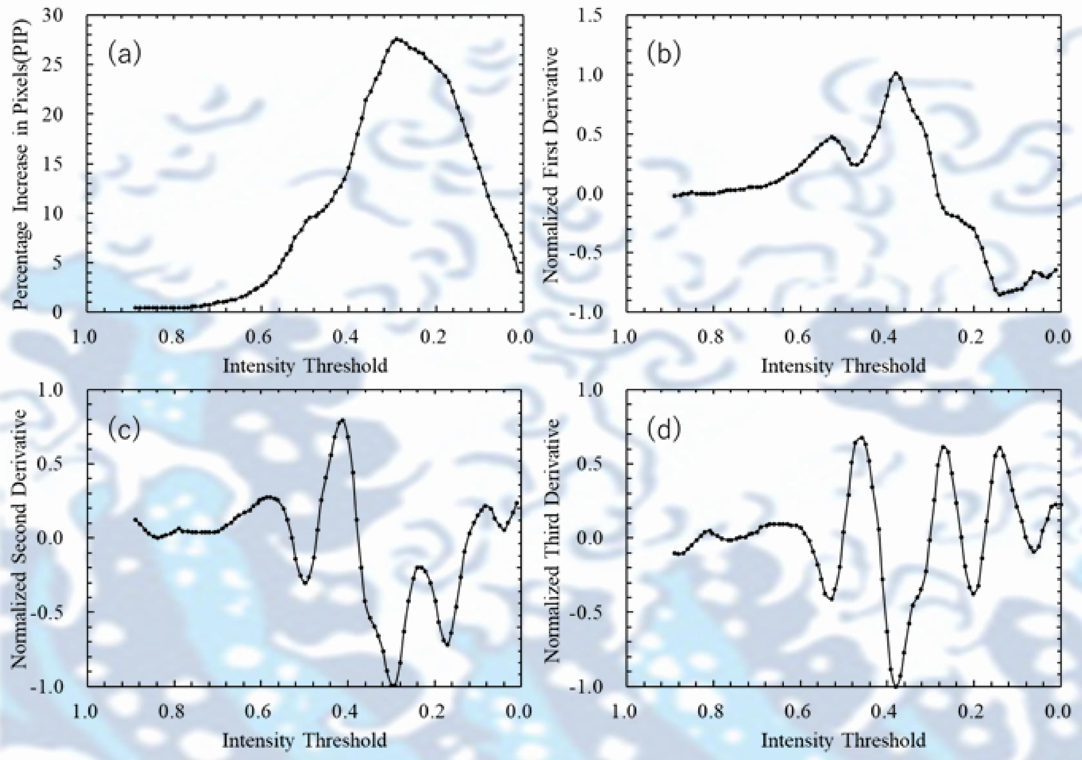

Fig. 4 Analytical results based on AWE algorithm.

Automatic whitecap extraction (AWE) is an algorithm proposed by Callaghan and White (2008) to automatically determine the coverage of whitecap, which does not need to determine a subjective threshold by researcher. By setting a suitable threshold for each sea image, we can prevent the error by detecting non-whitecap region, and can calculate the value of whitecap coverage more accurately. In order to determine the threshold for AWE, PIP (percentage increase in the number of pixels) and the image structure must be used, where PIP is defined as Eq. (1). As an example of the analytical results, Fig. 3 shows the variation of PIP with the intensity threshold on the ocean surface image. In this study, since the PIP fluctuated greatly as shown in Fig. 3, the results have been smoothed by the four-point moving average to make the derivatives of PIP. The derivative equation is given by the Eq. (2). Φ denotes PIP and its first and second derivatives. After the first derivative of PIP was calculated, it was smoothed again by the four-point moving average, and then Eq. (2) is used again for the second derivative. In addition, after smoothing in the same way, the third-order differential is performed. An example of a series of the processes is provided in Fig.4. The AWE algorithm increases the threshold from the minimum luminance value to the maximum luminance one, and identifies a zero crossing point where the negative value changes first to the positive one. In Fig. 3(b), it can be confirmed that the threshold exists between 0.28 and 0.29. Thus, the threshold of 0.28 is set as the lower threshold for subsequent processing.

