Albedo of the Sea Surface[1]

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(Manuscript received 1 December 1971, in revised form 6 March 1972)

ABSTRACT

An experimental study of the albedo of the sea surface for shortwave solar radiation has been carried out on a fixed platform. Fifteen-minute totals of upward and downward irradiances were recorded continuously for four months over a wide range of atmospheric and sea conditions. The resulting albedo values, the ratio of upward to downward irradiance, are expressed in terms of a particularly convenient pair of parameters, sun altitude and atmospheric transmittance (T). The latter is defined as the ratio of observed downward irradiance to the irradiance at the top of the atmosphere and has not been used before in describing albedo. Examples of albedo values are 0.061 ± 0.005 for heavily overcast skies ($0.0 < T \leqslant 0.1$), indicating isotropic radiance distribution, and a range for clear skies ($T > 0.65$) of 0.03 for high sun to as large as 0.45 at sun altitudes $< 10°$. The uncertainty in the values is less than 7% for sun altitudes $> 25°$ and increases to 25% for very low sun altitudes. The effect of wind, through surface roughness, is shown to be small but predictable. Effects of whitecaps are not noticeable at wind speeds up to 30 kt, the highest observed in the study.

Application of the results is made to climatological studies of the absorption of solar energy by the surface waters of the ocean. Monthly average albedos are calculated for the Atlantic Ocean to compare with Budyko's latitudinally dependent values, and it is shown that although the sets of results agree within 10% at latitudes up to 40°, there are discrepancies at higher latitudes as high as 100%. Finally it is shown with climatological albedo values calculated from the results of this study, that the accuracy of climatological estimates of solar energy absorbed in the ocean are now limited by the accuracy of climatological estimates of downward irradiance.

1. Introduction

Described in this paper is a set of measurements of the albedo of the sea surface undertaken to obtain an accurate and detailed description of the albedo over a wide range of sky and sea conditions in terms of parameters which are conveniently and precisely measured or calculated. The incentive was to improve estimates of solar energy absorbed by the sea.

The albedo is defined as the ratio of upward to downward irradiance just above the sea surface, i.e.,

$$\alpha = E_U/E_D. \qquad (1)$$

The rate at which solar energy is absorbed per unit surface area is then

$$I_A = E_U - E_D = (1-\alpha)E_D. \qquad (2)$$

It was felt that the new set of albedo values could improve estimates of I_A, particularly in two situations: (i) in detailed studies where observations of E_D are made and values of I_A are sought as a function of time of day; and (ii) in studies of daily totals of I_A at high latitudes where daily average albedos approach 0.4–0.5.

The upward irradiance above the sea surface has two components, light scattered back from below the surface (emergent irradiance) and light reflected from the surface. A study of the emergent irradiance (Payne, 1971) in coastal water (Buzzards Bay, Massachusetts) and in the Sargasso Sea showed that the ratio of emergent to downward irradiance is 0.005 ± 0.0005. The measurements were made over a range of cloud and sea conditions and particulate concentrations representative of those encountered in most of the world's oceans. Since the albedo has a minimum value of 0.03, the emergent irradiance constitutes at most about 15% of the total upward irradiance. Reflectivity at a smooth or roughened sea surface is a strong function of source altitude as is shown in Fig. 1 [values calculated by Saunders; for method see Saunders (1967)]; this indicates that a major independent variable in the albedo is the radiance distribution about the sky. The parameters in terms of which the albedo is expressed must reflect this radiance distribution. In the present study the parameters chosen are sun altitude and atmospheric transmittance defined by

$$T = E_D/(S \sin\theta/\gamma^2), \qquad (3)$$

where S is the solar constant (1.94 cal cm^{-2}min^{-1}), θ the sun's altitude, and γ the ratio of actual to mean earth-sun separation. The denominator represents the downward irradiance without an atmosphere.

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[1] Woods Hole Oceanographic Institution Contribution No. 2770.

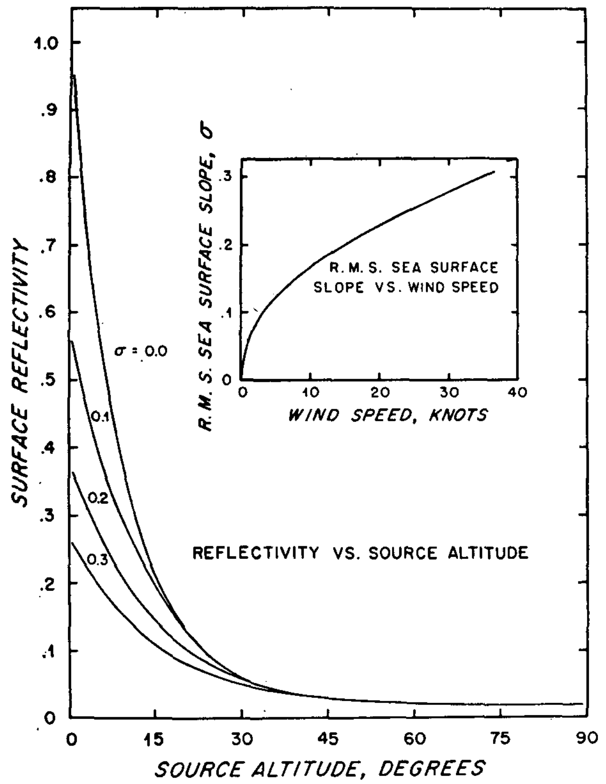

FIG. 1. Reflectivity of a water surface as a function of source altitude and surface roughness (rms surface slope) (Saunders, 1967).

The atmospheric transmittance provides a quantitative measure of the effect of scattering and absorption of sunlight by the atmosphere and can be used as an indicator of the effect of scattering on the radiance distribution. Atmospheric transmittance was chosen as a sea surface albedo parameter for several reasons:

1) As will be shown in this paper, T adequately represents the effects on the albedo of the modification of the light field by clouds.
2) T is precise and objective.
3) T can be calculated from instrument (pyranometer) records and does not require a human observer.

With no atmosphere, $T = 1.0$ and all the light comes from the direction of the sun. Adding atmosphere and clouds increases scattering and absorption such that as T decreases, the radiance distribution is spread out more and more over the sky. For heavily overcast conditions, $0 < T < 0.1$, the radiance distribution is nearly isotropic.

