Effective reflectance of oceanic whitecaps

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The effective reflectance of the foam on the ocean surface together with the fraction of the surface covered with foam describes the optical influence of whitecaps in the solar spectral range. This effective reflectance is found to be ~22% in the visible spectral range and is presented as a function of wavelength for the solar spectral range. With the fraction of the surface covered with foam, taken from the literature, the results lead to a good agreement with satellite measured radiances and albedo values. The effective reflectance is more than a factor of 2 lower than reflectance values used to date in remote sensing and radiation budget studies. Consequently, the optical influence of whitecaps can be assumed to be much less important than formerly supposed.

I. Introduction

In the solar spectral range the reflectance of the ocean increases with the proportion of whitecaps. Consequently, the variability of whitecaps gives rise to a variation in the radiance and the radiant flux densities at the bottom and the top of the atmosphere.[1]

So, the correct optical influence of whitecaps must be taken into account, both for remote sensing and in radiation budget (climate) studies. In remote sensing measurements, where the actual optical influence of whitecaps is not precisely known, there is an equivalent uncertainty in the remotely sensed quantity.[2–4] In climate studies the correct optical influence of whitecaps should be taken into account, since oceanic foam has an effect on the albedo of the ocean, affecting the solar heating of its upper boundary layer which may result in an alteration of the water temperature and the depth of the mixed layer.

Austin and Moran[5] have characterized the reflection properties of the ocean surface with foam by determining the fraction of the surface with reflectance within a given interval (a histogram of the surface area as a function of the surface reflectance). Unfortunately they have analyzed too few cases to establish a quantitative relationship between reflectance of the sea surface and wind speed.

However, statistical data are available which give the fraction covered with foam, W, as a function of wind speed U.[6–11] In computations of radiance or radiant flux over an ocean surface, whitecaps are usually taken into account as the product of their percentage area and a reflectance value between 0.5 and 1.0.[1,4,12] These rather high foam-reflectance values are in the right order of magnitude for fresh, dense foam but not for real foam on water surfaces with patches of all ages and consequently very different reflectances.

The aim of this paper is to determine the effective reflectance of whitecaps which allows one to use the $W(U)$ values from the literature to describe the optical influence of whitecaps.

II. Reflectance of Ocean Surface

In the solar spectral range the reflectance of an ocean surface, R_{oc}, is composed of three components: reflection at foam, specular reflection, and underlight:

$$R_{oc} = R_{f,\mathrm{tot}} + (1 - W) \cdot R_s + (1 - R_{f,\mathrm{tot}}) \cdot R_u. \quad (1)$$

The first term in Eq. (1) gives the reflectance of the total number of foam patches and streaks, $R_{f,\mathrm{tot}}$. It is the product of the fraction covered with whitecaps and the reflectance of the whitecaps. It is described in detail in the next section.

The second term describes the specular reflectance at the water surface without foam. This component can be calculated for a flat surface with the Fresnel formula and therefore depends on the angles of incidence and reflection and on the refractive index of the water. Small spectral variations of this refractive index in the spectral range between 0.4 and 1.5 μm (Ref. 13) result in an unimportant decrease of the R_s values in this range. The slope of the waves of the usually rough ocean reduces and broadens the glint,[14,15] an effect which must be taken into account in R_s, e.g., with data after Cox and Munk.[16] The R_s value in Eq. (1) is weighted by $(1 - W)$, the area not covered with whitecaps, since specular reflection is possible only at that part of the surface.

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The third part describes the reflectance due to underlight R_u. Although the underlight is scattered at water molecules and suspended material in the water, it can be described as a reflectance.[17] To take into account the reduction of underlight due to whitecaps, R_u in Eq. (1) is weighted by the factor in the parentheses. This factor is based on the assumption that the reflectance of whitecaps is the same for light coming from above or below. The reflectance due to underlight can be assumed to be isotropic[17,18] due to the multiple scattering processes inside the water and to the spreading of the radiance field emerging upward through the water surface. The R_u values show strong spectral behavior,[17] depending on the material in the water. In ocean water R_u can be neglected at wavelengths longer than 0.7 μm due to the spectral absorption of the water. In turbid waters with high sediment load, however, underlight is possible even at wavelengths above 1.0 μm.[17,19]

The contributions due to whitecaps and underlight are of the same order of magnitude. As mentioned above, they depend on the wavelength, on the water quality, and on the foam coverage. If an angle-dependent reflection function of the ocean surface is used to calculate radiances, Eq. (1) is also valid, but instead of reflectances the angle-dependent reflection function must be introduced. In this case, in directions outside the sun glint where the specular reflected component is low, the contribution due to the diffuse components underlight and whitecaps becomes important. Therefore their exact values must be used and the effective reflectance of the whitecaps is required.

III. Reflectance of Whitecaps

The spectral reflectance of dense foam of clear water, R_f, is ~55% in the visible part of the spectrum as measured by Whitlock *et al.*[20] in laboratory conditions. The value of ~55% is valid up to 0.8-μm wavelength; toward longer wavelengths the reflectance decreases due to absorption of liquid water. The reflectance has two relative minima at 1.5 and 2 μm and can be assumed to be zero at 2.7 μm. Calculations with a simple model for a whitecap consisting of more than twenty-five uniform bubble layers also give a reflectance value of ~55% in the spectral range below 1 μm.[21]

The angle-dependent reflection function of whitecaps has not yet been studied. Usually they are assumed to be isotropic reflectors[1–4,22,23] which is in agreement with visual inspection.

The relative area covered with whitecaps, W, is determined by different authors[6–11] as a function of the 10-m elevation wind speed U. They use photos of the ocean surface where the outline of the white area is traced, more or less, and the area is measured.[8] The surface is divided into subregions that are deemed, in the judgment of the investigators, to contain white water, all other regions are consequently dark water.[5] However, the threshold reflectance value that the investigators used as their decision criteria for white is not known. The white water must stand out against the water without foam. Consequently the threshold reflectance for white increases toward the horizon, and little account is taken of the less dense wind-generated foam streaks.[24] Each of the photos contains whitecaps of different ages; it follows that in the published $W(U)$ values whitecaps of different ages are taken into account.