Results

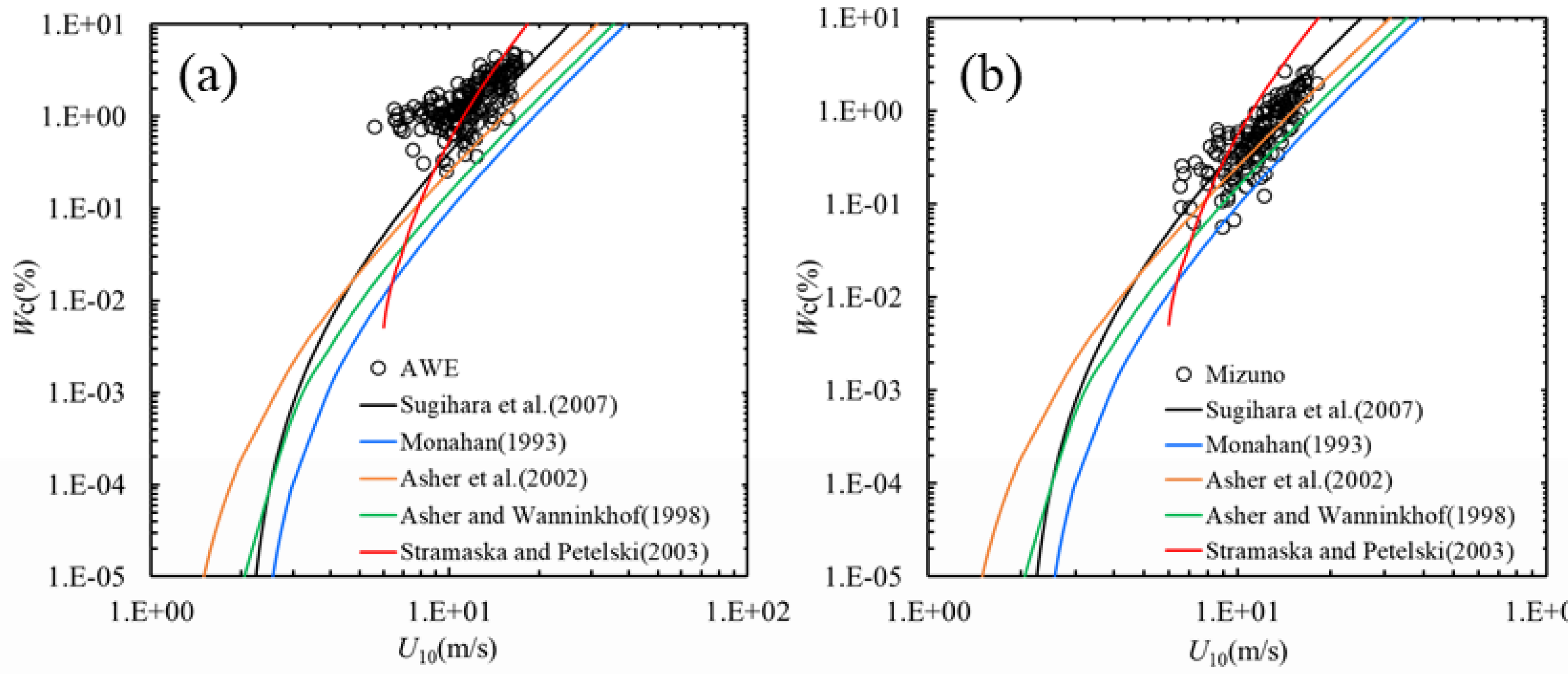

Fig. 5 Relations of Wc _AWE, Wc _FT with 10-m wind speed U_{10}

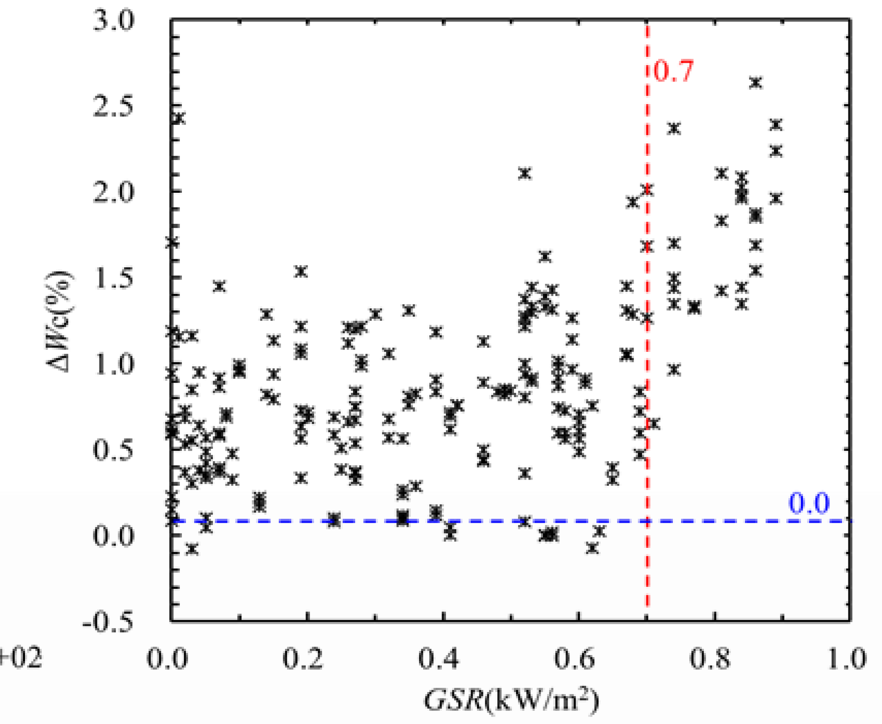

Fig. 6. Relation between ΔWc and GSR

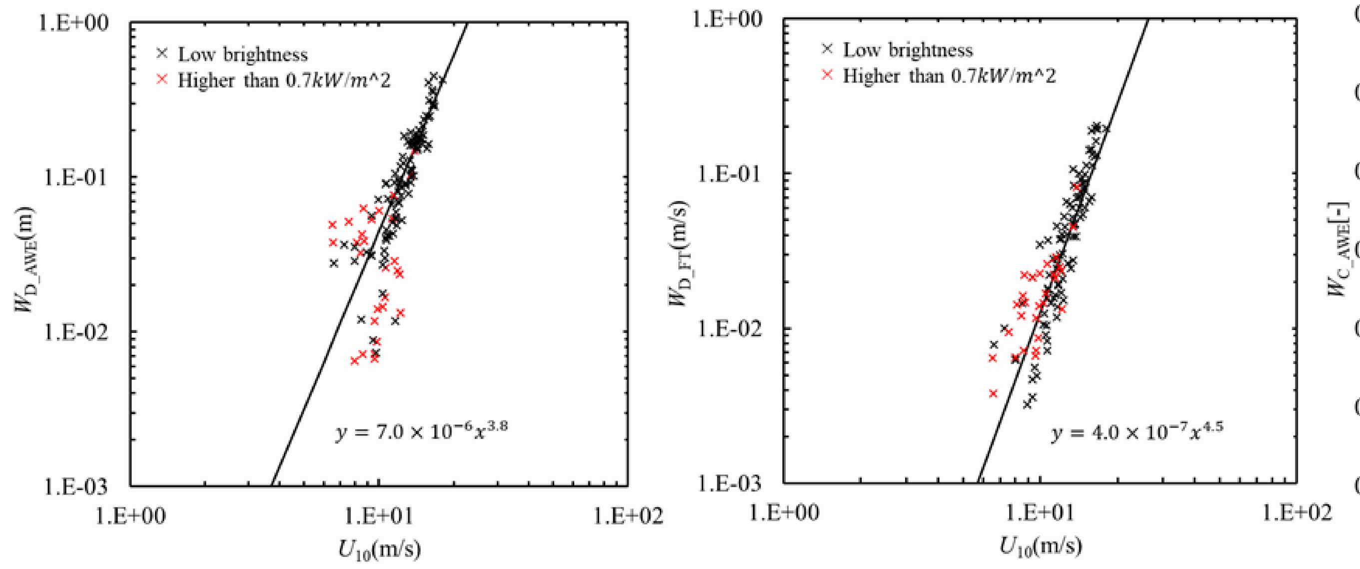

Fig. 7 Relationships between W_D_AWE, W_D_FT and U_{10}

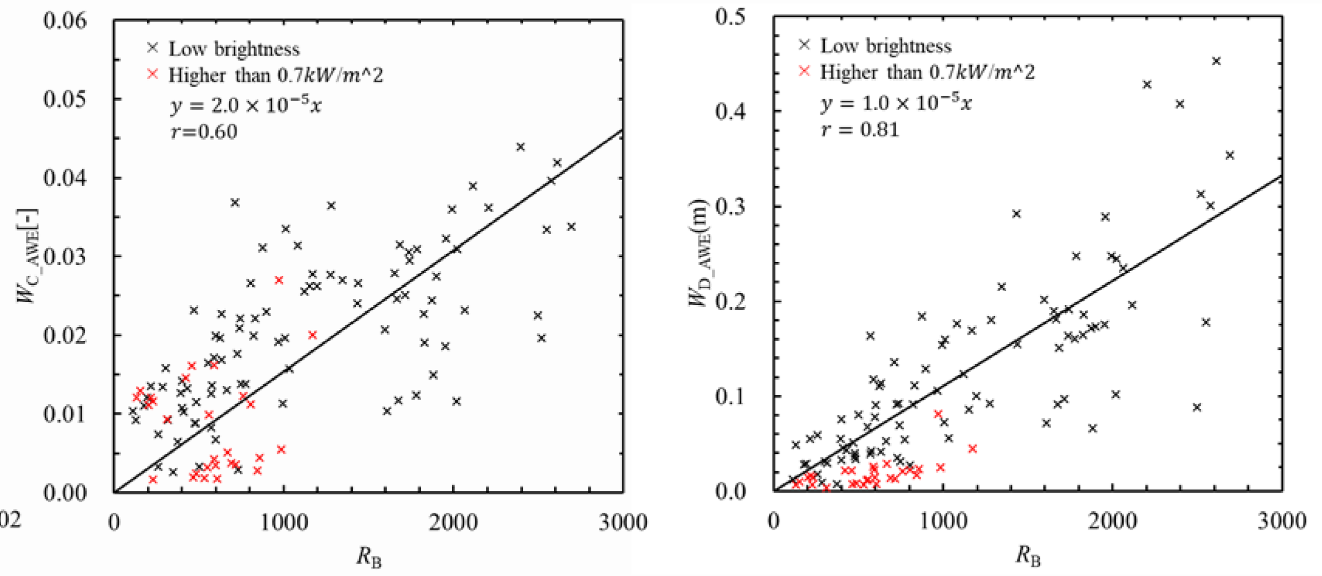

Fig. 8 Relationships between W_c_AWE, W_D_AWE and R_B

- ◆It is seen from Fig. 5 that when 10-m wind speed becomes 5m/s or higher, W_c _FT is in good agreement with the empirical relations of Monahan (1993) and Sugihara et al. (2007). The value of W_c_AWE is larger than their relations, but indicating high consistency with the relation of Stramaska and Petelski (2003).
- ◆In Fig. 6, ΔW as the difference between Wc _FT and Wc _AWE is compared with the amount of the solar radiation GSR. When GSR exceeds about 0.7 kW/m^2, the value of ΔW is increase considerably. It is seen that due to the influence of solar radiation, it is usually difficult to calculate whitecap coverage under the condition of strong sunlight. Therefore, in order to investigate properly the behavior of whitecap coverage, we should exclude the data of whitecap coverage when the solar radiation exceeded 0.7 kW/m^2.
