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On the Albedo of Radiation of the Sea Surface*

(2) On the reflection of light by a roughened water surface

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Abstract: It is important to know the light reflected from the sea surface for the knowledge of the albedo of radiation of the sea surface. The measurements of the light reflected from the roughened surface of the wind disturbed ocean are too difficult to be carried out, and the problem may be made accessible to the experimental treatment by using a small wind tunnel containing a water boundary. The results show that Fresnel's law may be applicable not only for the smooth surface, but also for the roughened wavy surface by considering the individual wave slopes as the reflected plane of the incident light. Referentially, the changes in the mean values of the albedo with the latitude of the earth are represented for the smooth surface and for three wavy surfaces by application of the above results.

1. Introduction

The upward light from the sea water was discussed by the author in the previous report. The problem of the radiative and thermal balance of the sea water contains also the important factor such as the reflection of light on the sea surface. In this case, Fresnel's law may be applicable for the amount of light reflected by a flat water surface, and some results were obtained for the direct radiation from the sun and the scattered radiation from the sky (H. GRIESSEIER, and W. E. K. MIDDLETON etc.). In the normally ruffled or wavy condition of the sea, however, the circumstance is different and complicated. W. BURT attacked this case theoretically, using Andreson's observation data on Lake Hefner, and Д. Л. Грищенко carried out the observations at Black Sea. Besides those, the observations may be considered scarce, owing to the difficulty in practice on the sea *in situ*. On the other hand, the measurements of the probability distribution of slopes on the wavy surface have been made by A. H. SCHOOLEY, and by C. COX and W. H. MUNK, using the optical method.

Those works suggested the author to treat the problem by the nearly reverse process. That is, the amounts of light reflected from the wind-roughened water surface were measured, using a small water-wind tunnel. In this case, the angles of incident light as well as that of reflected light were varied and also the states of water surface were changed by changing the wind velocity. The purpose of the present paper is to report the results of experiment and to show some further computation.

2. Method of experiment

Fig. 1 is a schematic presentation of the method and a photograph of the equipment which has been used in this experiment. The simple water-wind tunnel was constructed to generate the wind-wave surface. This was similar to Schooley's method, though the size was somewhat larger. The clear plastic walled channel of 100 cm length between the two end containers is 10 cm wide and the water depth is 20 cm. Air is drawn from left to right by the two vacuum cleaner blowers and the wind velocity is measured by the hot wire type anemometer, of which probe is inserted in the air stream. The wind velocity is adjusted by changing the electrical input voltage in a blower motor. This tunnel is, of course, closed, except for the necessary holes to pass the incident light and reflected light to and from a wind-wave surface when the measurement is being done.

The optical system used in this experiment

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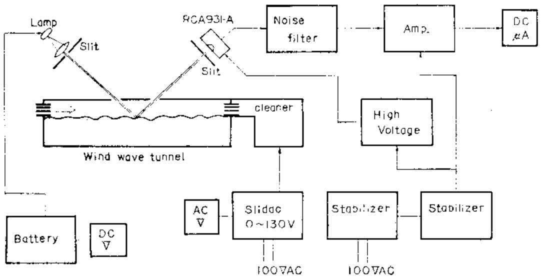

Fig. 1 (a). Block diagram of experimental procedure.

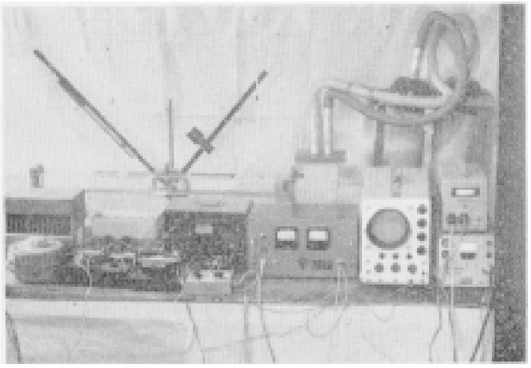

Fig. 1 (b). Photograph of apparatus.

was consisted of the light source, and the light receiver with amplification system, being kept constant by two kinds of stabilizers. The light source was a small lamp, which was used at voltage of 8 volts. By the use of the pinhole and lens, the rather accurate parallel ray was obliquely impinged in a vertical plane upon a water surface, and on the other side, the reflected ray was received by the photomultiplier tube. The light source and light receiver were set on bars, which could be rotated around the same horizontal axis in a vertical plane, in order to measure the angular distribution of light intensities at any angle and to meet the conditions set forth above. The size of the slit which regulated the area of light was 4.4×2.4 mm at the light source, and 4.4×13.1 mm at the light receiver respectively. This is because the effect of up and down motion of the roughened surface may be avoided as possible. The electric current from the photomultiplier tube was rather pulse-shaped in general, and so it was flattened through the noise filter, and then amplified by the stable linear amplifier. The current was read by the ammeter of D.C. 250 μA.