The fraction covered with whitecaps, however, not only depends on the wind speed but also on the fetch[9] and on the factors altering the mean lifetime of the whitecaps, such as water temperature[25] and thermal stability of the lower atmosphere.[11] Consequently, an expression for $W(U)$ only as a function of the wind speed, in the form given by Eq. (2),

$$W = \alpha \cdot U^{\lambda}, \tag{2}$$

has a large uncertainty; different authors or different statistical methods give different results.[10,11] Nevertheless, due to the lack of appropriate additional data, the user will usually take an expression like Eq. (2) to determine the area covered with whitecaps. In this paper, the optimal $W(U)$ expression by Monahan and O'Muircheartaigh,[11]

$$W = 2.95\ 10^{-6} \cdot U^{3.52}, \tag{3}$$

is used, which is valid for water temperatures higher than 14°C.

The optical influence of all the individual whitecaps, the total foam reflectance $R_{f,\mathrm{tot}}$, is obviously the sum of the optical influence of the individual whitecaps. The optical influence is given by the product of the area of each individual whitecap with its corresponding reflectance. These individual data are not, in general, available; as mentioned above, usually a fixed R_f value between 0.5 and 1.0 independent of wavelength or a wavelength-dependent R_f after Whitlock *et al.*[20] is combined with $W(U)$ to describe the optical influence of whitecaps:

$$R_{t,\mathrm{tot}} = W \cdot R_f. \tag{4}$$

However, the area of an individual whitecap increases with its age while its reflectance decreases. An example of this well-known behavior is shown in the photos in Fig. 1 taken at 1-sec intervals. The figures to the left of the fields give the age of the dominant whitecap with an uncertainty of 0.5 sec.

Since whitecaps of different ages are taken into consideration in the W values, the combination of W with R_f values valid for dense, fresh foam gives $R_{f,\mathrm{tot}}$ values that are too high. Consequently, a lower effective reflectance R_{ef} must be used [Eq. (5)]:

$$R_{f,\mathrm{tot}} = W \cdot R_{\mathrm{ef}}. \tag{5}$$

The available photos yield R_{ef} values only in the spectral range up to 0.8 μm. But they can be used to determine an efficiency factor f_{ef}, independent of wavelength, which allows the combination of spectral R_f values, as measured by Whitlock *et al.*,[20] with the W values depending on wind speed:

$$R_{f,\mathrm{tot}}(\lambda) = W \cdot f_{\mathrm{ef}} \cdot R_f(\lambda). \tag{6}$$

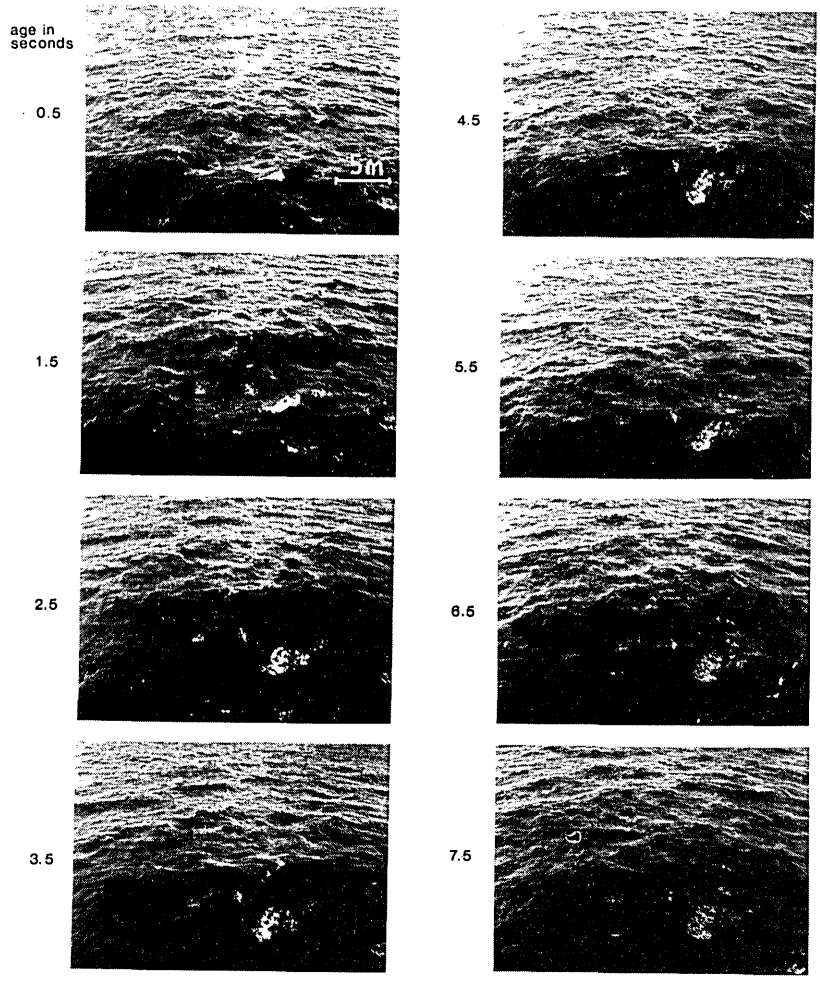

Fig. 1. Examples of the variation of a whitecap at 1-sec intervals, beginning at an age of 0.5 sec with an uncertainty of ±0.5 sec: wind speed, 7.5 m · sec^{-1}; water temperature, 15.7°C; viewing elevation, 60°; distance to foam patch, 35 m.

IV. Method

The variation in the size and reflectance of individual whitecaps as a function of time was determined from several series of photos. They were made from the upper deck (30-m height) of the research platform "Nordsee" in the German Bight at 50°43′N and 7°10′E between 22 Aug. and 21 Sept. 1978. The reason for working on the platform was to obtain ground truth measurements to calibrate the European satellite Meteosat.[26] This was done mostly in summer in low cloud coverage conditions and, unfortunately, also low wind speed conditions. Only a few series of photographs were made, but the material allows determination of an approximate value of the effective reflectance.

