# Observations of oceanic whitecaps in the north polar waters of the Atlantic

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[1] Digital photographs of the sea surface were analyzed for the fraction of aerial coverage by whitecaps (stage A and B) in the north polar region of the Atlantic. Photography was accompanied by measurements of wind velocity, air temperature and humidity, sea surface temperature, and observations of significant wave height. Whitecap coverage increased significantly with an increase in wind speed (or wind friction velocity). Our data exhibit lower values of the average whitecap coverage at low and moderate wind speeds than previous estimates from literature. In addition, our results indicate that the prediction of whitecap coverage can be improved if the state of the development of surface waves is taken into account. Changes in sea surface temperature (2 to 13°C) and near-water air stability showed no discernible effect on whitecap coverage at any given wind speed within our data set. *INDEX TERMS:* 4560 Oceanography: Physical: Surface waves and tides (1255); 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 4207 Oceanography: General: Arctic and Antarctic oceanography; 3360 Meteorology and Atmospheric Dynamics: Remote sensing; *KEYWORDS:* whitecaps, air-sea interactions, wave breaking, polar Atlantic, sea surface, sea state

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## 1. Introduction

[2] Whitecaps produced by waves breaking at the sea surface are one of the most striking features of the ocean under stormy conditions. Recently, the interest in understanding the variability of whitecap coverage has increased significantly due to the efforts to refine the atmospheric correction for remote sensing of ocean color [*Gordon*, 1997]. The importance of oceanic whitecaps for satellite ocean color measurements becomes apparent if we recall that during stormy days, whitecaps are visible as patches of sea surface much brighter than the adjacent water not covered by whitecaps. Because the reflectance of the newly formed whitecap in the visible spectral range can be about 10 times the reflectance of the neighboring whitecap-free sea surface [*Moore et al.*, 2000], it is obvious that when whitecaps cover more than 1% of the ocean surface, the radiance measured by a satellite or aircraft sensor will be significantly enhanced.

[3] In order to improve the retrieval of pigment concentration and other bio-optical properties from ocean color, the influence of whitecaps on the radiance received by remote sensors must be accounted for in the atmospheric correction algorithm [e.g., *Estep and Arnone*, 1994; *Gordon*, 1997]. The approach to quantify this influence combines two components. The first component includes the wavelength-dependent description of whitecap reflectance [*Frouin et al.*, 1996; *Moore et al.*, 2000]. The second component includes a description of the fractional foam coverage of the ocean surface as a function of environmental conditions [*Koepke*, 1984; *Monahan and O'Muircheartaigh*, 1986]. At present, the second component is based on the relationship between the whitecap coverage and wind speed, which is characterized by a relatively large scatter of experimental data points. Therefore, there is a significant uncertainty in the present whitecap correction algorithm. More field data are needed for better quantification and prediction of the variability of whitecap coverage under various environmental conditions, which will ultimately help reduce errors in the ocean color data products [*Gordon and Wang*, 1994; *Gordon*, 1997].

[4] Wave breaking and associated whitecaps have also a great impact on other oceanographic processes. For example, wave breaking is related to the transfer of mechanical energy from the wind to waves and drift currents [*Toba and Chaen*, 1973]. *Melville and Rapp* [1985] showed that the momentum flux to the ocean by wave breaking may be comparable to that transferred directly from wind. Breaking waves and whitecaps are responsible for the injection of seawater droplets into the air. This represents the primary mechanism which controls the rate of sea-salt aerosol generation over the ocean [e.g., *Blanchard and Woodcock*,


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1957; *Koga*, 1981; *Monahan et al.*, 1983a, 1983b, 1986]. Under stormy conditions, the emission of droplets from breaking waves and whitecaps may significantly affect the evaporation and heat exchange at the sea surface [e.g., *Stramska*, 1987; *Resch*, 1989; *Andreas et al.*, 1995]. Whitecaps and bubbles produced by breaking waves may augment air-sea gas transfer velocities [*Asher and Wanninkhof*, 1998; *Asher et al.*, 2002]. Bubble clouds and whitecaps modify light-scattering properties of ocean water and light fields within and leaving the ocean [*Terrill et al.*, 2001; *Stramski and Tegowski*, 2001]. Whitecaps and bubbles need to be taken into account in radiation estimates for the ocean-atmosphere system, including the estimation of regional albedo and radiation budgets [e.g., *Gordon and Jacobs*, 1977; *Stabeno and Monahan*, 1986; *Frouin et al.*, 2001].

[5] Fundamental to all of the above-mentioned problems is a necessity to understand the variability of whitecap coverage and its dependence on various environmental factors. Over the years, many efforts to obtain a reliable expression for whitecap coverage have been made. For example, whitecap coverage has been studied as a function of wind speed [*Blanchard*, 1971; *Monahan*, 1971; *Ross and Cardone*, 1974; *Toba and Chaen*, 1973; *Monahan and O'Muircheartaigh*, 1980], wind stress, and wind friction velocity [*Wu*, 1979, 1988; *Monahan*, 1993]. The results of these studies indicate that there is a relatively large scatter of data in such relationships. This scatter can be attributed to the fact that the overall degree of wave breaking is determined by a combination of various conditions characterizing both wind and wave fields. Therefore, approaches that incorporate the information on the dependence of whitecap coverage on waves and stability of the near-water layer of the atmosphere have been undertaken [*Toba and Chaen*, 1973; *Bortkovskii*, 1987; *Toba and Koga*, 1986; *Wu*, 1988; *Bortkovskii and Novak*, 1993]. It has been shown that wave-breaking and whitecap coverage is well correlated with energy dissipation rates of wind waves [*Cardone*, 1969; *Hanson and Phillips*, 1999]. It has been also suggested that the temperature of surface water has a substantial influence on whitecap coverage because of changes in the kinematic viscosity of seawater [*Bortkovskii*, 1987; *Monahan and O'Muircheartaigh*, 1986].