- ◆Thorpe (1986) and Yoshioka et al. (2003) used the reflection intensity of sound beams in the ocean surface boundary layer to visualize the vertical distribution of bubbles underneath the ocean surface. Their observations demonstrated that the depth of bubbles generated by wave breaking becomes about 4 to 5 times of the significant wave height H_s. Based on the findings, the product of whitecap coverage W_c and the bubble penetration depth will be useful for expressing three-dimensional characteristics of the bubbly region of whitecaps. In this study, we propose a new characteristic quantity as whitecap depth W_D. Figure 7 shows the relations of W_D_AWE and W_D_FT with U_{10}, both of which show a strong linear correlation, suggesting that W_D is recognized as a suitable quantity that can evaluate whitecaps more accurately than whitecap coverage.
- ◆A typical outcome is the work of Toba and Koga (1986), and they proposed that a dimensionless parameter R_B. As shown in Fig.8, there is a linear relation between W_c_AWE and R_B, with a correlation coefficient of 0.6 as the linear regression, whereas the relation of W_D_AWE with R_B has a higher correlation coefficient as 0.81, which shows that as the new physical quantity for evaluating ocean whitecaps W_D is more persuasive and expectable than whitecap coverage W_C.

Conclusion

- ✓ In this study, by comparing whitecap coverage calculated by AWE with that of fixed threshold method, the usefulness of AWE in long-term observation was examined.
- ✓ After selecting the effective data of whitecap coverage, it was shown that the correlation coefficient between Wc_AWE $^{1/3}$ and U_{10} was 0.76.
- ✓ Whitecap depth W_D, and verified the relation between W_D and the windsea Reynolds number R_B. The present results demonstrated that W_D is in good correlation with R_B, and thus suggesting that whitecap depth is more suitable parameter than whitecap coverage, which is only two-dimensional information on whitecaps.

Acknowledgements

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