3. Determination of the slope of roughened surface

The profiles of a water surface were photographed by the flash-lamp camera in each measurement of reflected light intensities. Three examples of photographs are shown in Fig. 2. The centre of photographs was kept at the middle portion of the tunnel where a incident light was reflected on the water surface. Facet slopes were measured from those photographs of the different wave surfaces in the regions of ±5 cm from the centre above mentioned. The frequency distri-

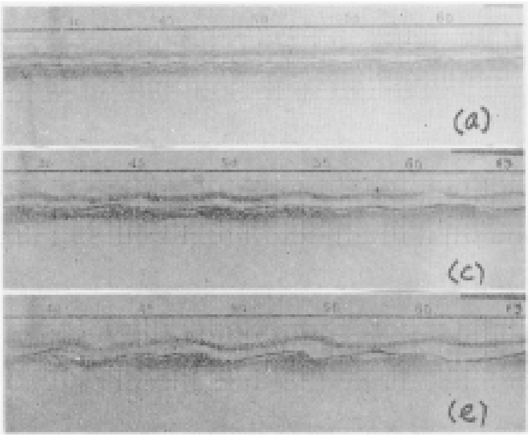

Fig. 2. Profiles of a wave in a water wind tunnel. (Wind velocities are (a) 4.4 m/s, (c) 6.8 m/s and (e) 10.2 m/s respectively.)

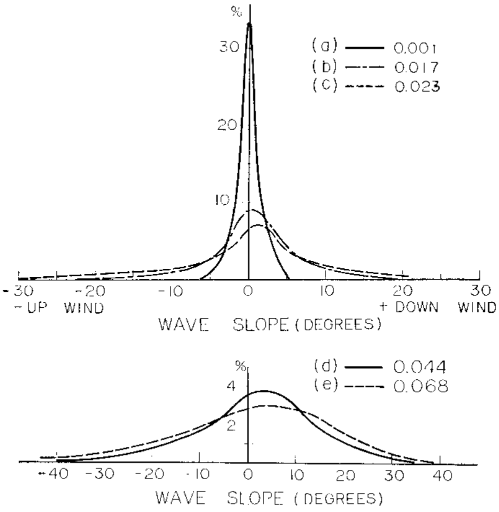

Fig. 3. Wave slope distribution curves. (Wind velocities are (a) 4.4 m/s, (b) 5.7 m/s, (c) 6.8 m/s, (d) 8.4 m/s and (e) 10.2 m/s respectively.)

butions of facet slopes are obtained with five cases of wind velocities as shown in Fig. 3, where the abscissa gives the slope of the facets in degrees, the signs of slopes being taken positive if the level of water is higher in downwind direction than in upwind direction, and negative if *vice versa*. The slopes are measured graphically at 1 degree intervals along the wave profiles for the weaker wind forces, and at 2 degrees intervals for the larger ones. Perhaps because of the features of wind-driven wave, the curves in Fig. 3 represent an upwind-downwind slice of the distribution function and extend broader in the upwind direction than in the downwind. Those tendencies may be seen rather remarkable for the stronger wind forces.

Referentially, the main features of wind-disturbed water wave used in this experiment are shown in Fig. 4, where wave lengths, wave steepnesses, and the mean square slopes are plotted as a function of wind velocity.

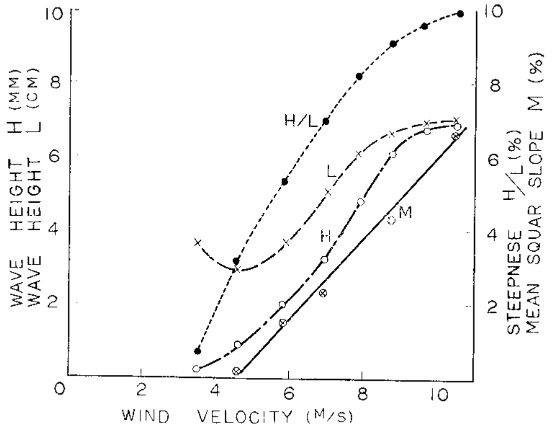

Fig. 4. Features of waves in a water wind tunnel.