2. Previous work

Although two reasonably comprehensive studies of the albedo have been published, neither meets our objectives. Anderson (1952) made measurements over a broad range of conditions but used as parameters sun altitude and verbal descriptions of cloud cover. The latter qualitative parameter restricts the accuracy with which albedos can be specified. Neumann and Hollman (1961) (see also Hollman, 1968) used sun altitude and the ratio of diffuse to total downward irradiance as the parameters in terms of which they expressed their observed albedo values. This ratio is unsuitable for our use since measurements of either the diffuse or direct component of downward irradiance require an extremely stable instrument, a difficult

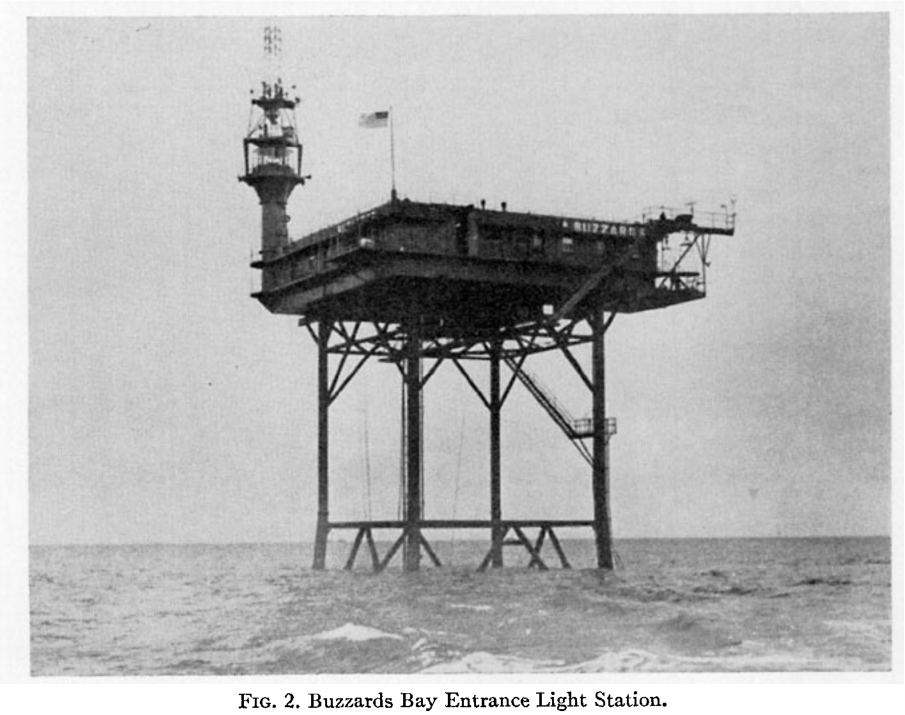

FIG. 2. Buzzards Bay Entrance Light Station.

requirement to meet on a ship or buoy experiencing average sea conditions.

In the Soviet Union, attention appears to have been focused on measurements of the albedo under extreme conditions, i.e., clear or completely overcast skies, and there is no report of experimental determinations for intermediate conditions.

3. The experiment

Upward and downward irradiances were measured continuously for four months with pyranometers mounted on the Buzzards Bay Entrance Light Station, a U. S. Coast Guard facility located at 41°24′N, 71°02′W in the mouth of Buzzards Bay, Massachusetts. The station, shown in Fig. 2 as viewed from the southeast, experiences a wide range of sea and weather conditions. The 20 m water depth ensures that light reflected from the bottom makes a negligible contribution to the upward irradiance. Standing on legs sunk into the bottom, however, the station provides a stable platform for the pyranometers, which must be held fixed in a horizontal orientation. The 30 m height of the station together with weekly inspections and cleaning when necessary prevented sensible accumulations of salt on the sensors.

In order to minimize interference by shadows, both pyranometers were mounted on the south side, the upward-looking pyranometer just above the top deck and the downward-looking pyranometer on a 2 m boom off the lower southeast corner of the platform. In addition, a downward-looking pyranometer was mounted on a blackened board on the northwest corner to measure the amount of diffuse light reflected from the northern sky. This latter instrument was employed to estimate the effect of the presence of the tower on the measurement of E_U.

Eppley Model 6-90 pyranometers were used to measure irradiances. Like Eppley's Standard Model 8-48 this more sensitive version has uniform sensitivity from 280–2800 nm including about 98% of the sun's energy which is incident at the earth's surface.

The electrical signals from the pyranometers were amplified and integrated over 15-min periods and these totals recorded on punched paper tape. Integration provided the equivalent of a large number of instantaneous data values without the attending data analysis problems. The 15-min period assured adequate resolution in sun altitude, 3° or better depending on the time of day. Data were recorded from 25 May to 28 September 1970 including the summer solstice with the maximum sun altitude, 72°, for this latitude.

a. Calibrations

Since, in the Model 6-90, the Eppley Laboratory employed a new type of construction whose long-term stability was unknown, the calibration constants of the pyranometers were checked carefully over the period of the experiment. Absolute calibrations were performed on all the pyranometers by the Eppley Laboratory during the year before the experiment began and again at the end of the experiment. In addition, the instruments were intercompared at the light station twice during the experiment and at its beginning and end. The absolute calibrations indicated that in the worst case a change of 3% in the calibration constant of one instrument occurred over the period of the experiment, but the intercomparisons indicated a worst case variation of only 1.5%.

b. Editing

During most of the measurement period the light tower[2] and station legs interfered seriously with the light field viewed by the pyranometers for several hours each afternoon. For this reason, only morning data were used. This halved the number of data points available for analysis, but the remaining points still covered adequately the full range of sun altitudes for each day.

The presence of fog makes sea surface albedo measurements exceedingly unreliable. The meteorological records kept at the station provided indications of fog. Deletion of data was prompted by entries stating that the sky was obscured and visibility 200 yards or less.

c. Correction

Although the light station offered minimal interference with upward irradiance in the mornings, the main body of the station did prevent some of the light emanating from the northern sky from being reflected into the downward-looking pryanometer on the southeast corner. We used the following expression to correct for the presence of the station:

$$E_U = E_{SE}[1+0.03(1-T)], \tag{4}$$

where E_U is the corrected total upward irradiance, E_{SE} the upward irradiance observed at the southeast corner, and T the atmospheric transmittance. For small T, i.e., heavy overcast, the correction to E_{SE} is 3% corresponding to the reflected irradiance from the portion of a uniformly illuminated sky obscured by the light station. When T is large, the correction falls to zero since most of the light is reflected from the direction of the sun to the south of the station.

The correction from Eq. (4) was compared to one calculated from the readings of the downward-looking pyranometer mounted on a blackened board on the northwest corner. The agreement between the two corrections was within 15%. Thus, because of the presence of the light station, a quite negligible uncertainty of 0.5% in E_U exists.

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[2] The term "light tower" refers to the tower on the light station on which the station's light was mounted. It can be seen in Fig. 2.