[6] In this paper we present results of our observations of whitecaps in the north polar waters of the Atlantic. Field data on whitecaps in the polar regions are scarce despite the fact that whitecaps may be especially important at high latitudes because of frequent periods of strong winds and storms. Few data that are available show a significant difference in the relationship for whitecap coverage versus wind speed between cold water regions and other regions [*Bortkovskii*, 1987; *Monahan and O'Muircheartaigh*, 1986; *Wu*, 1988]. Our main goal is to examine the variability of whitecap coverage in the north polar region of the Atlantic, to compare our results with other data sets available from literature, and to demonstrate the potential for improving the capability to predict whitecap coverage from the information on wind-wave conditions.

## 2. Observations

[7] Field data were collected in June-August of 1998, 1999, and 2000 during three cruises on the R/V *Oceania* operated by Institute of Oceanology, Polish Academy of Sciences. The study area extended between the northern part of the Norwegian coast (Tromso) and Svalbard, from about 70°N to 80°N within the meridional zone between 0° and 20°E (Figure 1). A broad set of oceanographic measurements was made on each cruise, but in this study we will focus on the sea surface photographs and meteorological observations.

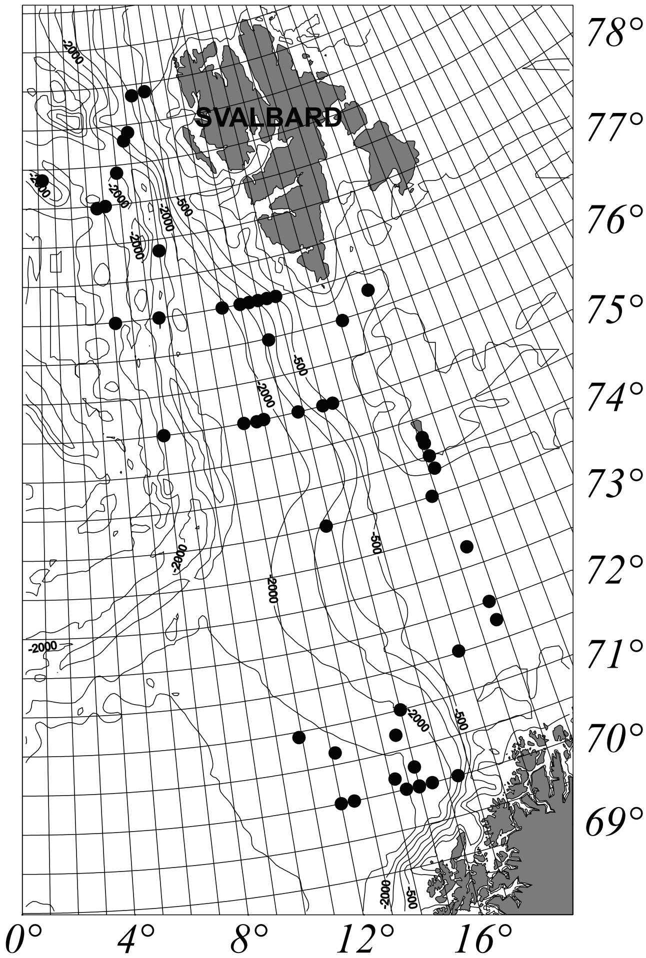


**Figure 1.** Map of the study region showing the location of stations where whitecap observations were made.

[8] Photographs of the sea surface were taken with a 35-mm digital camera (Epson Photo PC 600). Typically, at each station, 10–20 photographs were taken from approximately 15 m above the water level. The camera was positioned in such a way that it took an oblique photograph of the sea surface, which included a view extending slightly above the horizon (Figure 2). The tilt angle of the camera (the angle between the camera axis and the vertical line through the station) was around 75°. The photography was accompanied by observations of meteorological and sea surface conditions. The wind speed at 10 m above sea level ($U_{10}$) was measured with a cup anemometer, which was hand held in an appropriate position to the relative wind direction. Ship's course, speed, and position from GPS system were also recorded and used to correct the wind speed and direction. Air temperature ($T_a$) and humidity were determined from measurements of wet- and dry-bulb air



**Figure 2.** (a) Sea surface photograph taken on June 23, 1999. The wind speed was 11.2 m $s^{-1}$. (b) Sea surface photograph taken on August 8, 1999. The wind speed was 13.1 m $s^{-1}$. Our fractional whitecap estimates are based on the analysis of whitecaps in areas 2 and 3, while areas 1 and 4 were excluded form the analysis. See text for details.

temperatures with a sling (Assman) psychrometer. Sea surface temperature ($T_w$) was determined from CTD (Seabird) measurements. Significant wave height ($H_s$) and period ($T_s$) were estimated from a visual observation of the wave field. Regardless of photographs, these meteorological and sea surface observations were also made every 3 hours on each cruise.

## 3. Estimation of Whitecap Coverage From Photographs

[9] The digital photographs were analyzed for the fraction of the ocean surface covered by whitecaps ($W$). Image analysis was accomplished using the Matlab Image Processing Toolbox. This analysis can be summarized in the following way. First, each color image was displayed on a computer screen. This color image was converted to the gray image (Figures 2a and 2b). A coordinate system for the image was defined by applying the principles of high-oblique photography and the location of the apparent horizon visible on the photograph [e.g., *Wolf*, 1983]. In such a coordinate system, every pixel of the photograph corresponds to a well-defined area, which is smallest in the foreground and largest near the apparent horizon.