4. Considerations on the reflection of light

For perfectly smooth water surface, it is well known that Fresnel's law may be applicable for the reflected light intensities as in the following fomula.

$$J(\theta)=\frac{1}{2}\left[\left\{\frac{\tan(\theta-\theta')}{\tan(\theta+\theta')}\right\}^2+\left\{\frac{\sin(\theta-\theta')}{\sin(\theta+\theta')}\right\}^2\right], \quad (1)$$

where $J(\theta)$ is the light intensity reflected in the direction of θ, when incident light intensity is taken unity, θ is the angle of incident light and reflected light, and θ' is the refractive angle of water for the incident angle of θ.

In this experiment it was checked that this law holds for the smooth water surface with no wind.

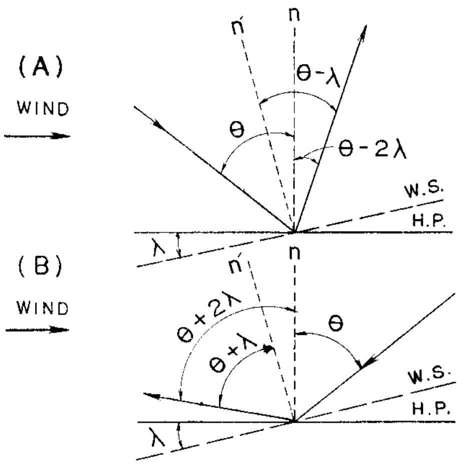

Fig. 5. Reflection of light at the incident surface. (W.S. : water surface, H.P. : horizontal plane)

Now, the wind-roughened water surfaces will be considered. Fig. 5 shows the relation of incident angle and reflected angle to the slope of inclined water surface. If we take the incident angle θ with respect to the horizontal plane and the slope of water surface is λ, then we get the reflected light angle θ_r as to the horizontal plane and the incident angle θ_i as to the inclined plane as follows:

$$\theta_r=\theta\mp 2\lambda;\quad \theta_i=\theta\mp\lambda \quad (2)$$

respectively. The sign is taken negative or positive if the direction of incident light is the same as the wind direction or opposite to the wind direction. The intensity of reflected light J_r in the direction of θ_r from the horizontal plane is given by equations (1) and (2) in the following.

$$J_r(\theta_r)=J_r(\theta\mp 2\lambda)=J(\theta\mp\lambda) \quad (3)$$

Next, we consider the case where the plane of incidence of light is the wavy surface having the slope distribution function represented by $P(\lambda)$. If the inclination angle of slope λ changes by unit angle, then the reflected angle may change by twice, and the intensity of the reflected light per unit angle decreases to half, compared to

