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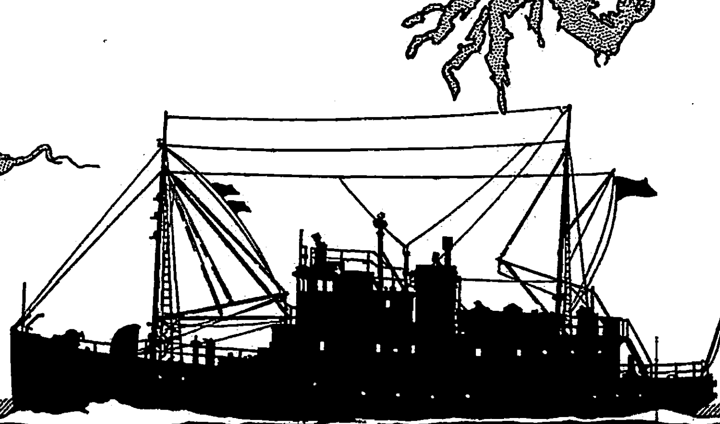

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UNIVERSITY OF WASHINGTON DEPARTMENT OF OCEANOGRAPHY
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ALBEDO OVER WIND-ROUGHENED WATER

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ABSTRACT

The observed albedo over a natural water surface, as a function of solar elevation and cloud cover, is reproduced semi-theoretically by considering the distribution of slope on the sea surface. The relation of the albedo to the wind velocity and the turbidity of the atmosphere is also considered.

1. Introduction

Albedo measurements of short-wave solar radiation over a wind-roughened water surface yield numerical values which differ from those which would be expected if Fresnel's laws of reflection for direct radiation striking a smooth water surface were to apply. If the sun is near the horizon, the measured values are much lower than the theoretical values. For high solar elevations, measured values usually exceed theoretical values. Anderson (1952) furnishes an excellent series of albedo measurements over Lake Hefner, Oklahoma, which can be used to study the above anomaly. In the past, the differences have sometimes been accounted for by reflection of diffuse skylight at Schmidt's (1915) theoretical rate of 0.170.

Middleton (1952a), Griesseier (1952), Duntley (1952) and Burt (1953) all point out that diffuse radiation is reflected at a rate of approximately one-third of Schmidt's theoretical value.

A second explanation of the above differences may be based upon the effects of large slopes on the sea surface, which would tend to increase the net reflection of direct solar radiation when the sun is near the zenith and decrease the reflection when the sun is near the horizon. Ordinary gravity waves have insufficient areas with large enough slope to be of importance; hence we must look to the effects of capillary waves which, according to Munk (1951), "determine largely the optical effects of the sun on the surface" and "are also largely responsible for what might be termed as the inherent roughness of the surface." The literature contains little detailed information on this part of the wave spectrum.

Cox and Munk (1952) have treated problems associated with these wavelets in their work on the sun's glitter pattern on the water surface.

Duntley (1952) has determined experimentally that the statistical time distribution of surface slope in any given direction may be expressed by

$$n_\phi/n_0 = \exp(-h^2 \tan^2 \phi), \qquad (1)$$

where $(n_\phi/n_0)(\Delta\tan\phi)$ is the relative amount of time that the water surface has a slope between $\tan\phi + \frac{1}{2}\Delta\tan\phi$ and $\tan\phi - \frac{1}{2}\Delta\tan\phi$ in any given direction. Thus, (1) "is a satisfactory representation of the probability of the occurrence of a slope component of a given magnitude" (Duntley, 1952). The parameter h^2 completely describes the distribution of slope. Values of h^2 between 10 and 100 were most commonly observed. The smaller values of h^2 correspond to the very rough surfaces, and the larger values to the nearly smooth surfaces. In his illustration, Duntley gives an example of h^2 equal to 19.2 for a wind of 18 kn. Duntley's experiments also show approximately similar distributions of slope in the downwind, upwind and crosswind directions. Both Munk (personal communication), working with the sun's glitter pattern, and Schooley (1954), using a flash gun technique, have found less symmetry to the slope distributions.

Dorsey (1940) furnishes a complete review and bibliography on the interaction of light and water.

