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:

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

The first term in Eq. (1) gives the reflectance of the total number of foam patches and streaks, \(R_{f,tot}\). 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 \(\mu\)m (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.
The third part describes the reflectance due to under
light \( R_u \). 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 ac-
count 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 reflect-
ance 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 wave-
lengths longer than 0.7 \( \mu \text{m} \) due to the spectral absorp-
tion of the water. In turbid waters with high sediment
load, however, underlight is possible even at wave-
lengths above 1.0 \( \mu \text{m} \).\(^{17,19}\)

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-depen-
dent 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 ef-
fective reflectance of the whitecaps is required.

III. Reflectance of Whitecaps

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

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 de-
termined 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 in-
vestigators used as their decision criteria for white is not
known. The white water must stand out against the
water without foam. Consequently the threshold re-
fectance 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 ac-
count.

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),

\[
W = \alpha \cdot U^3, \tag{2}
\]

has a large uncertainty; different authors or different
statistical methods give different results.\(^{10,11}\) Never-
theless, 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,\(^{11}\)

\[
W = 2.96 \times 10^{-6} \cdot U^{3.52}, \tag{3}
\]

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

The optical influence of all the individual whitecaps,
the total foam reflectance \( R_{f,tot} \), 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 re-
fectance. 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:

\[
R_{f,tot} = W \cdot R_f. \tag{4}
\]

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 con-
sideration in the \( W \) values, the combination of \( W \) with
\( R_f \) values valid for dense, fresh foam gives \( R_{f,tot} \) values
that are too high. Consequently, a lower effective re-
fectance \( R_{ef} \) must be used [Eq. (5)]:

\[
R_{f,tot} = W \cdot R_{ef}. \tag{5}
\]

The available photos yield \( R_{ef} \) values only in the
spectral range up to 0.8 \( \mu \text{m} \). 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:

\[
R_{f,tot}(\lambda) = W \cdot f_{ef} \cdot R_f(\lambda). \tag{6}
\]
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. 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. The water temperature was between 15 and 16°C.

The camera was a 6 × 6-cm² 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 streaks 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. 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 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. and as calculated by Stabeno and Monahan 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.

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 β = 0.25 and γ = 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 β = 0.7 and γ = 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_{eff} 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):

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

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_{eff} 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_{eff}, which is derived as the ratio of the effective reflectance to the reflectance of dense foam:

$$f_{eff} = \frac{R_{eff}}{R_f} = \frac{R_{eff}}{0.55}.$$  

Consequently, this efficiency factor can be combined with spectral reflectance values R_{f}(λ) of fresh, dense foam as measured by Whitlock et al.:

$$R_{eff}(\lambda) = f_{eff} \cdot R_{f}(\lambda),$$

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. 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 \( \tau \) of Individual Whitecaps (See Text)

<table>
<thead>
<tr>
<th>( \tau ) (second)</th>
<th>Foam patches ( R_{ef,p} ) (%)</th>
<th>( f_{ef,p} )</th>
<th>Foam streaks ( R_{ef,s} ) (%)</th>
<th>( f_{ef,s} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>41.0</td>
<td>0.75</td>
<td>10</td>
<td>0.18</td>
</tr>
<tr>
<td>2</td>
<td>35.0</td>
<td>0.63</td>
<td>10</td>
<td>0.18</td>
</tr>
<tr>
<td>3</td>
<td>30.0</td>
<td>0.55</td>
<td>10</td>
<td>0.18</td>
</tr>
<tr>
<td>4</td>
<td>28.0</td>
<td>0.50</td>
<td>10</td>
<td>0.18</td>
</tr>
<tr>
<td>5</td>
<td>25.0</td>
<td>0.45</td>
<td>9.9</td>
<td>0.18</td>
</tr>
<tr>
<td>6</td>
<td>23.0</td>
<td>0.41</td>
<td>9.6</td>
<td>0.17</td>
</tr>
<tr>
<td>7</td>
<td>21.0</td>
<td>0.38</td>
<td>9.5</td>
<td>0.17</td>
</tr>
<tr>
<td>8</td>
<td>19.0</td>
<td>0.35</td>
<td>9.4</td>
<td>0.17</td>
</tr>
<tr>
<td>9</td>
<td>18.0</td>
<td>0.32</td>
<td>9.2</td>
<td>0.17</td>
</tr>
<tr>
<td>10</td>
<td>16.0</td>
<td>0.29</td>
<td>9.0</td>
<td>0.16</td>
</tr>
</tbody>
</table>

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 \( \pm 0.5 \) sec, as explained above. The increase of the area \( a(t) \) can be described by an exponential function of the form

\[
a(t) = 1 - \exp(-\beta \cdot t^\gamma),
\]

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 \( \sim 1.5 \) 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 \( \sim 10\% \), 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 \( \tau \), the last age at which the foam is taken into account in the \( W(U) \) values. The \( \tau \) 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 \( \tau = \sim 7.5 \) sec for the patches from Fig. 5 and to \( \sim 4.5 \) sec for the streaks from Fig. 6.