[10] A portion of the imaged ocean surface rather than the whole image was used in our calculations. Several factors were considered when choosing which part of the photograph should be used in the analysis. For example, we anticipated errors at the bottom of the picture due to interference of the ship and the wave field. We also expected that the picture geometry could lead to an overestimate of whitecap area at far distances (near the horizon), especially under the conditions of high wind speed. Therefore, it seemed prudent to exclude from the analysis the top and the bottom portions of the image. On the other hand, the statistical errors in the estimates of average whitecap coverage tend to increase if the sea surface area included in the analysis is too small. Due to the memory limitation of our camera, we could not take more than 20 photographs at each station; therefore it was important to analyze as large as possible a portion of each photograph. As a compromise, the sea surface area used for the analysis extended from pixels in row 40 to pixels in row 450 below the apparent horizon (Figure 2a, areas 2 and 3). The actual true sea surface area from this portion of a photograph is approximately 0.084 $km^2$. Thus the total sea surface area analyzed for 10–20 photographs from a given station ranged from 0.84 to 1.65 $km^2$, which is comparable to the aerial resolution of the ocean color satellites (1 $km^2$ for high-resolution data from SeaWiFS).

[11] In the next step the gray image was converted by thresholding to the image containing only black and white (B&W) pixels (Figures 3a, 3b, and 3c). The threshold gray level determined which pixels were converted to the white color and which pixels were converted to the black color. Because the variability in weather and color of the sea affects the contrast within the pictures, the threshold level was established for every picture individually, based on a visual comparison of black and white images with original images. Photographs affected by the reflection of the direct sunlight were excluded from the analysis. Only when we observed a good similarity between the original image and the distribution of white patches visible on the black and white image was the analysis continued. We made our analysis as objective as possible by scanning each image several times using different thresholds until the gray level was found, for which the estimated whitecap coverage varied very little with changes in the threshold. This is illustrated in Figures 3a, 3b, and 3c, which were obtained by converting the sea surface photograph shown in Figure 2a, with thresholds of 0.63, 0.64, and 0.65, respectively. As can be seen, Figure 3a is not a good representation of whitecaps seen in Figure 2a; therefore it was not used for further calculations. In contrast, both Figures 3b and 3c are similar to Figure 2a. The fraction of the area of the ocean surface covered by whitecaps, $W$, was calculated for each of these images from the ratio of the total area of white pixels to the total area of the ocean surface examined (Figure 2a, areas 2 and 3). The estimated fractional whitecap coverage from images shown in Figures 3b and 3c was 0.006 and 0.0058, respectively, and we used the average of these two numbers as our final estimate of $W$.

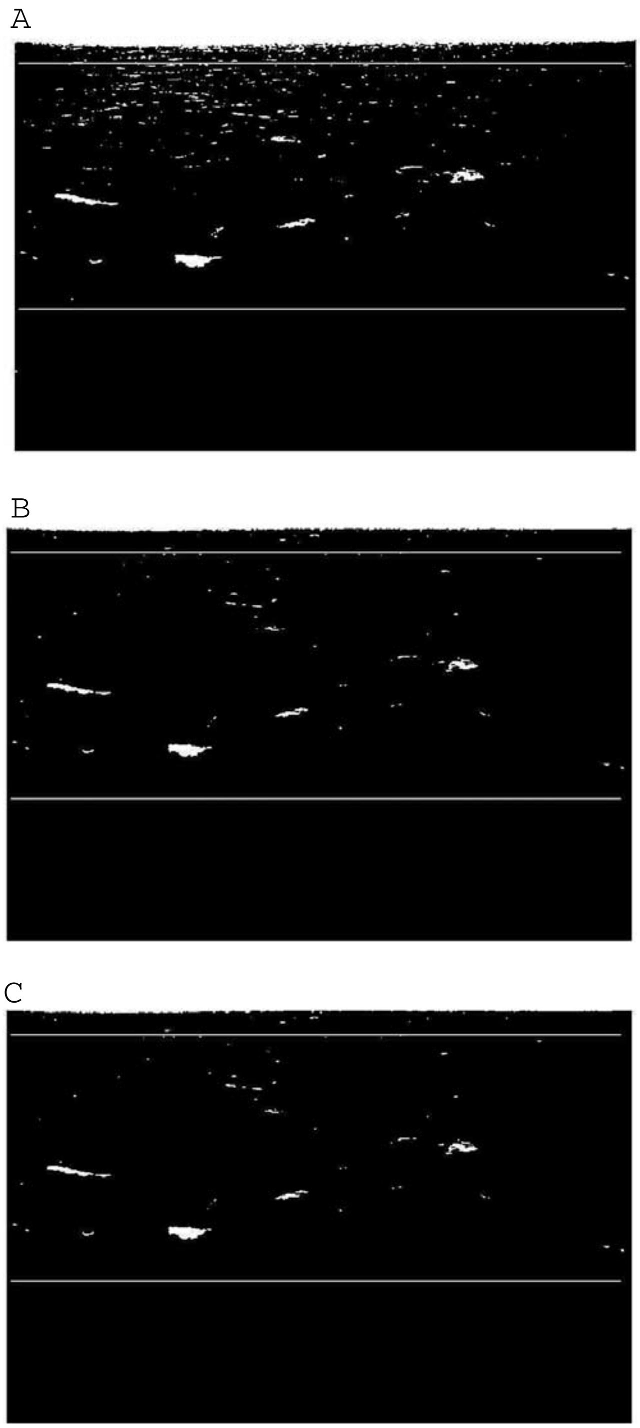


**Figure 3.** Sea surface photograph from Figure 2a converted to the black and white image using thresholds of (a) 0.63, (b) 0.64, and (c) 0.65. The section indicated by the two horizontal lines includes areas 2 and 3 from Figure 2a, which were analyzed to estimate *W*. See text for details.