Meteorological and oceanographic parameters, such as wind speed and direction, wave height and period, and water and air temperature, were continuously recorded by the equipment on the platform. The wind speed at the 10-m level was estimated from that measured at the 47-m level using the logarithmic law with a roughness length of 0.15 mm.[27] The water temperature was between 15 and 16°C.

The camera was a 6- × 6-cm^2 Hasselblad equipped with a motor drive, a red filter to enhance the contrast, and a wide-angle lens with a focal length of 50 mm. The photos were taken as a series of ~10, at intervals of 1 sec and facing away from the sun. The elevation angle of the camera was varied between 45° and 60°, resulting in a distance to the analyzed whitecaps of between 33 and 60 m.

An analysis was made of the lifetimes of thirteen individual whitecaps, resulting from winds of ~8 m · sec^{-1}, and of six individual foam streaks from winds between 14 and 15 m · sec^{-1}. Each whitecap detected for the first time in a series must have been formed the second before, since it was not present in the preceding photo. Consequently, its age is 0.5 sec with an uncertainty of ±0.5 sec, as is also true for all the following pictures taken at 1-sec intervals. Due to a restriction of the lengths of the series, not all the whitecaps could be followed until they vanished.

Figure 1 shows an example of the lifetime of an individual whitecap. Figure 2 shows 10 sec of the lifetimes of different foam streaks. The streaks are fairly stable and only vary slightly in size and reflectance. Since the lifetime of such foam streaks is longer than 10 sec, neither their beginning nor their end can be seen. Due to this lack of information, in the evaluation it is assumed that all foam streak were seen for the first time at an age of 3.5 sec.

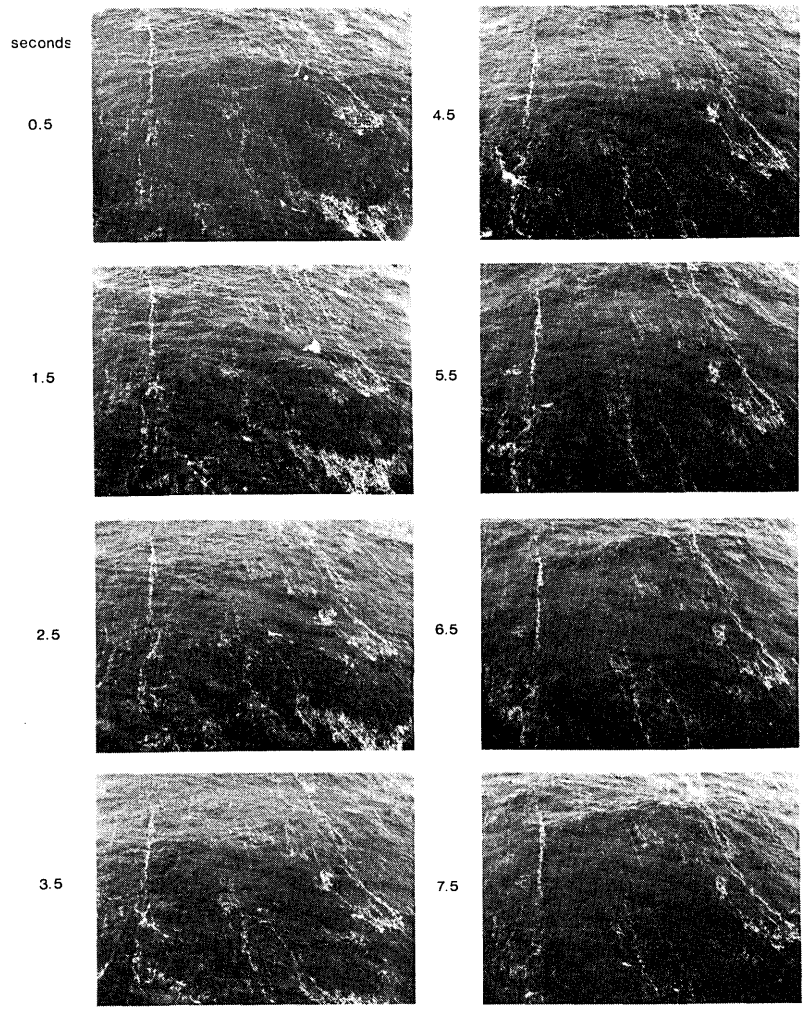

Fig. 2. Examples of the variation of an ocean surface with foam streaks at 1-sec intervals: wind speed, 14.5 m · sec^{-1}, water temperature, 15.7°C; viewing elevation, 50°; distance to the center of the image, 50 m.

To determine the area covered by a particular whitecap, a common method was used: The photos were projected onto graph paper, the outline of the white area was traced, and the area was measured. The area of each whitecap was normalized to be one at its maximum. So normalized values of the area of foam as a function of its age, $a(t)$, are the results presented in Figs. 3 and 4. It can be seen that the area of the foam patches increases during their lifetime.

The reflectance of the whitecaps was analyzed from the film density, similar to the method described by Austin and Moran.[5] If the reflectance of two points in the target can be established, the density curve can be graduated. These two reflectance values are the Fresnel reflectance of the nonwhite vicinity of the whitecap and the maximum diffuse reflectance of the dense, fresh whitecap. To analyze the reflectance of foam streaks, it was assumed that small portions found with density values comparable with that of dense whitecaps really have the maximum reflectance of dense whitecaps. Due to the wide variation of the reflectance over the area of the foam patches[5] the film density was measured at many positions, and mean values were determined. A mean value also was used as the density of the film in the vicinity of the whitecap to try to account for the variability of the reflectance due to the scope of the wave without foam. The camera transmittance curve was not taken into account, since the whitecap in each series was placed in a fixed position.

The maximum reflectance was taken to be 55% as measured by Whitlock *et al.*[20] and as calculated by Stabeno and Monahan[21] for the spectral region of the film material. Since this value was used as the mean value for the total area of the fresh, dense foam patches, it is also in agreement with the value found by Austin and Moran.[5]

It can be assumed that the slope of the film density curve is stable for at least ten pictures. So this slope, starting at density values of the reflectance of dark water in the vicinity of the whitecap, was used to determine the reflectance of the whitecap, $r(t)$, in each picture of the series. Figures 5 and 6 show the decrease in the reflectance as the whitecaps age.