The values for the patches clearly decrease with increasing \( \tau \), 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 \( \tau \) 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 \( \tau \) value used in the determination of \( W(U) \). Foam streaks\(^8\) contribute to the area of white water at wind speeds higher than \( \sim 9 \) m \( \cdot \) 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:

\[
R_{tot} = R_p \cdot (W_p \cdot f_{ef,p} + W_s \cdot f_{ef,s}).
\]

Figure 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 $W$, must be explained by $W(U)$. This is possible using a streak-to-whitecap ratio $SP$:

$$SP = \frac{W_s}{W_p}. \quad (12)$$

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

$$SP = 0, \quad U \leq 8.5 \text{ m sec}^{-1},$$
$$SP = -2.1 + 0.24 \cdot U, \quad U > 8.5 \text{ m sec}^{-1}. \quad (13)$$

However, as mentioned in Sec. III, in the $W(U)$ values determined by different authors, not all the streaks are taken into account, 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:

$$W(U) = W_p(U) + x \cdot W_s(U). \quad (14)$$

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

$$W_p(U) = \frac{W(U)}{1 + x \cdot SP(U)}, \quad (15)$$
$$W_s(U) = \frac{W(U) \cdot SP(U)}{1 + x \cdot SP(U)}. \quad (16)$$

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

$$R_{tot}(U) = W(U) \cdot f_{ef}(U) \cdot R_f = W(U) \cdot R_{ef}(U), \quad (17)$$

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

$$f_{ef}(U) = \frac{f_{ef,p} + f_{ef,s} \cdot SP(U)}{1 + x \cdot SP(U)}. \quad (18)$$

As may be seen in Eq. (17), $f_{ef}(U)$ 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 $f_{ef}(U)$ 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 $f_{ef}(U)$ value. Figure 7 shows this behavior for $f_{ef}(U)$ values calculated from maximum, minimum, and the means $f_{ef,p}$ and $f_{ef,s}$.

The right $x$ value depends on the criteria used in the different $W(U)$ determinations. 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. Due to subjective judgment both in the $W(U)$ and in the $W_p$ and $W_s$ values, other $x$ values may occur. But the use of other $x$ values seems too sophisticated compared with the approximate $f_{ef,p}$ and $f_{ef,s}$ values.

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

$$f_{ef}(U) = 0.4 \pm 0.2, \quad R_{ef}(U) = (22 \pm 11)\%. \quad (19)$$

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

The effective reflectance as a function of wavelength, $R_{ef}(\lambda)$, is calculated with Eq. (9) from the average efficiency factor given in Eq. (18) together with the spectral reflectance values from Whitlock et al. 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.

<table>
<thead>
<tr>
<th>$U$ (m/sec)</th>
<th>$W$ (%)</th>
<th>$f_{ef}$ (%)</th>
<th>$R_{ef}$ (%)</th>
<th>$R_{tot}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.0</td>
<td>0.4</td>
<td>22</td>
<td>0.0</td>
</tr>
<tr>
<td>5</td>
<td>0.1</td>
<td>0.2</td>
<td>22</td>
<td>0.0</td>
</tr>
<tr>
<td>6</td>
<td>0.2</td>
<td>0.4</td>
<td>22</td>
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Fig. 8. Effective reflectance of oceanic foam as a function of wavelength, after Eq. (9).
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. For a first comparison, the results found by Austin and Moran 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 $r_i$ 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:

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

$$r = \frac{1}{a_i} \sum_{i=1}^{a} a_i \cdot r_i$$

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. 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 $R_{t, tot}$, the total reflectance due to foam being 0.036. Using Eq. (16) gives an efficiency factor of $f_{ef} = 0.265$ and, equivalently, an effective reflectance of $R_{ef} = 14.6\%$. 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, 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 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 of ±0.003. The wind speed of 15 m sec$^{-1}$ gives $W = 4.1\%$. Compared with the case without whitecaps, such a fraction of whitecaps would lead to an increase in the calculated albedo of 0.017, if the literature data of $W$ and $R(\lambda)$ 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 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 spectral transmission curve, 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 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. 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 reactivity due to the total foam coverage \( R_{t,\text{tot}} \) in Table II and so the optical influence of oceanic whitecaps on the radiation field over the ocean.

The values of the effective reactivity 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 reactivity 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 reactivity 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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