[12] In order to verify that our estimates of *W* are not significantly affected by the obliqueness of the photographs, we carried out an additional analysis for 100 images taken under conditions of high winds (10–13 m/s). On each image, the area of interest defined above was divided into two horizontal strips (strips 2 and 3 shown in Figure 2a). Strip 2 of the image corresponds to approximately 0.07 $km^2$, and strip 3 corresponds to 0.014 $km^2$ of the sea surface. The results of this analysis show that the average *W* was 0.018 and 0.019 while the standard deviation was 0.018 and 0.028 for the strips 2 and 3, respectively. This indicates that the estimates of average fractional whitecap coverage are not biased due to the geometry of the examined area. The estimates of *W* from a larger area were characterized by smaller values of standard deviation, and this is why it seemed advantageous to use both strips 2 and 3 for our final calculations of whitecap coverage.

[13] Our estimates of whitecap coverage encompass two types of whitecaps, i.e., stage A and stage B whitecaps. According to *Monahan* [1993], stage A whitecaps are the crests of actively breaking waves, while stage B whitecaps include the foam that is visible on the sea surface for some short time after the wave breaks (timescale of 3.5–4.3 s). The information about the total whitecap coverage (including stage A and B whitecaps) is of interest to the studies on global albedo, global climate models, and atmospheric correction for satellite ocean color remote sensing [e.g., *Frouin et al.*, 2001; *Moore et al.*, 2000], while the information about stage A whitecaps is more relevant to research on wind-wave evolution and energy dissipation by breaking waves [e.g., *Hanson and Phillips*, 1999]. It would be advantageous to obtain individual estimates of $W_A$ and $W_B$, but a major obstacle in obtaining such results in our analysis was the fact that both of these whitecap stages are characterized by relatively high albedo values. According to *Monahan* [1993], the albedo of type A and type B whitecaps is 0.5–0.6 and 0.2–0.5, respectively. Therefore the relative brightness of a whitecap alone is not a sufficient criterion for distinguishing between these two stages. Note, for example, that in the central part of the sea surface photograph shown in Figure 2a there are two stage A whitecaps where the air entrainment is still occurring, and at least two stage B whitecaps. In another example, the whitecap shown in the center of Figure 2b includes an actively breaking wave, but a considerably larger area around whitecap A is occupied by stage B whitecap. The brightness of the image does not change significantly from one stage of whitecap to the other.

[14] Because it was not possible to objectively classify all the whitecaps present in our photographs into type A and B, we measured the total whitecap coverage. Our definition of whitecap area does not account for very thin patches of surface foam or for submerged bubble clouds, which may be residual features after the breaking wave. Such features are outside the resolution of our technique because they are not readily visible on the large area sea surface photographs. Like our study, many historical data sets discuss the variability of whitecaps in terms of the total whitecap coverage [e.g., *Monahan*, 1971; *Toba and Chaen*, 1973; *Wu*, 1988].

## 4. Results

[15] Our data were collected during summer seasons of 1998, 1999, and 2000 in the North Atlantic region, which includes waters of the Norwegian Sea, confluence zone of the Norwegian and Barents Seas, West Spitsbergen Current,

and the eastern part of the Greenland Sea (Figure 1). Some stations were visited on two or three cruises in different years and some stations were visited only on one cruise. In this study we discuss whitecap data from stations where no presence of sea ice in the water was observed. Sea surface temperature decreased from about 13°C near Norway to about 2°C in the northern part of the study area. Air temperature varied over a range of 0°C to 15°C, and relative air humidity between 83 and 97%. During the experiment, we observed mostly overcast sky conditions. Our study region was under the influence of frequent passages of atmospheric fronts coming from the west, which was reflected in the variable atmospheric pressure and wind stress. A typical wind fetch was on the order of the horizontal dimensions of the synoptic atmospheric weather systems (hundreds of kilometers). Winds at times exceeded 13 m s$^{-1}$, and during that time we observed that the fractional whitecap coverage reached 0.01–0.03, which is consistent with the prediction from the formula of *Monahan and O'Muircheartaigh* [1980].

### 4.1. Wind Effect on Whitecaps

[16] Fractional whitecap area coverage has been often analyzed in the past as a function of wind speed [e.g., *Monahan*, 1971; *Monahan and O'Muircheartaigh*, 1980]. In the older historical studies, the dependence of fractional whitecap coverage ($W$) on wind speed ($U_{10}$) was usually presented in a log-log space. Because it was found that an increase in $W$ is approximately proportional to the third power of $U_{10}$, in the more recent studies the historical data were reanalyzed to find the relationship between $W^{1/3}$ and $U_{10}$ in a linear space [*Monahan and Lu*, 1990; *Monahan*, 1993]. This approach implies that $W$ can be described by the following relationship:

$$W = a(U_{10} - b)^3,$$

where $a$ and $b$ are constants determined from a linear regression of the $W^{1/3}$ versus $U_{10}$ data. Our whitecap data plotted in Figure 4 show a good correlation between $W^{1/3}$ and $U_{10}$. Figure 4 includes also another group of data from the North Atlantic, which were obtained from the analysis of aircraft photographs taken under conditions of relatively high wind speed from 10 to 25 m s$^{-1}$ [*Nordberg et al.*, 1971; *Ross and Cardone*, 1974]. It is difficult to directly compare those data with our results, as most of the literature data are outside the range of wind speeds observed during our experiment. Nevertheless, the *Ross and Cardone* [1974] and *Nordberg et al.* [1971] data sets allow us to tentatively extend the $W$ versus $U_{10}$ relationship to very strong winds.