2. Distribution of slope

A rectangular coordinate system will be used, with z positive upward. The xy-plane is the level surface which the water would assume if it were undisturbed by wind, sea or swell. The axes are such that the sun is always in the positive quadrant of the yz-plane. The coordinates of the slope of any differential increment of the water surface are $\pm\tan\phi_y$ and $\pm\tan\phi_x$. The decimal fractions of time, $dt_{\tan\phi_y}/T$, that any infinitesimal range of slope $d\tan\phi_y$ would occur, is then

$$dt_{\tan\phi_y}/T = (h/\pi^{\frac{1}{2}}) \exp(-h^2\tan^2\phi_y)\, d\tan\phi_y; \qquad (2)$$

and similarly, for slope in the xz-plane,

$$dt_{\tan\phi_x}/T = (h/\pi^{\frac{1}{2}}) \exp(-h^2\tan^2\phi_x)\, d\tan\phi_x. \qquad (3)$$

The term $h/\pi^{\frac{1}{2}}$ appears in (2) and (3) to make the equations represent normal-distribution functions.

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By multiplying (2) by (3), one arrives at the decimal fraction of time with the infinitesimal ranges of slope $d\tan\phi_y$ and $d\tan\phi_x$ occurring simultaneously.

If it is assumed that the distributions of slope with time which Duntley measured also apply to the distribution of slope over a large area compared to the size of the individual capillary waves, one can substitute a decimal fraction of the area in the xy-plane, $d\sigma_{\tan\phi_y,\,\tan\phi_x}/S$, for the decimal fraction of time and write the product of (2) and (3) as

$$d\sigma_{\tan\phi_y,\,\tan\phi_x}/S = (h^2/\pi)\exp(-h^2\tan^2\phi_y)\exp(-h^2\tan^2\phi_x)\,d\tan\phi_y\,d\tan\phi_x. \quad (4)$$

This result will be used later.

3. Albedo

A, the effective short-wave albedo, or reflectivity as it is sometimes called, is defined by

$$A = \frac{H_{d,r} + H_{d,s} + H_{i,r} + H_{i,s}}{H_{d,0} + H_{i,0}}. \quad (5)$$

All the H terms in (5) have the dimensional units of irradiance, that is, energy passing through or striking a unit area in the xy-plane per unit time (Middleton, 1952b). The subscripts have the following meanings: d = direct solar radiation; i = indirect diffuse solar radiation from the sky or clouds; 0 = radiation approaching the sea surface from above; r = radiation reflected upward away from the sea surface; s = radiation scattered back up through the sea surface by bubbles, suspended matter, and water molecules.

The albedo will be computed in terms of ratios of the various terms given in (5).

4. Direct reflection

The ratio $R_1 = H_{d,r}/H_{d,0}$ is the fraction of direct solar radiation which is reflected back toward the sky at the sea surface. If the water surface is flat (throughout this paper the curvature of the earth's surface will be neglected as small), as in a dead calm with no swell, this ratio is a simple function, r_P, of the sun's altitude, P, and Fresnel's equations for reflection of unpolarized light from a flat water surface can be applied directly (Hardy and Perrin, 1932).

The refractive index of water varies from 1.34 to 1.30 between the wavelength limits of 400 mμ and 2000 mμ (Dorsey, 1940), which effectively cover the wavelength range of solar radiation (Kimball, 1924). In the computation of r_P, an average refractive index of 1.33 associated with a wavelength of 670 mμ was used. The use of this average refractive index introduces a maximum error of less than 0.005 in r_P for changes in the relative distribution of solar energy with wavelength associated with changes in solar elevation between 10 and 90 deg.

In the computation of r_P, which will be used later for determination of reflection ratios other than R_1, all of the radiation is considered to be unpolarized. Direct solar radiation, as well as radiation passing through clouds, is unpolarized (Hulbert, 1934). Skylight from clear skies ranges from zero to strong polarization, depending on the elevation of the sun, the part of the sky under consideration, and the kind and amount of turbidity in the atmosphere (Sekera, 1951). Fortunately the relative proportion of skylight to total light is small, except in the case of low solar elevations. For example, if the sun is at an elevation of 10 deg, at most less than one-third of the solar radiation striking the surface is polarized. The net effects of this polarized fraction of energy on the amount of energy which is reflected by a surface is minimized, due to the varying plane of polarization with the position about the sun. Light energy striking a surface with its plane of polarization at 45 deg to the angle of incidence has the same value of r_P as unpolarized light. Further, two beams of light of the same intensity, striking a surface at the same angle of incidence, with angles of polarization relative to the plane of incidence of $45 + \alpha$ and $45 - \alpha$ deg ($0 < \alpha < 45$ deg), respectively, will have the same average r_P as unpolarized light striking the surface at a like angle of incidence.