TABLE 1. Grouped and smoothed albedo values.*

Atmospheric transmittance	Sun altitude θ																						
T	0°	2°	4°	6°	8°	10°	12°	14°	16°	18°	20°	22°	24°	26°	28°	30°	32°	34°	36°	38°	40°	42°	44°
.00	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061
.05	.062	.062	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061
.10	.072	.070	.068	.065	.065	.063	.062	.061	.061	.061	.061	.061	.061	.061	.061	.061	.060	.061	.060	.060	.060	.060	.060
.15	.087	.083	.079	.073	.070	.068	.066	.065	.064	.063	.062	.061	.061	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060
.20	.115	.108	.098	.086	.082	.077	.072	.071	.067	.067	.065	.063	.062	.061	.061	.060	.060	.060	.060	.060	.060	.060	.060
.25	.163	.145	.130	.110	.101	.092	.084	.079	.072	.072	.068	.067	.064	.063	.062	.061	.061	.061	.060	.060	.060	.060	.060
.30	.235	.198	.174	.150	.131	.114	.103	.094	.083	.080	.074	.074	.070	.067	.065	.064	.063	.062	.061	.060	.060	.060	.059
.35	.318	.263	.228	.192	.168	.143	.127	.113	.099	.092	.084	.082	.076	.072	.070	.067	.065	.064	.062	.062	.060	.060	.060
.40	.395	.336	.290	.248	.208	.176	.151	.134	.117	.107	.097	.091	.085	.079	.075	.071	.068	.067	.065	.063	.062	.061	.060
.45	.472	.415	.357	.306	.252	.210	.176	.154	.135	.125	.111	.102	.094	.086	.081	.076	.072	.071	.068	.066	.065	.063	.062
.50	.542	.487	.424	.360	.295	.242	.198	.173	.150	.136	.121	.110	.101	.093	.086	.081	.076	.073	.069	.067	.065	.064	.062
.55	.604	.547	.498	.407	.331	.272	.219	.185	.160	.141	.127	.116	.105	.097	.089	.083	.077	.074	.069	.066	.063	.061	.059
.60	.655	.595	.556	.444	.358	.288	.236	.190	.164	.145	.130	.119	.107	.098	.090	.084	.076	.073	.068	.064	.060	.058	.056
.65	.693	.631	.588	.469	.375	.296	.245	.193	.165	.145	.131	.118	.106	.097	.088	.081	.074	.069	.065	.061	.057	.055	.052
.70	.719	.656	.603	.480	.385	.300	.250	.193	.164	.145	.131	.116	.103	.092	.084	.076	.071	.065	.061	.057	.054	.051	.049
.75	.732	.670	.592	.474	.377	.291	.246	.190	.162	.144	.130	.114	.100	.088	.080	.072	.067	.062	.058	.054	.050	.047	.045
.80	.730	.652	.556	.444	.356	.273	.235	.188	.160	.143	.129	.113	.097	.086	.077	.069	.064	.060	.055	.051	.047	.044	.042
.85	.681	.602	.488	.386	.320	.252	.222	.185	.159	.142	.127	.111	.096	.084	.075	.067	.062	.058	.054	.050	.046	.042	.040
.90	.581	.494	.393	.333	.288	.237	.211	.182	.158	.141	.126	.110	.095	.083	.074	.066	.061	.057	.053	.049	.045	.041	.039
.95	.453	.398	.342	.301	.266	.266	.205	.180	.157	.140	.125	.109	.095	.083	.074	.065	.061	.057	.052	.048	.044	.040	.038
1.00	.425	.370	.325	.290	.255	.220	.200	.178	.157	.140	.122	.108	.095	.083	.074	.065	.061	.056	.052	.048	.044	.040	.038

TABLE 1. *(continued)*

Atmospheric transmittance	Sun altitude θ																						
T	46°	48°	50°	52°	54°	56°	58°	60°	62°	64°	66°	68°	70°	72°	74°	76°	78°	80°	82°	84°	86°	88°	90°
.00	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061
.05	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061
.10	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060
.15	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060
.20	.060	.059	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060	.059	.059	.059
.25	.059	.059	.059	.059	.059	.059	.059	.059	.059	.059	.059	.059	.059	.059	.059	.059	.059	.059	.059	.059	.059	.059	.058
.30	.059	.059	.059	.059	.059	.059	.059	.059	.059	.059	.059	.059	.059	.059	.059	.059	.059	.059	.059	.059	.058	.058	.058
.35	.059	.059	.059	.059	.059	.059	.059	.058	.058	.058	.058	.058	.058	.058	.058	.057	.058	.058	.058	.058	.057	.057	.057
.40	.060	.060	.059	.059	.058	.058	.058	.057	.057	.057	.057	.057	.057	.057	.056	.056	.056	.056	.056	.056	.056	.056	.055
.45	.061	.060	.059	.058	.057	.057	.057	.056	.055	.055	.055	.055	.055	.055	.054	.053	.054	.053	.053	.054	.054	.053	.053
.50	.060	.059	.058	.057	.056	.055	.055	.054	.053	.053	.052	.052	.052	.051	.051	.050	.050	.050	.050	.051	.050	.050	.050
.55	.057	.056	.055	.054	.053	.053	.052	.051	.050	.050	.049	.049	.049	.048	.047	.047	.047	.046	.046	.047	.047	.046	.046
.60	.054	.053	.051	.050	.049	.048	.048	.047	.046	.046	.045	.045	.045	.044	.043	.043	.043	.042	.042	.043	.042	.042	.042
.65	.050	.049	.047	.046	.046	.044	.044	.043	.042	.042	.041	.041	.040	.040	.039	.039	.039	.038	.038	.038	.038	.038	.038
.60	.047	.045	.043	.043	.042	.041	.040	.039	.039	.038	.038	.037	.036	.036	.035	.035	.034	.034	.034	.034	.034	.034	.034
.75	.043	.041	.039	.039	.038	.037	.036	.036	.035	.035	.034	.033	.032	.032	.032	.031	.031	.031	.030	.030	.030	.030	.030
.70	.039	.037	.035	.035	.035	.034	.033	.033	.032	.032	.032	.029	.029	.029	.029	.028	.028	.028	.028	.027	.027	.028	.028
.85	.036	.035	.033	.032	.032	.031	.030	.030	.030	.030	.029	.027	.027	.027	.027	.026	.026	.026	.026	.026	.026	.026	.026
.90	.034	.033	.032	.031	.030	.029	.028	.028	.028	.028	.027	.026	.026	.026	.025	.025	.025	.025	.025	.025	.025	.025	.025
.95	.033	.032	.031	.030	.029	.028	.027	.027	.026	.026	.026	.025	.025	.025	.025	.025	.025	.025	.025	.025	.025	.025	.025
1.00	.033	.032	.031	.030	.029	.028	.027	.026	.026	.026	.026	.025	.025	.025	.025	.025	.025	.025	.025	.025	.025	.025	.025

* Values based on observations are within the outlined area.