Over a large area of the ocean, as analyzed in the $W(U)$ determination, it can be assumed that the age distribution of the whitecaps does not alter with time. Consequently, the mean effective reflectance of all the whitecaps in the area can be determined as the effective reflectance of an average whitecap, taking into account its total lifetime.

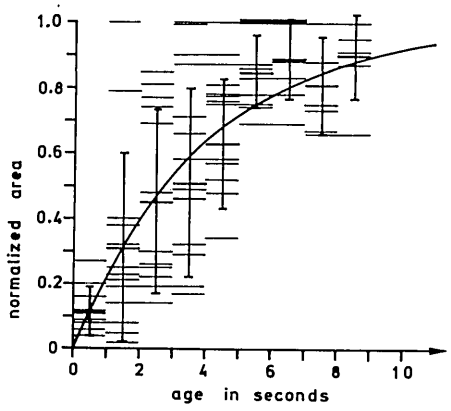

Fig. 3. Normalized area of whitecaps (foam patches) as a function of their age. The thicker stripes give the mean values. Wind speed between 7.5 and 8.5 m · sec^{-1}; water temperature between 15 and 16°C. The curve is calculated from Eq. (10) with $\beta = 0.25$ and $\gamma = 1$.

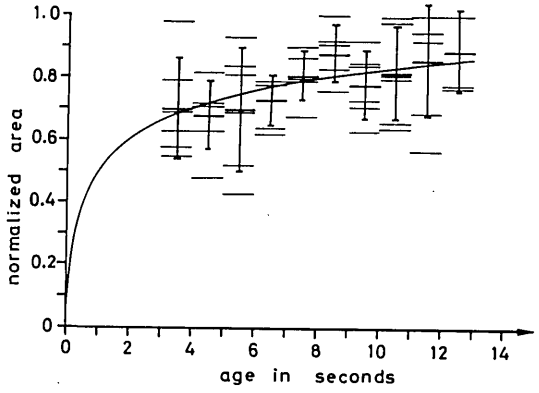

Fig. 4. Normalized area of foam streaks as a function of their age. The thicker stripes give the mean values. Wind speed between 14 and 15 m · sec^{-1}; water temperature between 15 and 16°C. The curve is calculated from Eq. (10) with $\beta = 0.7$ and $\gamma = 0.4$.

But in the $W(U)$ determination, whitecaps were ignored if they were decayed to a reflectance less than the threshold reflectance for white, which occurs at an age τ of the average whitecap. It follows that the integration to determine R_{ef} ends at time τ, since the values of the effective reflectance will be used in Eq. (5) in combination with $W(U)$ values. The effective reflectance can be evaluated with Eq. (7):

$$R_{ef} = \frac{\int_0^\tau a(t) \cdot r(t) \cdot dt}{\int_0^\tau a(t) \cdot dt}. \tag{7}$$

In the numerical solution, the products $a(t) \cdot r(t)$ of each individual whitecap are calculated and the integral is determined from the mean values of these products. The integration is performed as a sum with steps of dt = 1 sec.

The reduction of the effective reflectance of whitecaps due to the expansion of their area and the thinning of the foam can be assumed to be independent of the wavelength. The effective reflectance R_{ef} determined in the visible (and valid only for this spectral range if not written as a function of λ) can be converted to other spectral regions or wavelengths with an efficiency factor f_{ef}, which is derived as the ratio of the effective reflectance to the reflectance of dense foam:

$$f_{ef} = \frac{R_{ef}}{R_f} = \frac{R_{ef}}{0.55}. \tag{8}$$

Consequently, this efficiency factor can be combined with spectral reflectance values $R_f(\lambda)$ of fresh, dense foam as measured by Whitlock *et al.*[20]:

$$R_{ef}(\lambda) = f_{ef} \cdot R_f(\lambda), \tag{9}$$

resulting in spectral values of the effective reflectance.

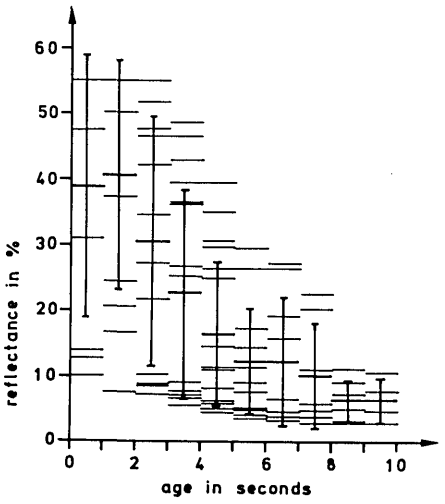

Fig. 5. Reflectance of whitecaps (foam patches) in the visible spectral range as a function of their age. The thicker stripes give the mean values. Maximum reflectance of fresh dense foam R_f = 55% after Whitlock *et al.*[20] Other data as in Fig. 3.

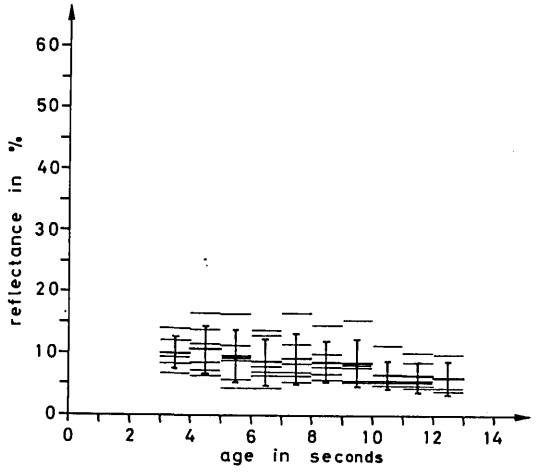

Fig. 6. Reflectance of foam streaks in the visible spectral range as a function of their age. Other data as in Fig. 4.