[17] Two least squares regressions representing the fractional sea surface coverage by stage A ($W_A$) and stage B ($W_B$) whitecaps obtained by *Monahan* [1993] from the compilation of data sets in various geographical regions are included in Figure 4 as well (lines 3 and 5). Note that these regressions indicate that on average the sea surface covered by stage B whitecaps is about 9–10 times higher than the area covered by stage A whitecaps [*Monahan*, 1993]. Therefore our estimates of the total whitecap coverage are expected to be dominated by $W_B$. A comparison of our estimates of $W$ with the regression line 5 shows that, on average, the values of $W$ at higher winds ($U_{10}$ > 10 m s$^{-1}$)

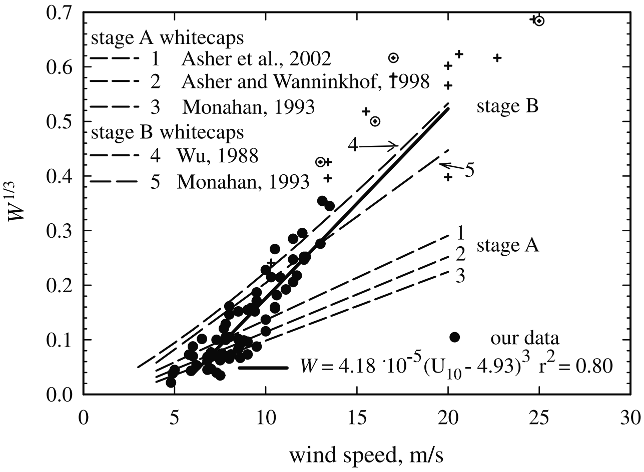


**Figure 4.** Whitecap coverage as a function of wind speed at 10 m above the sea level. Data points are for the total fractional whitecap coverage. Our results are indicated by solid dots, the *Ross and Cardone* [1974] data by pluses, and *Nordberg et al.* [1971] data by crosshair-circles. Solid line is a regression line obtained from our data points, and dashed lines indicate the relationships for type A whitecaps determined by: 1, *Asher et al.* [2002]; 2, *Asher and Wanninkhof* [1998]; 3, *Monahan* [1993]; and for type B whitecaps: 4, *Wu* [1988]; and 5, *Monahan* [1993].

are similar, but at low and moderate winds ($U_{10}$ < 10 ms$^{-1}$) our estimates of $W$ are lower than those predicted by Monahan's relationship.

[18] It is conceivable that differences in methods used to analyze the photographs contribute to the observed discrepancy between the results presented in Figure 4. The early estimates of $W$ included in the derivation of line 5 were based on the manual analysis of the sea surface photographs and could have led to somewhat different results compared to the present digital technique. The manual methods did not account for the geometry of oblique photography and tended to overestimate the near-field and underestimate the far-field contributions to $W$. In addition, our digital method does not account for thin foam and submerged bubble clouds, because these features do not show up as sufficiently bright patches on the sea surface photographs. Such features, however, were included as $W_B$ whitecaps in the previous manual methods. Also, while the small dark areas that fell within the larger whitecap area were included as part of the $W_B$ in manual methods (E.C. Monahan, personal communication, 2002), these areas show as black pixels in our black and white images, and therefore they do not contribute to our estimates of $W$.

[19] In view of these differences, we would expect the manual methods to yield somewhat higher estimates of $W$ than our digital method when there is not too many whitecaps present on the sea surface (i.e., at low winds). In such situations, a small whitecap in the near view or a barely visible bubble cloud or a thin layer of foam not resolved by our technique could significantly increase the estimate of $W$ in the manual methods compared to the digital technique. One could thus suggest that for low winds the historical data represent an upper limit of $W$, while our data represent a

lower limit, because only sufficiently "white" patches of water are included in our estimates. Depending on the purpose of the research, it may be advantageous to use either the upper or the lower estimate of $W$. For example, our estimates may be more appropriate if only highly reflective whitecap patches are to be accounted for in a model of the global radiation budget. An increase in back-scattering in the water body due to the submerged bubble clouds generated by breaking waves could be treated in such models as a separate process. Also, from the point of view of the atmospheric correction for the satellite ocean color remote sensing it is better to underestimate the effect of whitecaps than to overestimate it. Therefore it may be beneficial to use our estimates of $W$ in such applications.

[20] In general, however, the statistical error in the estimated whitecap coverage is expected to be especially large at low wind speeds. Under such conditions, the result of image analysis is typically based only on a few isolated whitecaps present within the photographs (even if a certain number of photographs obtained at a given wind speed are analyzed to reduce the statistical error). Therefore, both our data and historical data show much larger scatter of data points at low and moderate winds in comparison to higher wind speeds.

[21] It is also interesting to compare here a relationship estimated by *Wu* [1988] from several data sets collected over the years by Monahan and coworkers [*Monahan*, 1971; *Monahan and O'Muircheartaigh*, 1980, 1986; *Monahan et al.*, 1985]. *Wu* [1988] postulated that the variation of $W_B$ with $U_{10}$ can be described by the power law with the exponent of 3.75. Thus, the lines 4 and 5 in Figure 4 illustrate the small differences in the prediction of average $W_B$ from $U_{10}$, which can be attributed to the choice of different function to describe essentially the same whitecap data.

[22] It is also worthwhile to examine the differences in various whitecap data sets obtained with the same or similar methods. As an example, we included in Figure 4 two regression lines representing recent $W_A$ data collected and analyzed by Asher and coworkers [*Asher and Wanninkhof*, 1998; *Asher et al.*, 2002] with the methods consistent with *Monahan* [1993]. These regression lines clearly illustrate the fact that even when using the same methodology, some differences in the $W$ versus $U_{10}$ relationship are apparent between the various data sets.