4. Analysis and results

Albedos calculated from the 15-min irradiance totals were grouped in intervals of 2° of sun altitude and then averaged over intervals of 0.1 in atmospheric transmittance. The averages were smoothed with respect to both atmospheric transmittance and sun altitude. The smoothed values are reproduced in Table 1.

The overall range of the grouped and smoothed albedo values is 0.03–0.5 for ranges of 4–72° in sun altitude and 0–0.75 in atmospheric transmittance. Because other locations may experience higher values of atmospheric transmittance and sun altitude than does Buzzards Bay, it is desirable to extrapolate the curves derived from the measurements to extreme values of the parameters. Albedos were obtained for the limiting case $T=1.0$ (no atmosphere) by adding 0.005 (emergent irradiance contribution) to reflectivity values (see Fig. 1) calculated for a roughened sea surface by Saunders. Reflectivity values for a sea surface roughness corresponding to a wind speed of 7.5 kt were used since this is the mean surface roughness found for both heavily overcast and clear conditions. The smoothed albedo curves were extended and made to approach the appropriate values for $T=1.0$ with zero slope. Table 1 contains all the grouped and smoothed data and their extrapolation. The portion of the table based on observations is outlined.

In Table 2 albedo values from Table 1 are compared with values found by other investigators for clear and overcast conditions. Because of the variety of parameter choices by various investigators, comparable albedos cannot be specified for other than these extreme conditions. There is reasonable agreement for the values listed.

In Fig. 3 appear 2° groupings of original data points and final smoothed curves for sun altitudes of 10°, 24°, 32°, 70°. The points represent all the data points in these 2° intervals which were accumulated during the observation period. The scatter of points about the smoothed curves is quite small and justifies the empirical choice of atmospheric transmittance and sun altitude as parameters for determining the albedo of the ocean. The same choice can almost certainly be used in improving the specification of albedo for other natural terrestrial surfaces.

Table 2. Comparison of albedo values.

	Clear sky		Overcast sky
Observations	$\theta_s=10°$	$\theta_s=70°$	$\theta_s=70°$
Payne (present study)	0.28	0.035	0.061
Anderson (1952)	0.21	0.04–0.05	0.04–0.05
Hollman (1968)	—	0.03	0.05
Grischenko (1959)	0.33–0.47	0.05	—
Kondratyev (1969)	0.27–0.32	0.05	—
Kuzmin (1957)	—	—	—
Calculations			
Burt (1954)	0.24	0.05	0.06
Ter-Markariantz (1959)	0.26	0.04	0.07

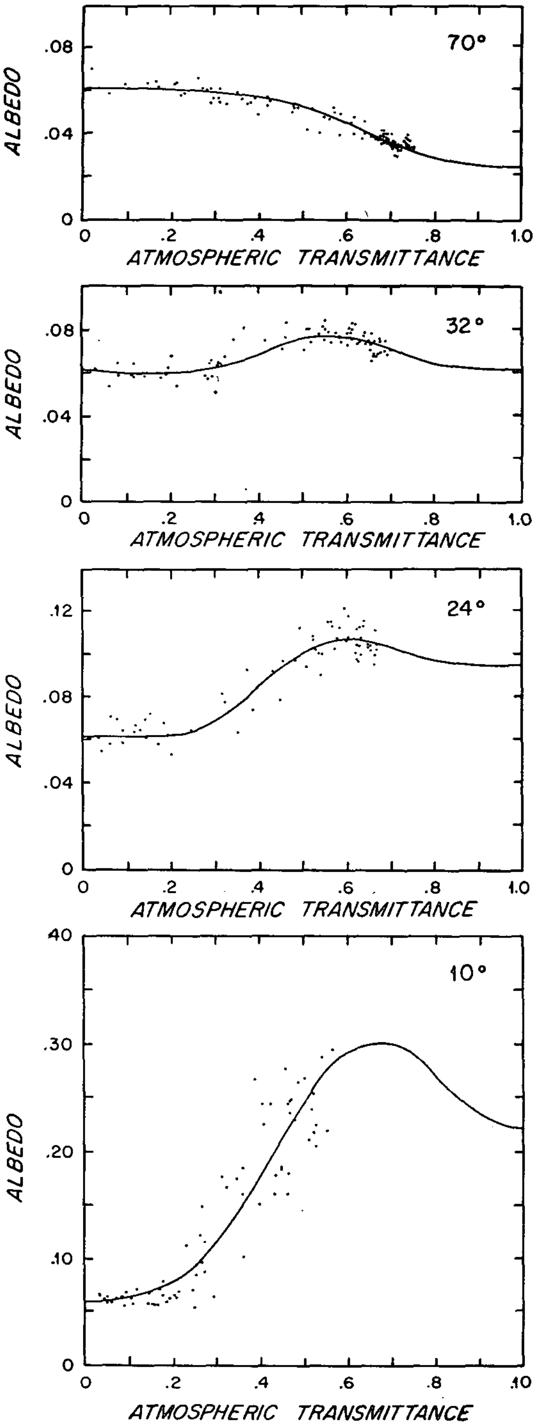

Fig. 3. Albedo vs atmospheric transmittance for sun altitudes of 70°, 32°, 24°, 10°.

A novel feature of the 24° and 32° curves in Fig. 3, which is also apparent in the other data in this altitude range, is the albedo maximum in the range $0.5<T<0.7$, which corresponds to partially cloudy to clear condi-

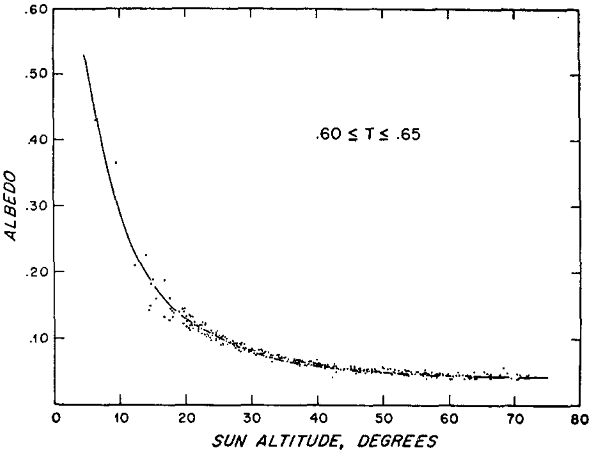

FIG. 4. Albedo vs sun altitude for clear skies.

tions. This feature can only be a result of the distribution of radiance about the sky under these conditions and the following explanation is advanced.