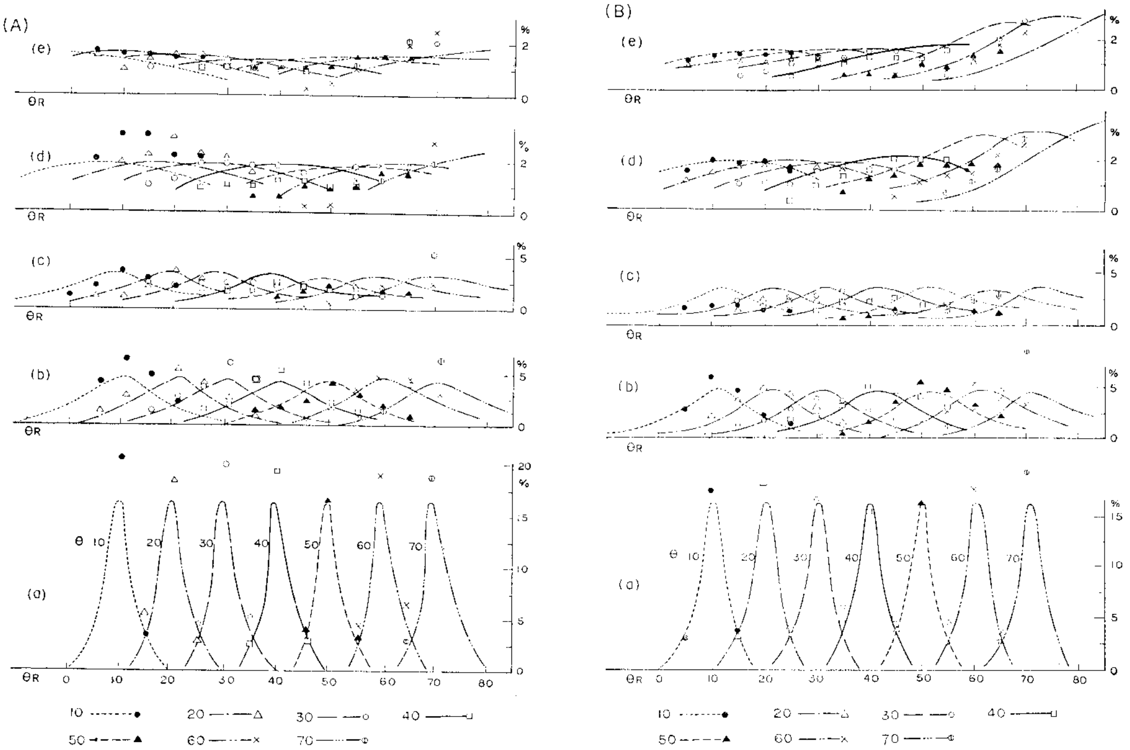

Fig. 6. Angular distribution of reflected light intensities.
(A) Direction of incident light is the same as that of wind.
(B) Direction of incident light is opposite to that of wind.
(Five cases of (a)~(e) are the same as in Fig. 3. Lines indicate theoretical values and points observed values. θ and θ_R indicate incident and reflected angle as to the horizontal plane.)

the case of perfectly flat surface. Consequently, the angular distribution of reflected light intensity per unit angle may be shown in a manner

$$Q(\theta_r)=\frac{1}{2}\frac{J(\theta\mp\lambda)}{J(\theta)}P(\lambda)\,, \qquad (4)$$

if we take the intensity of reflected light for the smooth case ($\lambda=0$) as the standard with respect to the incident angle of θ. Taking the slope distributions in Fig. 3, the angular distributions of reflected light intensity Q are evaluated for five cases of wind roughened surfaces and also for the cases where the direction of incident light is the same as or opposite to the wind direction.

On the other hand, reflected light intensities were measured, varing the incident light angle between 10° and 70° at 10 degrees intervals, and changing the angle of reflection at 5 degrees intervals in the region of $\pm 20°$ around the reflected angle in the case of perfectly smooth surface for each incident angles. The measured values and computed values before mentioned are plotted in Fig. 6. It is difficult to estimate the total experimental errors that may enter into the presentation of the data given in this figure, because there is the fact that the profiles of the waves at the channel boundary are not identical with that they would be away from the boundary, and the photographic determination of the slope of wave surface may introduce errors. And so, taking those errors into consideration, the distributions of light intensity reflected at the water-roughened surface seem to be obtained by the application of Fresnel's law for the slope distribution of wave surface from the examination of Fig. 6. The difference between the measured values and computed values appears larger in the case of the larger waves, perhaps because the wave is treated as one-dimentional in the theoretical deduction.

5. Albedo of radiation

If the sun of which altitude is h throws radiation on the sea surface, the albedo of radiation of the surface may be deduced in the following way. By integrating $Q(\theta_r)$ in equation (4) in the region of $\frac{\pi}{2}>\theta_r>-\frac{\pi}{2}$, neglecting the secondary reflection of light upon the surface and putting $h=\frac{\pi}{2}-\theta$, we find the ratio of the albedo on the wind-roughened surface to that on the perfectly smooth surface. Now, if we assume the amount of incident light is unity, the albedo of radiation A on the wind-roughened surface will be

$$A=\int_{\alpha}^{\beta} J\left(\frac{\pi}{2}-h\mp\lambda\right)P(\lambda)d\lambda$$
$$\left(\begin{array}{ll} \alpha=-\frac{h}{2}, & \beta=\frac{\pi-h}{2} \\ \text{or}\ \ \alpha=\frac{h-\pi}{2}, & \beta=\frac{h}{2} \end{array}\right). \tag{5}$$