If the surface is not smooth, the numerical value of R_1 becomes both a function of solar elevation and the roughness of the surface. The value of R_1 will be arrived at by considering the reflection at any given time over a surface area S, in the xy-plane, where S is large compared to the dimensions of the individual capillary waves that make up the roughness of the surface.

A differential increment of area, dA, of the actual water surface will have a projected area, $d\sigma$, in the xy-plane. The normal to the area dA, and a line running from dA to the sun, will form the angle of incidence of the direct solar radiation which will be designated β.

From the geometry of the situation, it can be shown that the direct solar energy which is intercepted by the area dA per unit time is $d\sigma\, H_{d,0}(1 + \cot P \tan\phi_y)$. The average value of the ratio R_1 for the large surface S is the ratio of the reflected energy summed over the area S divided by the incoming intercepted energy summed over the same area.

$$R_1 = \frac{\int_S r_\beta H_{d,0}(1 + \cot P\tan\phi_y)\,d\sigma}{\int_S H_{d,0}(1 + \cot P\tan\phi_y)\,d\sigma}, \quad (6)$$

where r_β is the decimal fraction of energy striking dA which is reflected at the angle of incidence β (Hardy and Perrin, 1932). Equation (6) is perfectly general, but the integrals cannot be taken directly, both because of the complexity of the function r_β and the fact that both β and ϕ_y are unknown functions of the position x and y over the area S.

A close approximation of the numerical value of R_1 can be obtained by approximations of the integrals in (6). First, it is assumed that the optically effective shape of the water surface can be approximated by considering that the surface is made up of small rectangular facets. Secondly, it is assumed that the decimal fraction, $\Delta\sigma_{\tan\phi_y,\tan\phi_x}/S$, of the total surface with facets with slopes of $\tan\phi_y$ and $\tan\phi_x$ can be obtained by integrating (4) between the limits $\tan\phi_y - \frac{1}{2}\Delta\tan\phi_y$ and $\tan\phi_y + \frac{1}{2}\Delta\tan\phi_y$ in the yz-plane, and between the limits $\tan\phi_x - \frac{1}{2}\Delta\tan\phi_x$ and $\tan\phi_x + \frac{1}{2}\Delta\tan\phi_x$ in the xz-plane. The angle β, used to determine r_β, is equal to arc-cosine $(\tan\phi_y \cos P + \sin P)/(\tan^2\phi_y + \tan^2\phi_x)^{\frac{1}{2}}$.

After cancellation of like constants from the numerator and denominator, (6) can now be written in terms of summations of the energy intercepted and reflected from each of the $\Delta\sigma$'s:

$$R_1 = \frac{\sum_S r_\beta(1 + \cot P \tan\phi_y)\,\Delta\sigma_{\tan\phi_y,\tan\phi_x}}{\sum_S (1 + \cot P \tan\phi_y)\,\Delta\sigma_{\tan\phi_y,\tan\phi_x}}. \qquad (7)$$

The true value of R_1 in (7) is approached in the numerical summation as the increments of slope $\Delta\tan\phi_x$ and $\Delta\tan\phi_y$ are decreased in magnitude. The summation is carried out on the assumption that no appreciable error will be introduced if it is assumed that all areas that are shaded from the sun have a statistical distribution of slope the same as the whole area.

Computations of R_1 were carried out for solar altitudes of 10, 30, 50 and 90 deg, for values of h^2 equal to 10, 20 and 30, for numerical increments of slope of 0.02 in both the xz- and yz-planes. The results of the computations are presented in table 1, along with values of R_1 for a perfectly smooth surface (*i.e.*, $h^2 = \infty$).

The figures presented in table 1 indicate that increasing wind velocity tends to decrease markedly the reflection at low solar elevations. At a solar elevation somewhere between 10 and 30 deg, the effect of the wind is not felt. At an elevation of 30 deg, it is seen that increasing wind velocity tends to increase reflection. For solar elevations greater than 30 deg, the reflection tends always to increase with increasing wind velocity, although the effect becomes almost negligible when the sun is at the zenith.