With the sun at 32° altitude and an atmospheric transmittance of 1.0 (no atmosphere), the transmittance will decrease as atmosphere and then clouds are added. At this solar altitude the albedo is 0.06 for both no atmosphere and heavily overcast conditions. With no atmosphere the light all comes from the direction of the sun, but, as atmosphere is added, small-angle scattering spreads out the region of the sky from which most of the light comes. From Fig. 1 we can see that the reflectivity for light from above the sun decreases slowly with increasing altitude while the reflectivity for light from below the sun increases rapidly with decreasing altitude. In addition, results of Kimball and Hand (1921) and Richardson and Hulburt (1949) show that for clear skies ($T>0.6$), the intensity of sky radiance is greater below the sun than above it. The net effect is to cause the albedo for scattered light to be higher than that for direct light, and, therefore, the total albedo is higher also. With increasing cloud thickness, and, as a result, decreasing atmospheric transmittance, the radiance distribution becomes fairly isotropic and the albedo decreases to its limiting value of 0.06. The maximum in the albedo does not seem to have been noticed before, and it indicates that, except under heavily overcast conditions, it is inappropriate to assume that scattered light has an isotropic radiance distribution.

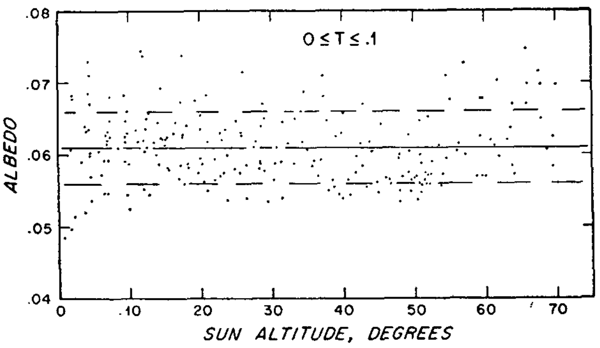

FIG. 5. Albedo vs sun altitude for completely overcast skies.

In Fig. 4 albedo values are plotted against sun altitude for clear skies, $0.60\leqslant T\leqslant 0.65$. The points are all the data points in this atmospheric transmittance interval, and the curve is drawn through albedo values interpolated from Table 1 for $T=0.625$. The albedo limit as the sun altitude gets large is 0.040. From Fig. 1, adding 0.005 for the emergent irradiance, we see that the albedo of direct sunlight for high altitudes is 0.026 so that an additional 0.014 is contributed by the scattered sunlight.

In Fig. 5 appear all the data points for which the atmospheric transmittance has values $0<T\leqslant 0.1$. There is no discernible dependence of the albedo on sun altitude. The mean of all the albedo values, 0.06 ± 0.005, is the limiting value of the albedo for small values of the atmospheric transmittance. All uncertainties in this paper represent one standard deviation.

Sea surface reflectivities for overcast conditions (Table 3) were calculated from Saunders' reflectivities for several wind speeds using both the isotropic sky radiance distribution and the cardioidal radiance distribution recommended by Moon and Spencer (1942), i.e.,

$$R(\theta)=R(90°)(1+2\sin\theta)/2, \tag{5}$$

where θ is the altitude above the horizon and $R(90°)$ is the zenith radiance. Albedos were obtained from the reflectivities by adding 0.005 to account for the light scattered back from beneath the sea surface. For the isotropic radiance distribution the observed mean albedo of 0.061 corresponds to a mean wind speed of 7.5 kt, and the standard deviation of ±0.005 corresponds to a wind speed range of about 3–15 kt, both of which are quite reasonable for Buzzards Bay in the summer. In contrast, the cardioidal distribution does not appear to be valid for heavily overcast conditions since the observed albedo is somewhat higher than this distribution can predict. From these results, the sky radiance distribution is apparently very nearly isotropic for heavily overcast conditions.

TABLE 3. Calculated albedos for roughened sea surface and overcast sky.

		Albedo (including emergent component)	
Wind velocity (kt)	Sea surface slope (rms value)	Isotropic radiance distribution	Cardioidal radiance distribution
0	0	0.073	0.057
3	0.1	0.066	0.054
15	0.2	0.057	0.048
35	0.3	0.050	0.043

From Fig. 1 it is apparent that the effects of sea surface roughness on the reflectivity of the surface are most pronounced for the source at low altitudes. This suggests that surface roughness effects are most likely to be observed for clear skies and low sun altitudes. As the sun altitude decreases, however, the proportion of direct light in the total downward irradiance also decreases as more light is absorbed and scattered by the increasing atmospheric path length. Examination of the albedo data showed that maximum effects of sea surface roughness on the albedo occurred for sun altitudes in the range 17°–25° and for atmospheric transmittance >0.6.

Because the variation of albedo with sun altitude and atmospheric transmittance within the range examined was expected to be as large as the effect of surface roughness, each observed albedo was normalized by the appropriate value interpolated from Table 1. Direct-light albedo values ($T=1.0$) were calculated for three wind velocities, 0, 3 and 15 kt, by adding 0.005 for the emergent light to reflectivities from Fig. 1 and normalized with values interpolated from Fig. 1 for $\sigma_T=0.15$ (7.5 kt). These are compared with the observed results.

Graphs of normalized albedos for two ranges of sun altitude are presented in Fig. 6. The points represent normalized observed albedo values, and the open circles denote normalized albedos calculated for direct light. In the upper graph, $50°\leqslant\theta_{\text{sun}}\leqslant 54°$, any effects of surface roughness are small, as expected, and are masked by the scatter of the points. In the lower graph, $17°\leqslant\theta_{\text{sun}}\leqslant 25°$, a trend is clearly evident which agrees quite well with the trend indicated by the points derived from Saunders' reflectivities. The slope indicates a variation of about 1% of the normalized albedo per knot of wind speed. Since the plotted ratios have the value 1.0 at a wind speed of 7.5 kt, the Table 1 albedo values can be considered albedos for a wind velocity of approximately 7.5 kt agreeing with the results for overcast conditions.