From this equation, the albedo for three cases of wave slope distributions in experiment may be computed and the results are shown by the curve in Fig. 7, where the abscissa is the sun's latitude. It is seen from this figure that the albedo at the wind-roughened surface appears to be slightly larger than that at the smooth surface, when the sun's altitude is higher, though the difference between them is neglisible in practice, while the albedo at the wind-roughened surface becomes smaller and the difference may be rather remarkable as the wave is higher, when the sun's altitude is lower. And also it is to be noted that the value of albedo on the wind-roughened surface may take the maximum in the range where the altitude of sun is 0°～10°, though the value gradually changes with the altitude in the case of perfectly smooth surface. The data obtained in Black Sea by Д. Л. Грищенко which is reproduced in Fig. 8 may show the features similar to curves in Fig. 7, though the slight difference is shown if we compare both figures precisely. This is considered to be caused by the fact that the sky light, the emergent light from the sea water and the long wave back radiation are measured with the reflected sun light in the case of measurements of the albedo *in situ*, and those amounts may be several percent, being not so related to the sun's altitude.

Finally, the mean albedo of the sea surface in the actual ocean will be estimated referentially, using the results above mentioned. For simplicity, we confine to the direct sun light only, neglecting the other factors such as the sky light and the various meteorological conditions which affect the sun-light. Furthermore, the sun's altitude changes ceaselessly with place and

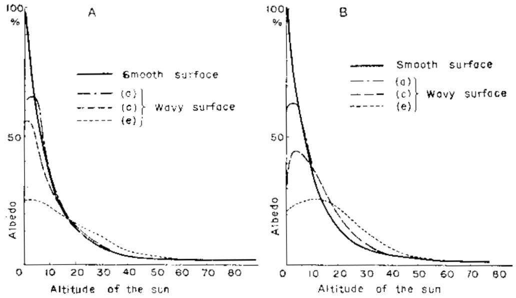

Fig. 7. The relation between the albedo and the altitude of the sun computed by authors. (A and B are the same as shown in Fig. 6.)

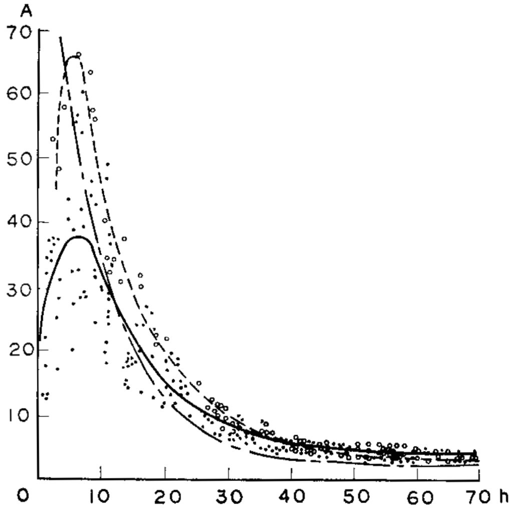

Fig. 8. The relation between the albedo and the altitude of the sun h given by Грищенко. (chain line: computed from Fresnel's law; solid line: observed at a wavy surface; broken line: observed at a smooth surface.)

with time, and so the exact computation may be rather unvaluable for this purpose. Then, the simple and rough estimation will be carried out in the following way. The altitudes of the sun are computed in each hour on one day for four months (Jan. Apr. July and Oct.) for the latitudes of every twenty degrees. For those values, the albedo is obtained by the curves of Fig. 7 and their mean values are computed. The results are shown in Fig. 9 for the case of perfectly smooth surface and three cases of wind-roughened surface.

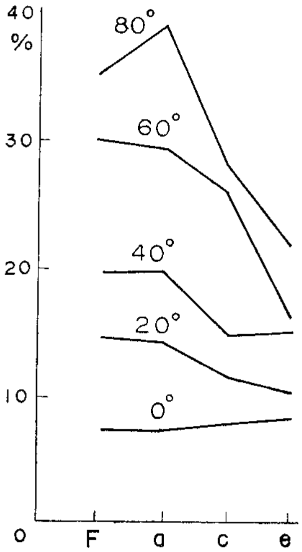

Fig. 9. Mean values of the albedo at the flat surface F and at three wavy surfaces (a), (c) and (e) for latitudes of 0°~80°.

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