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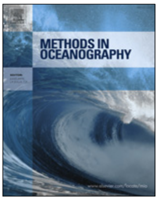

Full length article

Oceanic wave breaking coverage separation techniques for active and maturing whitecaps

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ABSTRACT

Whitecaps on the ocean surface mark localized areas where interactions between the atmosphere and ocean are enhanced. Contemporary methods of quantifying total whitecap coverage rely on converting color sea surface images into their binary equivalent using specific threshold-based automated algorithms. However, there are very few studies that have separated and quantified whitecap coverage into its active (stage-A) and maturing (stage-B) evolutionary stages, which can potentially provide more suitable parameters for use in breaking wave models, air–sea gas transfer, aerosol production, and oceanic albedo studies. Previous active and maturing whitecap studies have used a pixel intensity separation technique, which involves first separating the whitecap and background pixels, and subsequently establishing a second threshold to distinguish between active and maturing whitecaps. In this study, a dataset of more than 64,000 images from the North Atlantic were initially processed to determine the total whitecap coverage using the Automated Whitecap Extraction method. The whitecap pixels of each image were then distinguished as either stage-A or stage-B whitecaps by applying a spatial separation technique which does not rely solely on pixel intensity information but also on the location (relative to the wave crest), visual intensity, texture and shape of each whitecap. The comparison between the spatial separation and pixel intensity separation techniques yielded average relative errors of 34.8% and −44.0% for stage-A and -B coverage, respectively. The pixel intensity method was found to be less suitable when compared to the spatial separation method as it relies on the

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assumption that the pixel intensity for stage-A is always greater than that for stage-B.

1. Introduction

Whitecap coverage on the ocean surface is a direct result of breaking waves and is a visual representation of areas on the ocean surface where enhanced air–sea interactions of gas and aerosols occur (Anguelova and Webster, 2006). Many studies have been carried out to quantify the area of ocean surface covered by whitecaps (W) (Monahan and O'Muircheartaigh, 1980; Anguelova and Webster, 2006; Sugihara et al., 2007; Callaghan et al., 2008; Goddjin-Murphy et al., 2010) and there have been many attempts to parameterize whitecap coverage with wind speed (see Figure 1 in Anguelova and Webster, 2006, for a summary of parameterizations over the past 42 years).

According to the nomenclature of Monahan and Lu (1990), there are two stages of evolution in the lifetime of a whitecap. At the initial occurrence of a wave breaking, the wave crest velocity exceeds that of the wave, spills, traps air, and entrains it below the sea surface. A condensed bubble plume is created beneath the surface. This initial phase is known as *stage-A* or *active* whitecapping and has a characteristic lifetime $\mathcal{O}(1\ \mathrm{s})$. Due to the strong gravitational forces and wave momentum present, a high mixing potential is created at the air–sea interface. Directly after the gravitationally driven stage-A event, bubbles are overcome by turbulence and buoyancy forces, the bubble plume expands, returns to the sea surface forming a large whitecap, and decays through bubble bursting processes. This phase is known as *stage-B* or *maturing* whitecap, and it is during this phase that the majority of bubble bursting occurs. Stage-B whitecaps typically have longer lifetime than that of stage-A, often being observed for times up to 10's of seconds (Callaghan et al., 2013). Fig. 1 shows a schematic of the evolution of a typical whitecap, from the stage-A occurrence to the evolution of a stage-B. Both stages of whitecapping can be quantified by measuring the area of the image containing the active and maturing whitecaps.

Active whitecaps play a strong role in the air–sea gas transfer due to their high mixing potential. Monahan and Spillane (1984), Woolf (1997) and Asher and Wanninkhof (1998) have attempted to use whitecap coverage estimates to obtain more accurate models for gas transfer velocities. Andreas and Monahan (2000) reported that stage-A whitecaps cycle roughly 4 orders of magnitude more air through the near surface ocean than do stage-B whitecaps for a given wind speed. Stage-A values have been regarded as the most suitable parameter for quantifying the rate of wave breaking, playing a vital role in modeling turbulence injected into the upper ocean due to wave breaking. Wave modelers such as Hanson and Phillips (1999) have used W estimates to parameterize the dissipation of wave-field energy as a wave breaks.

Decaying whitecaps, due to their bubble bursting nature, have been previously quantified and related to studies involving sea-salt aerosol particle production (Monahan et al., 1986), underlying the importance of the quantification of stage-B whitecaps. Bubble bursting in stage-B whitecaps result in film and jet droplets being produced, creating atmospheric aerosols which have been reported to impact on air–sea sensible and latent heat fluxes (Andreas et al., 1995). Anguelova and Webster (2006) states that sea spray processes must be adequately parameterized and included in climate models. Surfactant concentrations at the air–sea interface can strongly affect the persistence of stage-B whitecaps (Callaghan et al., 2013). Discriminating stage-A from W could potentially remove the dependence of surfactants from whitecap estimates, providing a more relevant parameter for gas-transfer models and rate of wave breaking.

Methods of quantifying W have developed over the past several decades, and it has generally involved the analysis of photographic and videographic images of the sea surface where areas of whitecap were identified and quantified. Initially, this involved labor-intensive methods whereby photographs of sea surface were physically dissected to remove the areas of whitecapping and