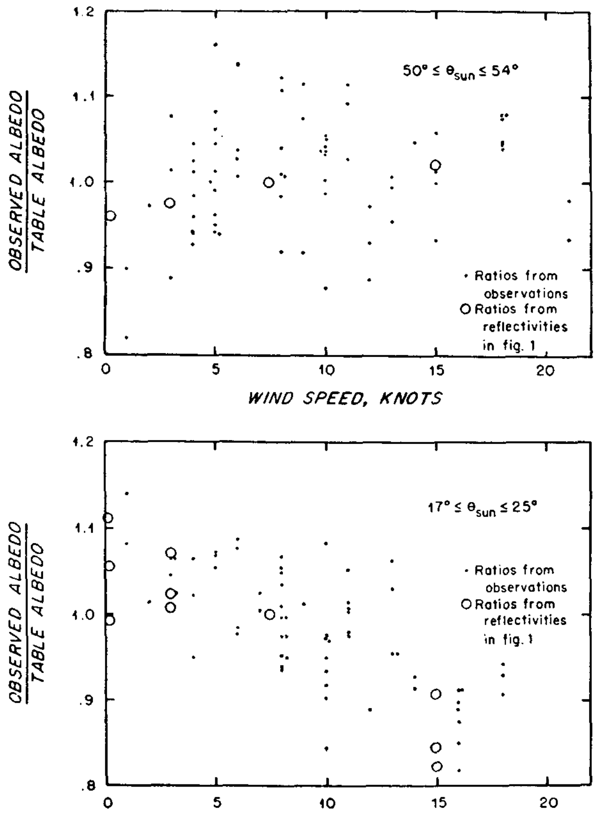

FIG. 6. Observed and calculated effects of sea surface roughness on albedo.

From the point of view of radiant flux considerations, these variations are negligible and can be ignored. This is the first time that the variation of albedo with surface roughness has been shown so clearly, however, and it is gratifying to note that the correspondence of theory and measurement suggests that the theory is sound and the measurements are of high quality.

All the albedo data indicate that for winds below 30 kt, the maximum experienced during the experiment, there are no discernible effects on the albedo from white caps. This result is consistent with estimates of 0.4–0.5 for the local albedo of a white cap (Lauscher, 1955) and estimates of no more than 10% of the sea surface covered by foam patches in 30-kt winds (Monahan, 1971).

5. Errors and uncertainties

The origins of the errors and uncertainties in measurements of light fluxes are twofold: they arise from imperfect instruments and from interferences with the light fields viewed by the instruments.

a. *Instrumental uncertainties*

From the results of the calibrations and intercomparisons described earlier, the long-term stability of the calibration constants of the Eppley 6-90 pyranometers used in the experiment varied from one instrument to another, with the worst case showing changes of 3% over the course of the experiment (Payne, 1972). This will be considered the uncertainty in the calibration constants of all the instruments and is the largest contribution to the experimental uncertainties of the albedo values. Other contributions are 1% maximum uncertainty due to non-ideal cosine response at low altitudes, 1.5% variation in calibration constant over the range of ambient temperatures experienced at the tower due to imperfect temperature compensation in the pyranometers, and 0.5% due to uncertainties in levelling the pyranometers.

b. *Light field interference*

Both upward- and downward-looking pyranometers have parts of the light station within their fields of view

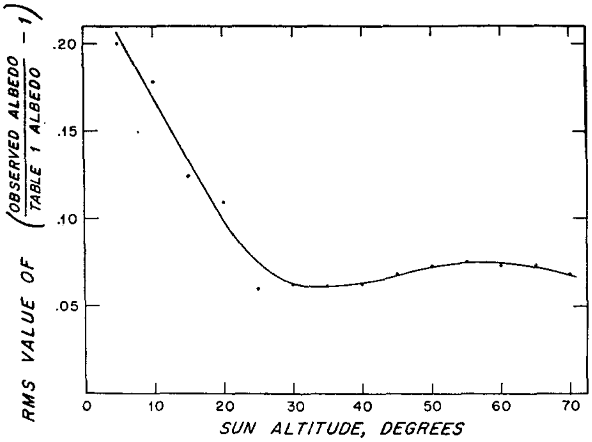

FIG. 7. Deviation of observed albedo values from values in Table 1 as a function of sun altitude.

slightly affecting their readings. In addition to being small, the effects on the two pyranometers tend to compensate in the albedo, and the maximum effect on the albedo is estimated as 2%. The uncertainty in the total upward irradiance due to imperfect correction of the reflected north sky radiance obscured by the light station is about 0.5% as estimated earlier in this paper.

The total uncertainty in the albedo values due to these errors and uncertainties is 4.3%. Thus, an albedo value calculated from the measured irradiances has an absolute accuracy of better than 5%. This does not mean, however, that instantaneous irradiance measurements at the same atmospheric transmittance and the same sun altitude will give the same albedo value. There are other variables such as surface roughness and sky radiance distribution which can cause real variations. To obtain a measure of the magnitude of these variations, the rms values of

$$\frac{\text{Observed albedo}}{\text{Table 1 albedo}}-1$$

were calculated for all atmospheric transmittances and 2° ranges of sun altitude at 5° intervals, i.e., 4–6°, 9–11°, 14–16°, etc., over the range of sun altitudes experienced during the experiment. The results appear in Fig. 7. From 25–70° the deviation is uniform at 6–7%. The steep increase for sun altitudes $<25°$ is due partly to variations in sea surface roughness but probably much more to variations in sky radiance distribution, the effects of which would be likely to be more pronounced at low sun altitudes. Thus, for sun altitudes $>25°$ we can expect a single observed albedo value to agree with the appropriate value from Table 1 within 7%, but the two values may differ by much more for altitudes $<25°$. The limit on the accuracy with which the albedo can be specified, then, is how well the parameters represent sky radiance distributions. From Fig. 7, the parameters sun altitude and atmospheric transmittance represent radiance distributions quite well except at the lower sun altitudes.

6. Albedo predictions

The albedo values listed in Table 1 are of particular value in detailed studies in which absorbed or reflected solar energy is desired as a function of time of day. Often, however, daily totals are desired, and it is convenient to use daily average albedos in calculating these. Three methods will be outlined for accurately estimating daily average albedos. The details of the methods appear in the Appendix.

METHOD 1. Downward irradiance totals of 5–30 min duration are available. Atmospheric transmittances are calculated from them, and with calculated sun altitudes, albedo values are interpretable from Table 1. The quotient of the daily sum of the upward irradiances (the product of albedo and downward irradiance) and the sum of the downward irradiances is then the daily average albedo. This method allows the most accurate estimate.

The next two methods allow estimation of daily average albedos when only daily totals of downward irradiance are available.

METHOD 2. The atmospheric transmittance is calculated from the daily total downward irradiance and it is assumed that the transmittance is constant throughout the day. Interpolation of 15-min albedo values from Table 1 for this atmospheric transmittance value and calculated sun altitudes allows us to estimate the daily average albedo as the quotient of the sums of upward and downward irradiance as in method 1.

METHOD 3. This method will be referred to as the air mass method and is similar to method 2 in that only daily totals of downward irradiance are available; however, the variation of atmospheric transmittance on clear days is taken into account.