[23] *Wu* [1979, 1988] pointed out that the rate of energy supplied to waves by wind is governed by wind stress ($\tau$), and therefore $W$ should be considered in terms of dependency on $\tau$ rather than $U_{10}$. The wind stress is proportional to the product of the wind stress coefficient ($C_D$) and the square of wind velocity. In turn, the wind stress coefficient varies with the wind velocity and atmospheric stability. Therefore, wind speed alone cannot be simply used as an alternate parameter for wind stress. Because the wind friction velocity ($u_*$) is proportional to the square root of the wind stress, *Wu* [1988] postulated that $W$ should be associated with the wind friction velocity instead of wind speed. A comparison of correlating $W_A$ and $W_B$ values with $u_*$ is given by *Monahan and Lu* [1990].

[24] In order to examine if the use of $u_*$ can provide a better prediction of $W$ than the use of $U_{10}$, we replotted our data in Figure 5, where $W$ is shown as a function of $u_*$. The

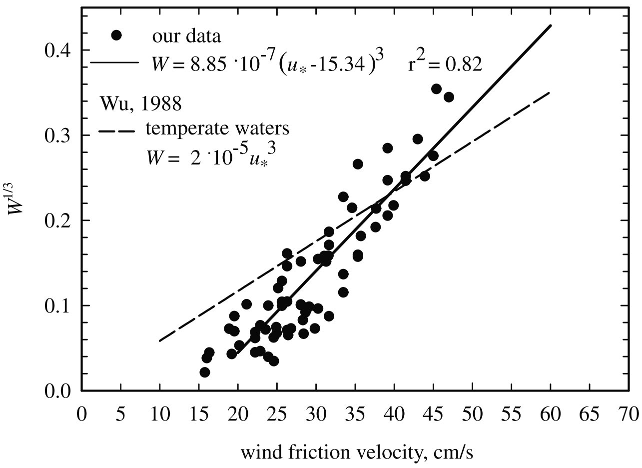


**Figure 5.** Oceanic whitecap coverage as a function of wind friction velocity. Solid line indicates a regression fitted to our data, dashed and dash-dot-dotted lines are functions proposed by *Wu* [1988] for warm and cold water regions, respectively.

estimates of $u_*$ were obtained from our measurements of $U_{10}$, $T_w$, $T_a$, and air humidity, using standard procedures described by *Liu et al.* [1979]. As can be seen from a comparison of Figures 4 and 5, the use of $u_*$ instead of $U_{10}$ did not significantly decrease the scatter of data points. The correlation coefficients for our data in Figures 4 and 5 are essentially the same. The dashed line included in Figure 5 illustrates the power law function fitted by *Wu* [1988]. These fits were obtained from a compilation of data from several experiments [*Monahan*, 1971; *Monahan and O'Muircheartaigh*, 1980, 1986; *Monahan et al.*, 1981, 1985]. It is seen that our data are characterized by a significantly stronger increase of $W$ with $u_*$ than predicted by the Wu relationship.

[25] Figures 4 and 5 reveal a significant scatter of data points in the relationship between $W$ and $U_{10}$ (or $u_*$). This scatter can be attributed partly to the errors inherent in the methods used to estimate $W$. On the other hand it is expected that environmental factors other than wind speed also influence the magnitude of $W$. For example, wind history, local hydrodynamic conditions such as currents and swell, directionality of the wave field, presence of biological surfactants, and variations in water temperature and atmospheric stability all can contribute to variability in the $W$ versus $U_{10}$ relationship. We will now evaluate how important some of these effects could have been during our experiments.

### 4.2. Effects of Other Environmental Factors on Whitecaps

[26] Apart from methodological differences, one possible reason for the observed difference between our data and the historical data sets shown in Figures 4 and 5 involves a potential dependence of whitecap coverage upon sea surface temperature. *Bortkovskii* [1987] observed a strong positive dependence of $W$ on $T_w$. *Monahan and O'Muircheartaigh* [1986] suggested that at least two factors may contribute to the dependence of $W$ on $T_w$. First, wind energy transferred to the waves in the case of equilibrium, that is, in the case of

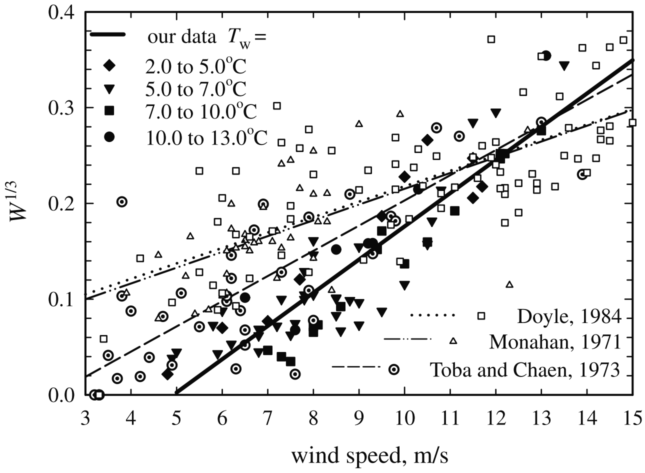


**Figure 6.** Oceanic whitecap coverage as a function of wind speed in the four ranges of sea surface temperature, as observed during our experiment. Solid line is the regression line estimated for all our data points (also shown in Figure 4). For comparison, warm water data from *Monahan* [1971] and *Toba and Chaen* [1973] and cold water data from *Doyle* [1984] are also shown.

fully developed wave spectrum, is balanced by energy dissipation due to wave breaking and the rate of viscous energy dissipation. Because the kinematic viscosity of seawater decreases significantly with an increase in $T_w$, the viscous dissipation decreases with $T_w$. As a result, for the same wind speed but at a higher $T_w$, more wave breaking per unit time per unit area of the sea surface might be required to accommodate the same amount of viscous energy dissipation in the same fully developed sea. Second, the time of life of an individual whitecap is expected to increase with $T_w$. This is because the bubble size distribution shifts toward smaller radii with increasing $T_w$, and these smaller bubbles have lower terminal rise velocity and longer lifetime than larger bubbles, even if the simultaneous change in water viscosity partly counteracts this effect.