Table I. Effective Reflectance in the Visible Spectral Range and Efficiency Factor Independent of Wavelength as a Function of Age τ of Individual Whitecaps (See Text)

τ	Foam patches		Foam streaks	
second	$R_{ef,p}$ (%)	$f_{ef,p}$	$R_{ef,s}$ (%)	$f_{ef,s}$
1	41	0.75	10	0.18
2	35	0.63	10	0.18
3	30	0.55	10	0.18
4	28	0.50	10	0.18
5	25	0.45	9.9	0.18
6	23	0.41	9.6	0.17
7	21	0.38	9.5	0.17
8	19	0.35	9.4	0.17
9	18	0.32	9.2	0.17
10	16	0.29	9.0	0.16

V. Result

Figure 3 shows the normalized area $a(t)$ of individual foam patches as a function of their age, together with the mean values and the standard deviation. The large standard deviation arises not only in the high variability of the individual whitecaps and in the relatively low number of series analyzed but also in the subjective judgment used to determine the values. The uncertainty in the age is ±0.5 sec, as explained above. The increase of the area $a(t)$ can be described by an exponential function of the form

$$a(t) = 1 - \exp(-\beta \cdot t^{\gamma}), \tag{10}$$

which is presented in Fig. 3 with $\beta = 0.25$ and $\gamma = 1$.

Figure 4 shows the $a(t)$ values determined for foam streaks. As mentioned above, they start with an assumed age of 3.5 sec. The streaks spread fastest when they have just been generated and spread more slowly as they grow older, as the figure shows. Taking this into account leads to values of $\beta = 0.7$ and $\gamma = 0.4$ in Eq. (10) which gives the curve in Fig. 4.

The reflectance of individual whitecaps and foam streaks is shown in Figs. 5 and 6 as a function of time, together with mean values and standard deviations. Again, the large standard deviation originates in the variability in the reflectance of individual whitecaps together with subjective judgment.

The reflectance of foam patches, seen in Fig. 5, has its highest value at ~1.5 sec after generation. Since the individual whitecaps reach their maximum reflectance value at different ages, the mean value of $r(t)$ is always lower than 55%. But, as mentioned above, to calculate R_{ef} with Eq. (7) the $r(t)$ values of the individual whitecaps are used, which reach 55% as a maximum.

The reflectance of foam streaks shown in Fig. 6 has values of ~10%, in agreement with the result for a single bubble layer found by Whitlock *et al.*[20] It slowly decreases with age. For the integration [Eq. (7)], the values are extrapolated to 10% at $t = 1$ and 2 sec.

In Table I the effective reflectance R_{ef} in the visible spectral range and the efficiency factors f_{ef} are given separately for foam patches (subscript p) and foam streaks (subscript s). They are calculated with Eq. (7) as a function of time τ, the last age at which the foam is taken into account in the $W(U)$ values. The τ values used in the different $W(U)$ determinations are not known. Assuming a reflectance of 10% as the threshold value for white, one can work back to τ = ~7.5 sec for the patches from Fig. 5 and to ~4.5 sec for the streaks from Fig. 6.

The values for the patches clearly decrease with increasing τ, as expected from the strong variation over time of the properties of the whitecaps. Due to their more stable behavior, the values for the foam streaks depend only slightly on τ in the first 10 sec.

The resulting average values are for foam patches (whitecaps)

$$R_{ef,p} = (22 \pm 8)\%,$$

$$f_{ef,p} = 0.4 \pm 0.15.$$

The values are given with high uncertainty, to take into account both the uncertainty of the individual data and the uncertainty due to the lack of knowledge of the τ value used in the determination of $W(U)$. Foam streaks[9] contribute to the area of white water at wind speeds higher than ~9 m · sec^{-1}. The resulting values are for foam streaks

$$R_{ef,s} = (10 \pm 4)\%,$$

$$f_{ef,s} = 0.18 \pm 0.07.$$

In this case, the uncertainty is stated to be even higher than the variability in Table I, to take into account the uncertainty due to the unknown real age of the streaks and the extrapolation back to the time $t = 0$ in addition to the uncertainty of the measured data.

In actual cases where the patches and streaks are highly variable, the total reflectance should be summed from a histogram giving the fraction of the surface having a particular reflectance value.[5] Since these data are not available, the total reflectance is summed from only two terms [Eq. (11)], with W_p the fraction of foam patches and W_s the fraction of streaks:

$$R_{t,tot} = R_f \cdot (W_p \cdot f_{ef,p} + W_s \cdot f_{ef,s}). \tag{11}$$

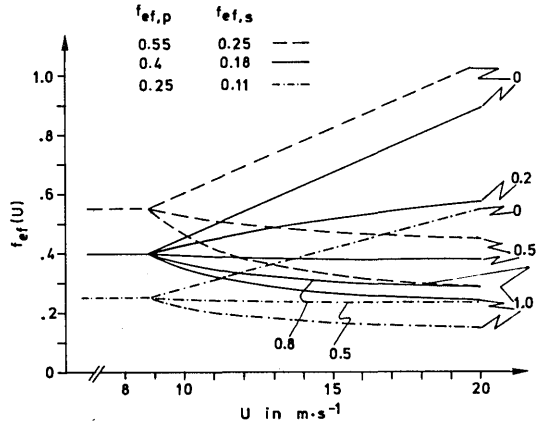

Fig. 7. f_{ef} values as a function of wind speed U. The numbers at the curves indicate what proportion x of the fraction of foam streaks is assumed to be taken into account in the $W(U)$ values; see text.