The results of the three methods of calculating daily average albedo are summarized in Table 4. The numbers represent the mean of the ratio of calculated to observed albedo averages with the standard deviation. The February–May data contained hourly totals only so that method 1 could not be used on it. The fact that half-daily totals were used in the May–September data probably accounts for the slightly lower standard deviations in methods 2 and 3. There is less chance of a marked change of cloud conditions over a half day than over a whole day.

TABLE 4. Daily average albedo, $\bar{\alpha}_{\text{calc}}/\bar{\alpha}_{\text{obs}}$, by three methods.

Period	Method 1 Observed T	Method 2 Constant T	Method 3 Air mass T
February–May		1.13±0.22	1.02±0.15
May–September	1.01±0.07	1.15±0.21	1.03±0.11

Table 5. Mean albedos for Atlantic Ocean by month and latitude.

Latitude	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
80N			0.33	0.14	0.10	0.09	0.08	0.08	0.12			
70N		0.41	0.15	0.10	0.08	0.07	0.07	0.09	0.11	0.25		
60N	0.28	0.12	0.09	0.07	0.07	0.07	0.06	0.07	0.07	0.10	0.16	0.44
50N	0.11	0.10	0.08	0.07	0.06	0.06	0.06	0.07	0.07	0.08	0.11	0.12
40N	0.10	0.09	0.07	0.07	0.06	0.06	0.06	0.06	0.07	0.08	0.10	0.11
30N	0.09	0.07	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.07	0.08	0.09
20N	0.07	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.07	0.07
10N	0.07	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.07
0	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
10S	0.06	0.06	0.06	0.06	0.07	0.07	0.06	0.06	0.06	0.06	0.06	0.06
20S	0.06	0.06	0.06	0.06	0.07	0.07	0.07	0.07	0.06	0.06	0.06	0.06
30S	0.06	0.06	0.06	0.07	0.08	0.09	0.08	0.07	0.07	0.06	0.06	0.06
40S	0.06	0.06	0.07	0.08	0.09	0.11	0.10	0.08	0.07	0.07	0.06	0.06
50S	0.06	0.07	0.07	0.08	0.10	0.13	0.11	0.08	0.08	0.07	0.06	0.06
60S	0.06	0.07	0.08	0.11	0.13		0.27	0.07	0.08	0.07	0.06	0.06

Method 1 using the observed 15-min totals of downward irradiance gives the best results. Indeed, the calculated values are very nearly as accurate as the measured values and have a similar standard deviation. Method 2, with constant atmospheric transmittance, consistently overestimates the upward irradiance by 10–15% because it does not take into account the decrease in atmospheric transmittance at the ends of the day, but may be accurate enough for some purposes with a correction for this overestimation. Method 3, taking into account variations of atmospheric transmittance with air mass, is a definite improvement on method 2 and yields quite acceptable results since the accuracy of measurement of downward irradiance is about 3%.

7. Climatological values

Traditionally, calculations of climatological values of the solar energy absorbed by the ocean have been made using the expression

$$A = D(1-\bar{\alpha}), \qquad (6)$$

where $\bar{\alpha}$ is the mean albedo over some period of time, often a month, and D is the downward irradiance total in that time. Probably the most commonly used sets of values of both quantities are those published by Budyko (1963). Using Budyko's monthly downward totals, albedo values averaged over longitude were obtained for the Atlantic Ocean using data and methods from the present study. These albedos were then compared with Budyko's albedo values.

To construct the table of albedos, monthly downward irradiance totals were read from Budyko's climatological charts at 10° intervals of latitude and longitude from 80N to 60S over the Atlantic Ocean. Monthly average atmospheric transmittance values were calculated from these and thence, by the air mass method, a monthly mean albedo value for each month and location. In Table 5 are given longitudinal averages of these mean albedos. In Table 6 appear the results of a comparison made between the albedo values in Table 5 and Budyko's corresponding albedo values. At latitudes up to 50–60° the sets of albedo values agree well and are not shown but at higher latitudes they differ by as much as a factor of 2. Values are given only for the Northern Hemisphere since Budyko's downward irradiance values are probably most reliable there.

The Budyko albedos are consistently higher and the larger differences may be the result of two possible deficiencies: Budyko's global longitudinally averaged albedo values may not provide adequate detail at high latitudes, and his albedo values for low sun altitudes may not be sufficiently accurate. It is also possible that the Budyko albedo values are higher at high

Table 6. Comparison of albedo values from Table 5 (P) with those of Budyko (B).

	January		February		March		April		May		June	
Latitude	B	P	B	P	B	P	B	P	B	P	B	P
70N			0.23	0.41	0.16	0.15	0.11	0.10	0.09	0.08	0.09	0.07
60N	0.20	0.28	0.16	0.12	0.11	0.09	0.08	0.07	0.08	0.07	0.07	0.07
50N	0.16	0.11	0.12	0.10	0.09	0.08	0.07	0.07	0.07	0.06	0.06	0.06

	July		August		September		October		November		December	
Latitude	B	P	B	P	B	P	B	P	B	P	B	P
70N	0.09	0.07	0.10	0.09	0.13	0.11	0.15	0.25				
60N	0.08	0.06	0.09	0.07	0.10	0.07	0.14	0.10	0.19	0.16	0.21	0.44
50N	0.07	0.06	0.07	0.07	0.08	0.07	0.11	0.08	0.14	0.11	0.16	0.12

latitudes because he has taken ice coverage into account. We have not been able to discover a reference in which Budyko has described the methods by which his albedo values were derived. It should be noted that the accuracy of the Payne albedo values depends on the accuracy of Budyko's downward irradiance estimates.

The accuracy of our albedo values varies with latitude. At low latitudes the sun rises from the horizon nearly to the zenith each day and thus, averaged over a day, the light from the sun and sky is fairly evenly distributed over altitude regardless of whether the sky is cloudy or not. This is reflected in the nearly uniform albedo value of about 0.06 throughout low latitudes, which is the value observed for completely overcast skies. The accuracy of these low-latitude albedos is about 10%, limited by the calculation method. Poleward of this the sun does not rise as high in the sky and there can be considerable difference in the daily averaged distribution of radiance with altitude between a clear and an overcast day. For these higher latitudes the uncertainty probably rises as high as 20–25% because the uncertainties in the atmospheric transmittance are more critical and the changes in sun declination during the month are not represented. The uncertainty in absorbed energy caused by the uncertainty in albedo varies considerably with latitude. By Eq. (6) the albedo enters into the absorbed energy as $(1-\alpha)$. In low latitudes were $\alpha=0.06$ with an uncertainty of 0.006, the uncertainty contribution to the absorbed energy is 0.6%. At higher latitudes the uncertainty in $(1-\alpha)$ can rise as high as 15%, still better than the accuracy of most estimates of downward solar irradiance over the ocean.