[27] In order to examine our data in terms of the water temperature effect, we defined four ranges of $T_w$ as shown in Figure 6. Note that $T_w$ varied between 2°C and 13°C during our experiments. In spite of this relatively large range, our data do not seem to support the notion that changes in $T_w$ had some systematic influence on $W$ at any given $U_{10}$ within the range of observed $T_w$. In order to further analyze the effect of water temperature on whitecaps, we also plotted in Figure 6 the points from two warm water data sets [*Monahan*, 1971; *Toba and Chaen*, 1973] and from a data set collected during STREX experiment in cold waters [*Doyle*, 1984]. The sea surface temperature in warm water experiments ranged between 20° and 30°C and it varied between 5° and 11°C in the STREX experiment. We have chosen these data sets for comparison with our data, because the geometry of the sea surface photographs was similar as in our experiment, and the estimates of $W$, like ours, represent the total whitecap coverage (type A and B whitecaps). The main difference in the methodology is that the literature data are based on manual methods while we carried out a digital analysis. We note that our data points for low and moderate winds are within the range of $W$ values obtained by *Toba and Chaen* [1973] in a warm water region. We also observe a significant difference between the regression lines estimated for the two warm water data sets. In addition, the regression line for the STREX data set, with water temperatures quite similar as in our experiment, compares well with the regression line for the warm water data set by *Monahan* [1971]. Therefore, we conclude that there is no evidence to support the notion that the differences between our data and the historical data sets can be explained by the effect of the sea surface temperature on $W$.

[28] Another hypothesis to be examined is based on the study by *Monahan and O'Muircheartaigh* [1986], which suggested that whitecap coverage is affected by the thermal stability of the near-water air. They parameterized the air thermal stability by the difference between the sea surface water temperature and air temperature measured on the ship's deck ($\Delta T = T_w - T_a$). According to their results, for a given $U_{10}$, $W$ is larger in the case of unstable near-water atmosphere ($\Delta T$ positive) than in the case of neutral air stability. In order to establish the importance of stability of the near-surface atmosphere, we replotted our data using different symbols to distinguish four ranges of $\Delta T$ (Figure 7). For comparison, the prediction of $W$ for stable and unstable atmosphere according to the *Monahan and O'Muircheartaigh* [1986] model is also included in Figure 7. Our data do not reveal any clear effect of $\Delta T$ on $W$.

[29] Previous studies also suggested that, in addition to the effects of $U_{10}$, $T_w$, and $\Delta T$, the whitecap coverage $W$ varies with the duration and fetch of the wind [e.g., *Cardone*, 1969; *Ross and Cardone*, 1974]. Our data represent open ocean conditions with long fetch, so these data are not suitable to examine the effect of fetch on $W$. Nevertheless, we can compare the variability of $W$ under developed and undeveloped seas, assuming that during our

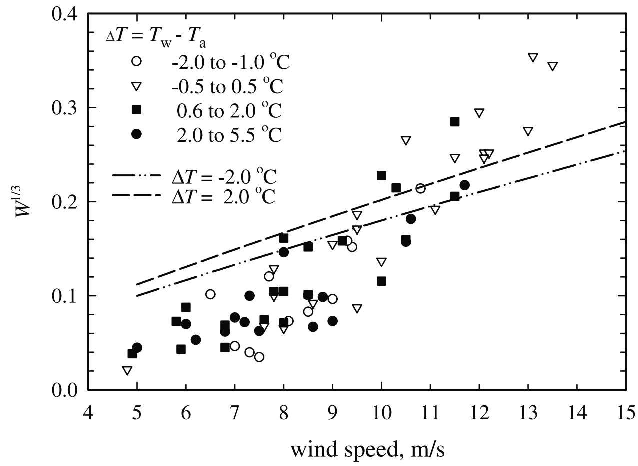


**Figure 7.** Oceanic whitecap coverage as a function of wind speed for four cases of the stability of the lower atmosphere (parameterized by the difference between the sea surface temperature, $T_w$ and air temperature, $T_a$). For comparison, the dash-dot-dotted and the dashed lines indicate $W$ predicted by the *Monahan and O'Muircheartaigh* [1986] relationship for stable and unstable atmospheric conditions.

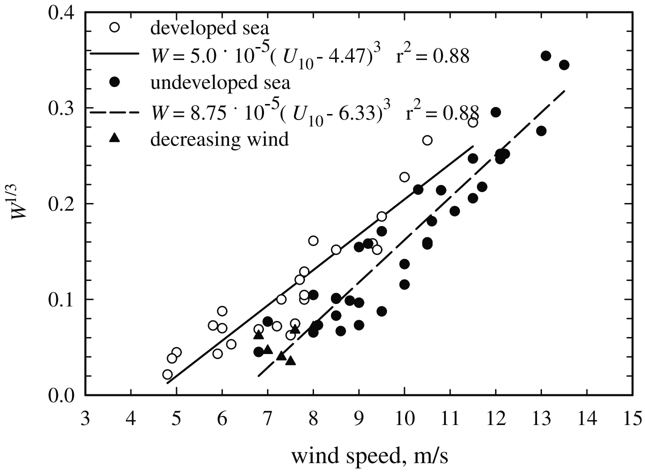


**Figure 8.** Oceanic whitecap coverage as a function of wind speed. Different symbols are used for the developed wave field, the undeveloped wave field, and the decreasing wind speed. See text for details.