Since the goal of this article is to use available $W(U)$ data, W_p and W_s must be explained by $W(U)$. This is possible using a streak-to-whitecap ratio SP[9]:

$$SP = W_s/W_p. \tag{12}$$

The equation for SP, recalculated from Fig. 4 in Ross and Cardone[9] and converted to a wind speed U (in m · sec^{-1}) at the 10-m level, is given in Eq. (13):

$$\begin{aligned} SP &= 0, & U &\le 8.5 \text{ m} \cdot \text{sec}^{-1}, \\ SP &= -2.1 + 0.24 \cdot U, & U &< 8.5 \text{ m} \cdot \text{sec}^{-1}. \end{aligned} \tag{13}$$

However, as mentioned in Sec. III, in the $W(U)$ values determined by different authors, not all the streaks are taken into account,[24] since the reflectance of the streaks may be less than the threshold value for white. The fraction taken into account, called x, may vary between 0 and 1:

$$W(U) = W_p(U) + x \cdot W_s(U). \tag{14}$$

Combining Eq. (14) with Eq. (12) gives

$$\begin{aligned} W_p(U) &= W(U)/[1 + x \cdot SP(U)], \\ W_s(U) &= W(U) \cdot SP(U)/[1 + x \cdot SP(U)]. \end{aligned} \tag{15}$$

Using Eq. (11) gives the total reflectance due to foam as a function of wind speed,

$$R_{f,\text{tot}}(U) = W(U) \cdot f_{\text{ef}}(U) \cdot R_f = W(U) \cdot R_{\text{ef}}(U), \tag{16}$$

with a wind-speed-dependent efficiency factor $f_{\text{ef}}(U)$:

$$f_{\text{ef}}(U) = [f_{\text{ef},p} + f_{\text{ef},s} \cdot SP(U)]/[1 + x \cdot SP(U)]. \tag{17}$$

As may be seen in Eq. (17), $f_{\text{ef}}(U)$ depends on the fraction of foam streaks assumed to be considered in $W(U)$. If x is small, the streaks not taken into account give an additional increase in the reflectance, resulting in a high $f_{\text{ef}}(U)$ value. If all streaks are taken into consideration in $W(U)$, the increasing streaks-to-whitecap ratio with increasing wind speed results in a dominance of streaks at higher wind speed, resulting in a low $f_{\text{ef}}(U)$ value. Figure 7 shows this behavior for $f_{\text{ef}}(U)$ values calculated from maximum, minimum, and the means $f_{\text{ef},p}$ and $f_{\text{ef},s}$.

The right x value depends on the criteria used in the different $W(U)$ determinations.[24] To determine an x value, different photos made at the "Nordsee" platform were analyzed for $W(U)$ values. The results agree well with values calculated with Eq. (3) when half of the area covered with streaks is taken into account. So x is assumed to be 0.5, in agreement with the data shown by Ross and Cardone.[9] Due to subjective judgment both in the $W(U)$ and in the W_s and W_p values, other x values may occur. But the use of other x values seems too sophisticated compared with the approximate $f_{\text{ef},p}$ and $f_{\text{ef},s}$ values.

Consequently, the results are an efficiency factor and an effective reflectance that only decrease slightly with wind speed, as seen in Fig. 7:

$$f_{\text{ef}}(U) = 0.4 \pm 0.2, \qquad R_{\text{ef}}(U) = (22 \pm 11)\%. \tag{18}$$

In spite of that, in Table II f_{ef} is presented as a function of wind speed, together with $R_{\text{ef}}(U)$ after Eq. (8), with $W(U)$ calculated from Eq. (3) and the total reflectance due to foam after Eqs. (16) and (17) using $x = 0.5$.

Table II. Wind Speed Dependent Values of the Area Covered with Foam $W(U)$, the Efficiency Factor $f_{\text{ef}}(U)$, the Effective Reflectance in the Visible Spectral Range $R_{\text{ef}}(U)$, and the Total Reflectance Due to Foam $R_{f,\text{tot}}(U)$ in this Spectral Range

U (m/sec)	W (%)	f_{ef}	R_{ef} (%)	$R_{f,\text{tot}}$ (%)
4	0.0	0.4	22	0.0
5	0.1	0.4	22	0.0
6	0.2	0.4	22	0.0
7	0.3	0.4	22	0.0
8	0.5	0.4	22	0.1
9	0.7	0.4	22	0.2
10	1.0	0.39	21.7	0.2
11	1.4	0.39	21.5	0.3
12	1.9	0.39	21.4	0.4
13	2.5	0.39	21.3	0.5
14	3.2	0.38	21.2	0.7
15	4.1	0.38	21.1	0.9
16	5.1	0.38	21.0	1.1
17	6.3	0.38	20.9	1.3
18	7.7	0.38	20.8	1.6
19	9.4	0.38	20.8	2.0
20	11.2	0.38	20.7	2.3
25	24.6	0.37	20.6	5.1

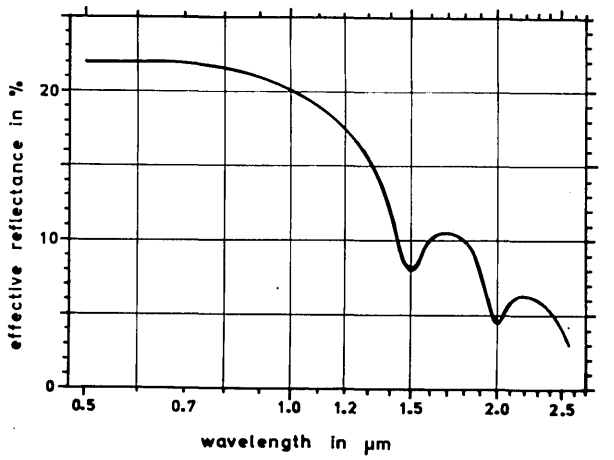

Fig. 8. Effective reflectance of oceanic foam as a function of wavelength, after Eq. (9).

The effective reflectance as a function of wavelength, $R_{\text{ef}}(\lambda)$, is calculated with Eq. (9) from the average efficiency factor given in Eq. (18) together with the spectral reflectance values from Whitlock *et al.*[20] The resulting spectral effective reflectance of oceanic foam, patches together with streaks, is presented in Fig. 8. As mentioned above, this effective reflectance is nearly independent of wind speed.

The large uncertainty of the results in Eq. (18) and consequently in Fig. 8 (but not shown there) takes into account the variability of f_{ef} due to x, presented in Fig. 7. The reasons for this uncertainty are discussed above; they are the same as those which result in the high uncertainty of the empirical formula that describes the $W(U)$ relations. Nevertheless, the new effective reflectance is an improvement on the values of the reflectance currently used, since these values were much too high.