TABLE 1. Reflection of direct solar radiation.

h^2	Solar elevation (deg) 0	10	30	50	90
10 (high wind)	100.0	0.1890	0.0722	0.0291	0.0206
20 (approx. 19 kn)	100.0	0.2370	0.0683	0.0268	0.0205
30 (light wind)	100.0	0.2624	0.0657	0.0256	0.0205
∞ (calm)	100.0	0.3480	0.0597	0.0245	0.0204

5. Diffuse reflection

Perfectly diffuse unpolarized solar radiation, coming from either sky or clouds, is reflected from a smooth water surface at the rate of 0.066. The following integral has been used to determine this percentage (Burt, 1953):

$$R_2 = H_{i,r}/H_{i,0} = \int_0^{\pi/2} r_P \sin 2P\,dP, \qquad (8)$$

where r_P is the decimal fraction of energy reflected from a flat, level water surface with a solar-elevation angle P. In the case of reflection of diffuse radiation from a rough water surface, the ratio R_1, which is a function of both angle of incidence to the level surface (xy-plane) and surface roughness (h^2), must be substituted for r_P in (8).

Computed values of R_1, which are listed in table 1, were used to estimate R_1 over the range of 0 to $\pi/2$. Equation (8) was then integrated graphically to obtain approximate values of R_2 for reflection from a rough water surface. The results were 0.055, 0.057 and 0.058 for h^2 equal to 10, 20 and 30, respectively. This indicates that reflection of perfectly diffuse energy decreases with increasing wind speed (decreasing values of h^2).

Equation (8) is only valid for perfectly diffuse radiation. Moon and Spencer (1942) state that the distribution of sky brightness under an overcast sky "is practically independent of the position of the sun and depends only on the zenith angle of the portion of the sky under consideration".

Middleton (1952a) used the distribution of light energy with zenith angle, suggested by Moon and Spencer, to compute the theoretical reflection of diffuse daylight under a cloud cover from still water and arrived at a reflection of 0.051. If R_1 is substituted into Middleton's equations in place of r_P, the ratio R_2 becomes nearly independent of roughness in the range of h^2 from 10 to 30. The numerical value of R_2 for rough water then drops to approximately 0.048, only 0.003 less than the value Middleton computed for a smooth surface.

The measured albedo data of both Neiburger (1948) and Anderson (1952) show that the effective albedo under overcast skies is a function of solar altitude, indicating that a part of the energy is probably undiffused when it reaches the water surface. Moon and Spencer do not take this variable direct energy into account. The simplest assumption that takes both direct and diffuse energy into account is that the total energy is always composed of two parts, direct energy from the sun and perfectly diffuse energy from sky and clouds.

Treatment of the diffuse energy as perfectly diffuse has been shown above to introduce a maximum increase in reflectivity of only 0.010, greater than that obtained from the distribution suggested by Moon and Spencer for a rough water surface.

All diffuse energy will be considered to be perfectly diffuse, both from the sky under clear conditions and from the sky and clouds under partly cloudy or overcast conditions. It is realized that this is undoubtedly an oversimplification of what actually occurs. R_2 is assigned numerical values of 0.055, 0.057, 0.058 and 0.066 for water-surface roughnesses corresponding to values of h^2 equal to 10, 20, 30 and ∞ (smooth water), respectively.

6. Back scattering

Utterback and Jorgenson (1936), Clarke (1936), Powell and Clarke (1936), Whitney (1938), Davis (1941), Atkins and Poole (1940) and Jerlov (1952) have measured the ratio of back-scattered solar energy to the energy traveling in a downward direction at various depths beneath the surface of the water. This back scattering includes the effects of bubbles, particulate matter, and water molecules. Numerical values of this ratio which were observed near the surface average close to 0.021. There were no clear significant relationships shown between the numerical value of the ratio and the cloud cover, presence or absence of fog, solar elevation (Jerlov's limited number of measurements indicated an increase in the numerical value of the ratio with decreasing solar elevation for energy in the ultraviolet and shorter-wavelength part of the visible spectrum, but this increase was insignificant for wavelengths over 500 mμ where the bulk of the solar energy lies), wind speed, or the roughness of the water surface. For this reason, the numerical value of the ratio will be assumed to be constant under all conditions for either or both direct and diffuse radiation. From this assumption, we have