experiment the sea state at a given wind speed was mostly determined by the duration of the wind action. Toward this goal, we divided our data into three groups. The first group of data represents the developed sea conditions, the second group represents the undeveloped sea conditions, and the third group represents stations where we observed a significant decrease of wind speed over a relatively short period of time ($U_{10}$ decreased by at least 2.5 m s$^{-1}$ during a 3-hour period). The criterion used to distinguish between the undeveloped and developed sea states has been based on a comparison of significant wave height ($H_s$) observed at any given station and a hypothetical significant wave height expected for a fully developed sea at the measured wind speed [e.g., *Pierson et al.*, 1955]. The data points were classified as representing the undeveloped sea state when the observed $H_s$ was at least 0.5 m less than the expected $H_s$ for a hypothetical fully developed sea. The 0.5-m criterion has been chosen due to the relatively low accuracy of our $H_s$ estimates. These estimates were based on the visual observation of the wave field, and therefore we decided to limit our discussion to differences in $H_s$ of 0.5 m or more. This criterion is not exact; nevertheless, it allows us to gain insights into the influence of sea state on $W$.

[30] Our results shown in Figure 8 support the hypothesis that wind duration was one of the important parameters influencing $W$ in our data set. At any given $U_{10}$, the fully developed seas were generally characterized by greater whitecap coverage than the undeveloped seas. One can speculate that the sensitivity of $W$ to wind history is, to some extent, responsible for the observed differences in the $W$ versus $U_{10}$ relationships shown in Figure 4. Note that atmospheric forcing and its timescales can show some characteristic differences between various geographic regions and seasons of the year. For example, winds in the trade wind regions are expected to vary on slower timescales than those experienced in the north polar regions of the Atlantic. As a result, the wave field in trade winds regions tends more toward fully developed seas, and hence, for a given wind speed we would expect to observe, on average, higher whitecap coverage than in regions with highly variable atmospheric conditions (where undeveloped seas are more likely to occur). The potential influence of latitudinal variation of wind duration and of surface water temperature on the global distribution of whitecaps was also suggested by *Monahan and O'Muircheartaigh* [1986].

## 5. Discussion and Conclusions

[31] Our results confirm that the traditional formulation of whitecap coverage as a function of wind speed shows a large scatter in the data, especially when applied to a broad range of wind-wave conditions. The observational evidence clearly suggests that the simple expression for $W$ versus $U_{10}$ should be replaced by more comprehensive relationships, which take into account additional environmental factors and their regional differentiation. We found that the $W$ versus $U_{10}$ relationship in the north polar waters of the Atlantic differs from historical relationships [*Monahan*, 1993]. These historical relationships are currently used in the atmospheric correction algorithm for ocean color remote sensing [*Gordon and Wang*, 1994; *Gordon*, 1997]. The regressions given by *Monahan* [1993] or *Wu* [1988] would overestimate our observations of $W$ by a factor of about 8 at $U_{10}$ = 7 m s$^{-1}$ and by a factor of about 2 at 9 m s$^{-1}$. From the point of view of the ocean color remote sensing, such overestimates of $W$ can lead to large errors in the satellite-derived data products. It was shown that it would be better to underestimate $W$ in the whitecap correction algorithm than to overestimate it [*Gordon*, 1997]. Because whitecaps have the potential to produce errors in the ocean color data products, it will be important to further improve our capability to predict $W$ and to validate whitecap algorithms with more field observations.

[32] In our experiments, we did not find any evidence that the $W$ versus $U_{10}$ relationship is significantly modified by changes in the sea surface temperature and near-surface air stability. On the other hand, our data indicated that the knowledge of wind history (duration of wind action) can improve the prediction of $W$ from $U_{10}$ in open ocean waters. We showed that even a simple partitioning of data into the developed and undeveloped sea state conditions could improve the accuracy of predicting $W$ from $U_{10}$. At present, the observed regional differences in the whitecap dependence on wind speed are not well understood, and the mechanisms that induce such differences are a matter of some speculation. Because our data suggest that the $W$ versus $U_{10}$ relationship is not very sensitive to water temperature and atmospheric stability, it seems that the variability in local wind-wave conditions (such as wind speed, wind direction, wind duration and fetch, and interaction of wind waves with swell and currents) plays a major role in the observed regional differentiation of whitecap coverage. This expectation is in agreement with other results that link wave-breaking probability to wind-waves age, wind trends, and the strength of currents [*Kraan et al.*, 1996; *Hanson and Phillips*, 1999].

[33] Present theoretical models for predicting oceanic whitecap coverage consider mostly wave-breaking statistics, which are related to whitecap area formation. Note, however, that the actual whitecap coverage as discussed in this paper depends on the formation of whitecaps and the

characteristic lifetime of already created whitecaps. This means that $W$ is somewhat different from the area of actively breaking waves because it also includes a residual foam cover. As pointed out by *Monahan and O'Muircheartaigh* [1986], the time constant characterizing the decay of individual whitecaps changes with water temperature, water salinity, and concentration of dissolved organic material. Therefore, this time constant can change with time and regionally. Nevertheless, breaking waves are the dominant factor controlling whitecap production in the open ocean, so any further progress in theoretical models and experimental methods allowing better understanding the mechanism and statistics of breaking waves [*Deane and Stokes*, 2002; *Melville and Matusov*, 2002] will be of great value. A fundamental problem common to analytical models for the fraction of the sea surface covered by actively breaking waves [e.g., *Snyder and Kennedy*, 1983; *Srokosz*, 1986; *Xu et al.*, 1998, 2000] is that these models include parameters that are not easily verifiable and measurable. It is therefore important to collect more observational data for validating such models, for justifying necessary approximations, as well as for improving our understanding of factors that control the variability of $W$ under real oceanic conditions.

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