VI. Comparison with Data in the Literature

Only a few works were found which give data on measured radiances or albedo values as a function of the amount of whitecaps or the wind speed. These data are compared with radiances or albedo values, calculated with the corresponding atmosphere model, using Eq. (1) as the ocean reflection function. The calculations take into account multiple scattering and absorption of atmospheric gases as described by Koepke.[26]

For a first comparison, the results found by Austin and Moran[5] seem appropriate. Unfortunately, their reflectance cumulative-distribution function gives the fraction of the surface having a reflectance less than the value shown at the abscissa and not the mean reflectance of a fraction of the surface. But this reflectance can be calculated from the histogram given in their Fig. 6. In this histogram the fraction a_i of the surface is given as a function of the surface reflectance r_i. Adding the columns of the histogram up to a specific column I, with reflectance r_I, gives the fraction of the surface a which has reflectance values less than r_I. The mean reflectance r of this surface fraction is the weighted sum of the reflectance values in the histogram:

$$a = \sum_{i=1}^{I} a_i$$

$$r = \sum_{i=1}^{I} a_i \cdot r_i / \sum_{i=1}^{I} a_i. \tag{19}$$

The data from Austin and Moran originate from a wind speed of 25 m · sec^{-1}, which results in $W(U) = 0.246$ after Eq. (3) and consequently in the fraction of the surface without foam $(1 - W)$ of 0.754. Adding the areas of the columns in the histogram, this value is reached at the 22nd column at a reflectance of 10%. So the use of Eq. (3) with the Austin and Moran values gives the result that a reflectance of 10% is the threshold value between a surface covered with foam and that free of foam. The mean reflectance of the surface without foam is 5.5% from Eq. (19). This value is in good agreement with literature data for a rough ocean in overcast conditions.[28] Adding all columns of the histogram gives a surface fraction of 100% with a mean reflectance of 7.73%. This value can be understood as the total reflectance of the analyzed ocean surface R_{oc}. It is used with Eq. (1), neglecting the underlight, to calculate $R_{f,\mathrm{tot}}$, the total reflectance due to foam being 0.036. Using Eq. (16) gives an efficiency factor of $f_{\mathrm{ef}} = 0.265$ and, equivalently, an effective reflectance of $R_{\mathrm{ef}} = 14.6\%$. These values confirm the need to use an efficiency factor in foam reflectance calculations. The value of the efficiency factor determined from the Austin and Moran data is even lower than the factor proposed in this paper, but it is well within the given uncertainty range. Better agreement cannot be expected, since at the high wind speed in the Austin and Moran data,[5] the $W(U)$ values are questionable and the problem of the fraction of streaks in the $W(U)$ data becomes especially important.

At lower wind speed conditions, the extensive measurements by Payne[28] allow a check of the efficiency coefficient. He found that in the albedo of the sea surface, effects of whitecaps are not noticeable at wind speeds up to 30 knots, the highest observed in that study. His measurements of the albedo are made for the total solar spectral range from 0.28 to 2.8 μm. So my calculation of the albedo values requires computations in this broad spectral range and is made only for one mean turbid, cloudless atmosphere at a solar zenith angle of 32.5°. The rms error which Payne found for this condition leads to an uncertainty in the measured albedo value of ±0.003. The wind speed of 15 msec^{-1} gives $W = 4.1\%$. Compared with the case without whitecaps, such a fraction of whitecaps would lead to an increase in the calculated surface albedo of 0.017, if the literature data of W and $R_f(\lambda)$ are used without the efficiency factor. Including the efficiency factor (Table II) reduces the increase in the calculated albedo to 0.006, which is still higher than the rms error found by Payne but well inside his range for single data points.

The Landsat data published by Maul and Gordon[12] allow another check on the influence of whitecaps on the ocean surface. They report an increase from digital number 20 to 22 in channel MSS-4 due to an increase in the fraction of whitecaps from 5% to 10%. With the spectral transmission curve of the filter and the equivalent-radiance resolution,[29] the resulting spectral radiances are determined to be 37.2 and 40.9 W · m^{-2} sr^{-1} μm^{-1}, respectively. Nadir radiances, calculated for the sun elevation of 53.9°, including the different amount of foam as well as the different underlight reported by Maul and Gordon[12] but without the efficiency factor, are 42.3 and 50.9 W m^{-2} sr^{-1} μm^{-1}, respectively. That means the values are too high and, moreover, they increase too strongly with increasing amount of whitecaps. However, if the efficiency factor is used, the calculated radiances for both of the foam fractions coincide with the measured values. They are within the digitization uncertainty of the measured radiances.

A last comparison is made with radiances measured by CZCS published by Viollier.[30] In a clear atmosphere, he found an increase of the ocean reflectance of 0.02 due to foam from 20 m · sec^{-1} wind. This is in very good agreement with radiances calculated with the complete model, if the efficiency factor is used. It can be seen from Eq. (1) with data from Table II that the foam reduces the specular reflection by 11% but gives an additional total reflectance of 0.023, resulting in an increase of the reflectance of 0.02, as measured.

VII. Conclusions

The effective reflectance of ordinary foam on the ocean is lower than the reflectance of fresh, dense foam. In the visible spectral range it was found to be only ~22%, nearly independent of wind speed; the efficiency factor was determined to be 0.4 which is used, together with the reflectance of fresh foam, to calculate the spectral effective reflectance in the solar spectral range.

The combination of the effective reflectance (R_{ef} in Table II) with the fraction of the surface covered with

foam [Eq. (3)] gives the wind-speed-dependent reflectance due to the total foam coverage ($R_{f,\mathrm{tot}}$ in Table II) and so the optical influence of oceanic whitecaps on the radiation field over the ocean.

The values of the effective reflectance and the efficiency factor have a rather high uncertainty, as do the values of the fraction of the surface covered with whitecaps presented by different authors, due to the wide variation of the data and the subjective judgment in the analysis. Moreover, the quantities depend on parameters other than just the wind speed, such as fetch, thermal stability, and water temperature. The effective reflectance should be determined with more data in different conditions. Nevertheless, radiances and fluxes calculated with the results given in this paper are in good agreement with measured values presented by different authors.