$$R_3 = H_{i,s}/(H_{i,0} - H_{i,r}) = 0.021, \quad (9)$$

$$R_4 = H_{d,s}/(H_{d,0} - H_{d,r}) = 0.021, \quad (10)$$

and

$$R_5 = H_{i,s}/H_{i,0} = 0.020. \quad (11)$$

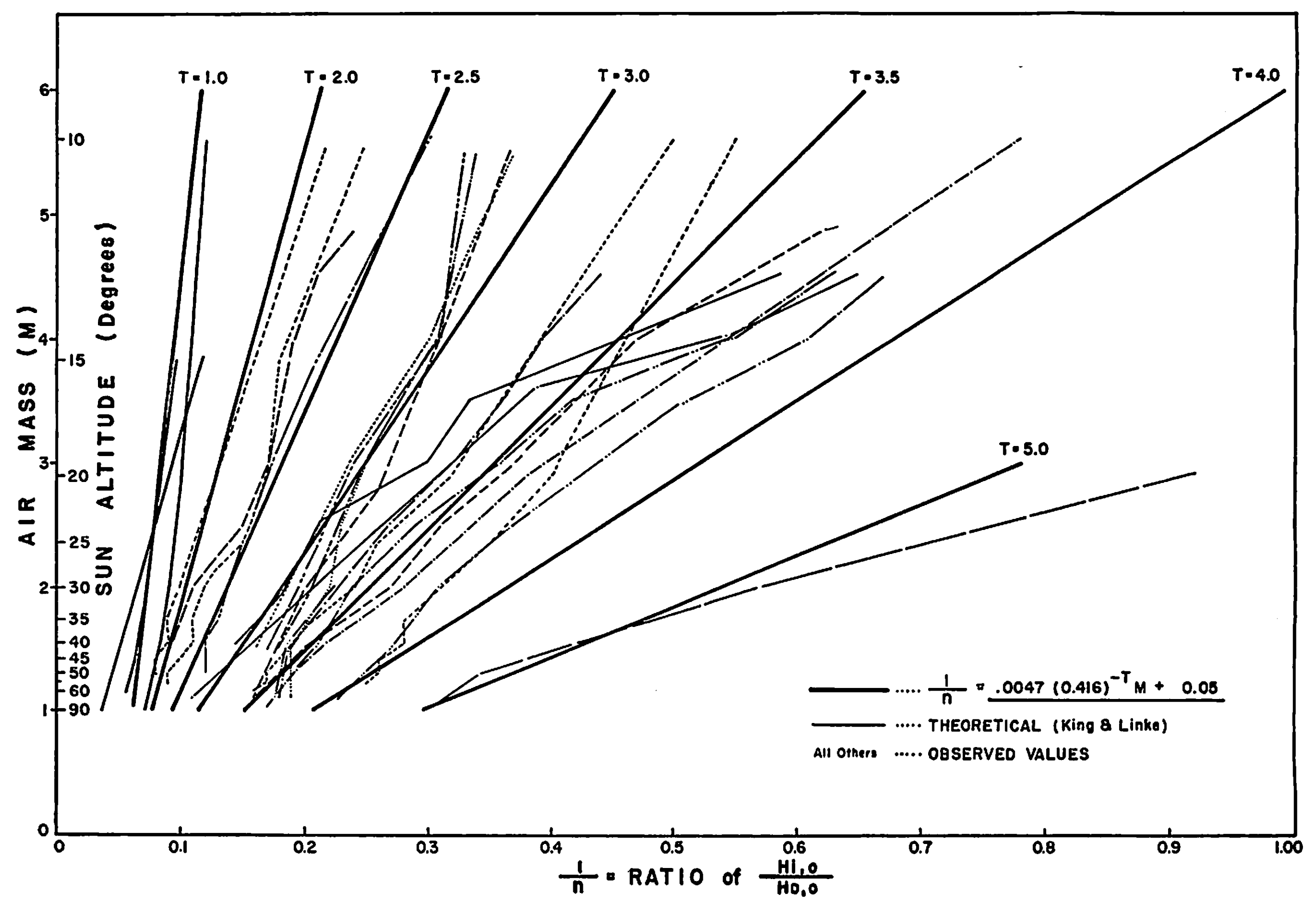

FIG. 1. Relationship between air mass (m), turbidity (T) and ratio of direct solar energy to diffuse solar energy from sky.

7. Computation of effective albedo

Equation (5) can be written in terms of the ratios which have been discussed above:

$$A = (nR_1 + nR_4 - nR_4R_1 + R_2 + R_5)/(n + 1), \quad (12)$$

where

$$n = H_{d,0}/H_{i,0}. \quad (13)$$

From (9) through (12), we can write the following working equation for the effective albedo:

$$A = n(0.979\, R_1 + 0.021)/(n + 1) + (R_2 + 0.020)/(n + 1). \quad (14)$$

R_1 (as a function of h^2 and P) can be taken from table 1, and R_2 (as a function of h^2) has been assigned values in section 5, above. This leaves only the determination of suitable values for the ratio n, to use (14) to compute the effective albedo.

8. Ratio of direct to diffuse energy

The ratio n is an unknown function of: type, effective thickness and amount of clouds; turbidity and water-vapor content of the air. Theoretical relationships between n and the solar-elevation angle P have been worked out for ideal atmospheres on the basis of scattering by air molecules (Linke, 1942; King, 1913). Measurements of n as a function of P for unclouded skies have been reported by Kimball (1919; 1924), Hand (1937) and Linke (1942). Fritz (1951) reports Kimball's (1919) data as being representative.

When all available theoretical figures and observed data from the above references are plotted on a graph (see fig. 1), with $1/n$ and m [Bemporade's optical air-mass, which is a function of P (Smithsonian Institution, 1951)] as coordinates, most of the plots show linear relationships. Linke (1942) lists the numerical value of his turbidity factor, T, for the air for several of the stations for which he presents observed data for the ratio n. Linke's data can be approximated by the following linear relationship:

$$1/n = 0.0047\,(0.416)^{-T}\, m - 0.05. \quad (15)$$

Plots of the empirical relationship presented in (15), for values of T ranging from 1 to 4.5, have the proper slopes and intercepts to fit most of the theoretical results and observed data in fig. 1. A narrower range of T, from 2 to 4, fits all but the extreme cases. This is in agreement with Haurwitz (1934), who lists the normal turbidities of air masses as falling within the range of 2 to 4.

It appears reasonable to assume that the effects of clouds (on increasing the diffuse fraction of solar energy) would be somewhat similar to the effects of materials causing turbidity in the air. For this reason, (15) will be used to determine the ratio, $1/n$, for cloudy and overcast skies by arbitrarily increasing the numerical value of T. The exact relationship between T and the extinction (Sverdrup *et al*, 1946), with clear skies, no longer pertains because of the difference in optical characteristics of cloud droplets in one case and dust and air molecules in the other. For this reason, T in (15) will be labeled T' when the equation is used for obtaining the ratio n for partly cloudy to overcast skies.

9. Results

The results of the computations are presented in table 2. The effective short-wave albedo, A, is presented in terms of the sun's elevation angle, P, the roughness of the water surface in terms of the parameter h^2, and the factor T or T' which denotes the relative distribution of direct and diffuse solar energy. To use this table for a variety of conditions, it will be necessary to obtain experimentally the relationship between wind speed and the parameter h^2 over the range of average wind velocities encountered over water surfaces. The factor T can be considered analogous to Linke's turbidity factor for clear skies. For partly cloudy to overcast skies, the numerical value of T will have to be determined experimentally over a range of conditions.

Anderson's (1952) Lake Hefner data can be used to test the computations shown in table 2. The average 24-hr wind speed over Lake Hefner during the period of observation was 11.5 kn (Harbeck, 1952). Due to the normal daytime maximum in wind velocity, the daytime average wind speed was probably near 15 kn. Duntley (1952) observed an h^2 value of 19.2 for a wind speed of 18 kn; hence, the average value of h^2 should be somewhat greater than 19.2, probably

Table 2. Effective albedo or reflectivity as a function of T', solar elevation (P) and the roughness of the water surface (h^2).

P (deg)	h^2	T' 2	3	4	5	6
90	10	.044	.044	.047	.051	.058
	20	.044	.045	.047	.052	.059
	30	.044	.045	.047	.052	.054
	∞	.044	.046	.049	.054	.063
50	10	.052	.053	.055	.059	.064
	20	.049	.050	.053	.058	.064
	30	.048	.050	.053	.057	.064
	∞	.048	.050	.053	.059	.068
30	10	.091	.089	.088	.085	.081
	20	.087	.086	.085	.083	.081
	30	.084	.084	.083	.082	.081
	∞	.080	.080	.081	.082	.084
10	10	.184	.168	.143	.116	.096
	20	.223	.202	.168	.133	.106
	30	.245	.219	.182	.141	.111
	∞	.307	.281	.229	.173	.131

between 20 and 30. The turbidity factor for clear skies would range from 2.5 to 3.5 (Anderson, 1952; Haurwitz, 1934). Effective albedos computed on a basis of a numerical value for T of 2.5 appear to fit Anderson's data for clear skies the best. For partly cloudy to overcast conditions, T' was computed according to the following arbitrary linear relationship:

$$T' = T + 0.2C + D, \quad (16)$$

where T equals the above-assigned value of 2.5 for clear skies, C is the average amount of clouds in tenths, and D is a constant which was added to take into account the greater average thickness of low clouds over high clouds. D was given a value of zero for high clouds and a value of 0.5 for low clouds. The numerical values of T' which were computed from (16) were rounded off to the nearest half integer.