The effective reflectance is more than a factor of 2 lower than reflectance values used to date in remote sensing and radiation budget studies. Consequently, the optical influence of oceanic whitecaps can be assumed to be much less important than was formerly supposed.

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References

1. H. R. Gordon and M. M. Jacobs, "Albedo of the Ocean–Atmosphere System: Influence of Sea Foam," Appl. Opt. **16**, 2257 (1977).
2. P. Koepke and H. Quenzel, "Turbidity of the Atmosphere Determined from Satellite: Calculation of Optimum Wavelength," J. Geophys. Res. **86**, 9801 (1981); Correction **87**, 7350 (1982).
3. S. Tassan, "The Influence of Wind in the Remote Sensing of Chlorophyll in the Sea," in *Oceanography from Space*, J. Gower, Ed. (Plenum, New York, 1981), p. 371.
4. P. Koepke and H. Quenzel, "Most Suitable Conditions for Aerosol Monitoring from Space," Adv. Space Res. **2**, 29 (1982).
5. R. W. Austin and S. Moran, "Reflectance of Whitecaps, Foam and Spray," in *Ocean Color Analysis* (U. California, VIS-Lab., San Diego, 1974), SIO Ref. 74-10.
6. D. C. Blanchard, "Whitecaps at Sea," J. Atmos. Sci. **28**, 645 (1971).
7. E. C. Monahan, "Oceanic Whitecaps," J. Phys. Ocean **1**, 139 (1971).
8. Y. Toba and M. Chaen, "Quantitative Expression of the Breaking of Wind Waves on the Sea Surface," Rec. Oceanogr. Works Jpn. **12**, 1 (1973).
9. D. B. Ross and V. Cardone, "Observations of Oceanic Whitecaps and Their Relation to Remote Measurements of Surface Wind Speed," J. Geophys. Res. **79**, 444 (1974).
10. J. Wu, "Oceanic Whitecaps and Sea State," J. Phys. Ocean **9**, 1064 (1979).
11. E. C. Monahan and I. O'Muircheartaigh, "Optimal Power-Law Description of Oceanic Whitecap Coverage Dependence on Wind Speed," J. Phys. Ocean **10**, 2094 (1980).
12. G. A. Maul and H. R. Gordon, "On the Use of the Earth Resources Technology Satellite (LANDSAT-1) in Optical Oceanography," Remote Sensing Environ. **4**, 95 (1975).
13. W. M. Irvine and J. B. Pollack, "Infrared Optical Properties of Water and Ice Spheres," Icarus **8**, 324 (1968).
14. P. M. Saunders, "Shadowing on the Ocean and the Existence of the Horizon," J. Geophys. Res. **72**, 4643 (1967).
15. G. N. Plass, G. W. Kattawar, and J. A. Guinn, Jr., "Isophotes of Sunlight Glitter on a Wind-Ruffled Sea," Appl. Opt. **16**, 643 (1977).
16. C. Cox and W. Munk, "Statistics of the Sea Surface Derived from Sun Glitter," J. Mar. Res. **13**, 198 (1954).
17. A. Morel, "In-Water and Remote Measurements of Ocean Color," Boundary-Layer Meteorol. **18**, 177 (1980).
18. H. R. Gordon, "Radiative Transfer: Technique for Simulating the Ocean in Satellite Remote Sensing Calculations," Appl. Opt. **15**, 1974 (1976).
19. C. H. Whitlock, L. R. Poole, J. W. Usry, W. M. Houghton, W. G. Witte, W. D. Morris, and E. A. Gurganus, "Comparison of Reflectance with Backscatter and Absorption Parameters for Turbid Waters," Appl. Opt. **20**, 517 (1981).
20. C. H. Whitlock, D. S. Bartlett, and E. A. Gurganus, "Sea Foam Reflectance and Influence on Optimum Wavelength for Remote Sensing of Ocean Aerosols," Geophys. Res. Lett. **9**, 719 (1982).
21. P. J. Stabeno and E. C. Monahan, "The Influence of Whitecaps on the Albedo of the Sea Surface," in *Whitecaps and the Marine Atmosphere*, Report 5, University College, Galway, Ireland (1983).
22. P. Koepke and H. Quenzel, "Turbidity of the Atmosphere Determined from Satellite: Calculation of Optimum Viewing Geometry," J. Geophys. Res. **84**, 7847 (1979).
23. H. Quenzel and M. Kaestner, "Optical Properties of the Atmosphere: Calculated Variability and Application to Satellite Remote Sensing of Phytoplankton," Appl. Opt. **19**, 1338 (1980).
24. E. C. Monahan, M. C. Spillane, and P. J. Stabeno, personal communication at the "Whitecap Workshop," 4–7 Sept. 1983, University College, Galway, Ireland (1983).
25. Y. Miyake and T. Abe, "A Study on the Foaming of Sea Water," J. Mar. Res. **7**, 67 (1948).
26. P. Koepke, "Vicarious Satellite Calibration in the Solar Spectral Range by Means of Calculated Radiances and Its Application to Meteosat," Appl. Opt. **21**, 2845 (1982).
27. S. Sethuraman and G. S. Raynor, "Surface Drag Coefficient Dependence of the Aerodynamic Roughness of the Sea," J. Geophys. Res. **80**, 4983 (1975).
28. R. E. Payne, "Albedo of the Sea Surface," J. Atmos. Sci. **29**, 959 (1972).
29. *NASA-ERTS Data Users Handbook*, Document Nr. 71 SP 4249, Goddard Space Flight Center, Greenbelt, Md. (1971).
30. M. Viollier, N. Baussart, and P. Y. Deschamps, "Preliminary Results of CZCS Nimbus-7 Experiment for Ocean Colour Remote Sensing: Observation of the Ligurian Sea," in *Oceanography from Space*, J. Gower, Ed. (Plenum, New York, 1981), p. 387.