Fig. 2 shows Anderson's (1952) "reflectivity of a natural water surface under clear skies". For a T of 2.5, the computed albedos for solar elevations of 30, 50 and 90 deg are almost identical for h^2 values of 20 and 30, and fall within 1 per cent of the observed values. At a solar elevation of 10 deg, the observed data indicate an albedo corresponding to an h^2 value between 20 and 30.

Fig. 3 shows Anderson's reflectivity measurements under various cloud covers, along with computed

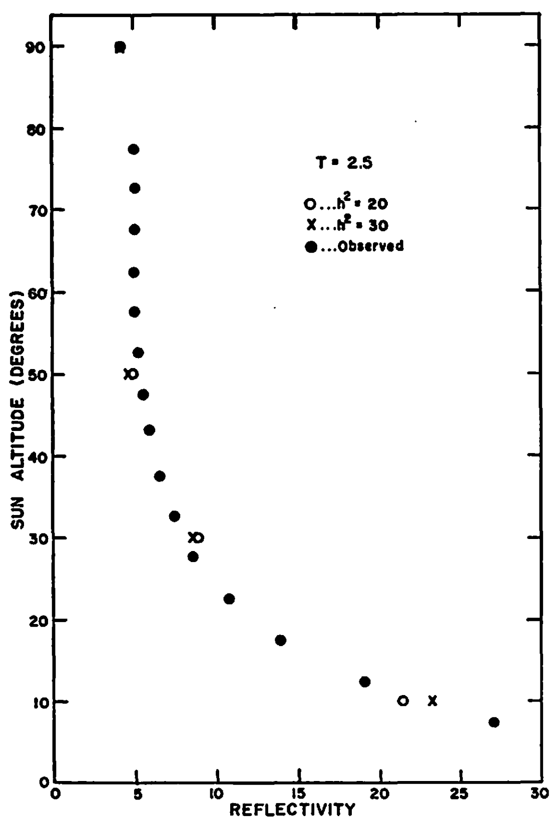

FIG. 2. Results of Anderson's (1952) effective albedo, or reflectivity, measurements over Lake Hefner with clear skies, along with effective albedo computed from (14) (see table 2).

effective albedos. At all elevations and for all cloud covers, except in the single case of 1/10 to 5/10 low clouds at a solar elevation of 10 deg, the computed effective albedo for an h^2 value of 30 reproduces the observed data with a maximum difference of approximately 0.01. The only consistently occurring difference of significance appears with a solar elevation of 30 deg, where the computed effective albedo is in most cases higher than the observed albedo by approximately 0.005.

Anderson (1952) also presents an excellent series of observations of reflectivity as a function of wind speed. From the material presented in tables 1 and 2 above, one would expect to find a positive correlation between wind speed and albedo for medium solar elevations, and a negative correlation between wind speed and albedo for low solar elevations. (No correlation would be expected for high solar elevations, due to the small net effect of surface roughness on the effective albedo.) To test this hypothesis, Anderson's data for solar elevations between 10 and 20 deg, and again between 35 and 45 deg, were used. Anderson presents four divisions of data for each of the selected solar-elevation angle increments, by plotting his data by 5-deg increments for each of two different air masses.

The individual correlations for each of the four divisions of data with solar-elevation angles between 10 and 20 deg were all negative, while the correlations for the data for solar elevations between 35 and 45 deg were all positive. Only two of the individual correlation coefficients were significant to the 5 per cent level in themselves, but the fact that all eight had the predicted sign is highly significant. The sign test (Mosteller and Tukey, 1949) was run on the results of the signs of the correlation coefficients, *i.e.*, eight out of eight the same as predicted by the hypothesis; it indicated that this result would have occurred by chance much less than one in a thousand times. Correlations were not computed for the rest of the data.

10. Summary

A semi-theoretical method is derived for computing the effective albedo over a wind-roughened water surface as a function of the roughness of the surface, the solar elevation, and an empirical factor T, or T', which determines the ratio of diffuse to direct light striking the water surface. Anderson's reflectivity measurements, made over Lake Hefner, Oklahoma, are adequately reproduced as functions of the above parameters.

The theory predicts a positive correlation between effective albedo and wind velocity for medium solar elevations, and a negative correlation for low solar

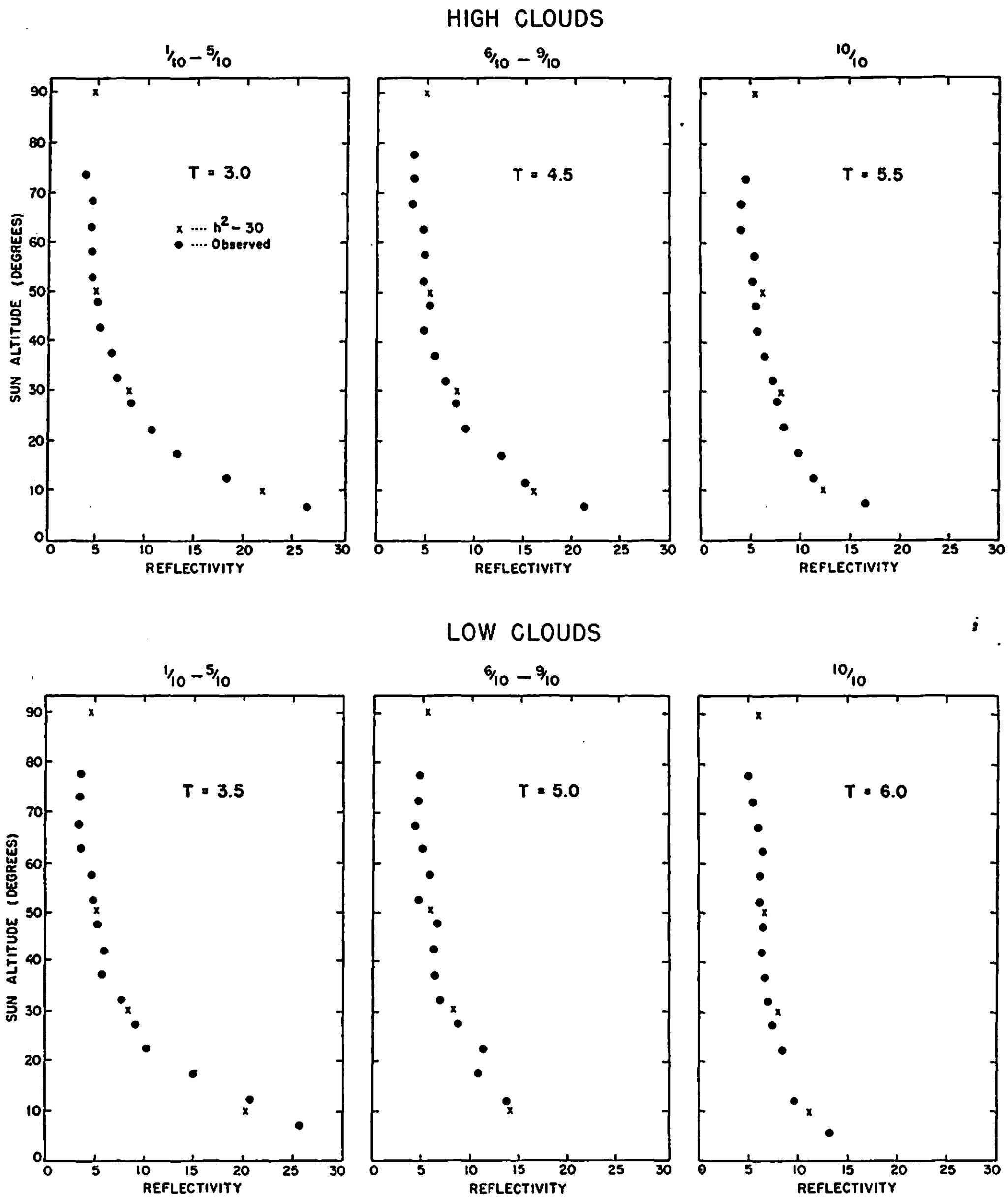

FIG. 3. Results of Anderson's (1952) effective albedo, or reflectivity, measurements over Lake Hefner with partly cloudy to overcast skies, along with effective albedo computed from (14) (see table 2).

elevations. Anderson's data for reflectivity as a function of wind speed bear out this hypothesis, despite the low correlations which were found to exist between wind speed and reflectivity.

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