8. Summary

A detailed and comprehensive set of measurements of the albedo of the ocean has been made and the albedo values expressed in terms of two particularly convenient and appropriate parameters, sun altitude and atmospheric transmittance. A total of 2600 fifteen-minute totals of upward and downward solar irradiances were recorded with sun altitude varying between 10–80°, atmospheric transmittance from nearly zero to more than 0.75, and wind velocities between 0–30 kt. The grouped and smoothed albedo values have an uncertainty of 6–7%, for sun altitudes greater than 25°. The uncertainty increases for smaller altitudes. Methods have been developed for obtaining daily average albedos when the daily total downward irradiance is known.

Climatological albedo values calculated from the results of this paper and climatological irradiance values from Budyko are consistently lower than Budyko's values at high latitudes higher than 50°. The results of this paper will allow accurate calculations of solar energy absorbed by the ocean on time scales down to 15 min if downward irradiance measurements are made on this time scale.

Acknowledgments. The author would like to express his appreciation to Peter Saunders of the Woods Hole Oceanographic Institution for suggesting the problem and for many helpful discussions.

The author would also like to acknowledge the support of the Office of Naval Research under Contract N00014-66-CO241.

APPENDIX

Calculation of Daily Average Albedo Values

a. Method 1

Fifteen-minute totals of downward irradiance D_i, defined by

$$D_i=\left(\int^{15} E_D dt\right)_i, \tag{A1}$$

are available as in the present study. From these are calculated 15-min averages of the atmospheric transmittance

$$T_i=D_i\Big/\left[\int_0^{15}(S\sin\theta/\gamma^2)dt\right]_i, \tag{A2}$$

where the denominator represents the downward irradiance which would be received in the ith interval in the case of no atmosphere. After calculating the sun altitude θ_i, the albedo $\alpha_i(T_i,\ \theta_i)$ is then interpolated from Table 1 for each interval. The 15-min total of upward irradiance is given by

$$U_i=\alpha_i D_i, \tag{A3}$$

and the daily average albedo by

$$\bar{\alpha}=U/D=\sum_{i=1}^{N} U_i\Big/\sum_{i=1}^{N} D_i, \tag{A4}$$

where N is the number of 15-min periods in the day when the sun is above the horizon, and U and D represent daily totals. Leaving out twilight introduces a negligible error.

b. Method 2

The daily total downward irradiance has been observed or estimated. The daily average atmospheric transmittance is calculated from

$$\bar{T}=D\Big/\left[\int_{\text{day}}(S\sin\theta/\gamma^2)dt\right]. \tag{A5}$$

Atmospheric transmittance is then assumed constant during the day so that

$$T_i=\bar{T}. \tag{A6}$$

The values of α_i are then determined for constant atmospheric transmittance but varying sun altitude.

Fifteen-minute downward irradiance totals can be calculated from

$$D_i=\bar{T}\left[\int_0^{15}(S\sin\theta/\gamma^2)dt\right]_i, \tag{A7}$$

using the definition of T_i. The daily average albedo is then given by

$$\bar{\alpha}=\frac{\sum_{i=1}^{N}U_i}{\sum_{i=1}^{N}D_i}=\frac{\sum_{i=1}^{N}\alpha_i\left[\int_0^{15}(S\sin\theta/\gamma^2)dt\right]_i}{\sum_{i=1}^{N}\left[\int_0^{15}(S\sin\theta/\gamma^2)dt\right]_i}. \tag{A8}$$

c. Method 3

This method is similar to method 2 in that only daily totals of downward irradiance are known, but the most significant cause of the regular variation of atmospheric transmittance within one day is taken into account, i.e., the variation with sun altitude on clear days. On clear days the variations of the atmospheric transmittance can be represented by

$$T_i=Ce^{-am_i}, \tag{A9}$$

where C and a are constants for each day chosen so that

$$D=\sum_{i=1}^{N}D_i=\sum_{i=1}^{N}T_i\left[\int_0^{15}(S\sin/\gamma^2)dt\right]_i, \tag{A10}$$

and m_i is the optical air mass for sun altitude θ_i, defined as the ratio of the atmospheric optical path length for direct sunlight for the sun altitude to the optical path for zenith sun. The air mass for the ith interval was determined by the approximate expression

$$m_i=\left[\left(\frac{R}{H}\sin\theta_i\right)^2+2\frac{R}{H}+1\right]^{\frac{1}{2}}-\frac{R}{H}\sin\theta_i, \tag{A11}$$

where θ_i is the average sun altitude in the ith interval, R the radius of the earth, and H the height of the atmosphere. This expression takes into account the curvature of the earth and its atmosphere but not the refraction of the atmosphere. For these calculations the atmosphere was assumed homogeneous so that H is given by

$$H=p_0/g\rho_0=8.4\text{ km}, \tag{A12}$$

where p_0 and ρ_0 are the atmospheric pressure and density at the earth's surface.

The factor a in the exponential in (A9) can be related to the atmospheric turbidity, but empirically, on the basis of my data, a value of 0.1 is sufficiently accurate for this study. This value represents the variation of atmospheric transmittance quite well on clear days as is shown in Fig. 8. Although assuming the same value of a on cloudy days may cause T_i to vary more than the observed values, the albedo is insensitive to variations in atmospheric transmittance on cloudy days, and this assumption introduces only a small error in albedo values.

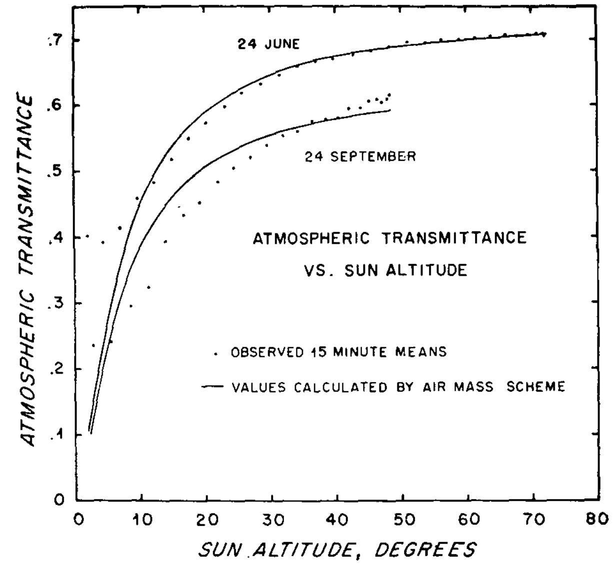

Fig. 8. Examples of variation of atmospheric transmittance with sun altitudes for cloudless skies.

The calculated atmospheric transmittance values and sun altitudes are used to interpolate albedo values. The daily average albedo is then given by

$$\bar{\alpha}=\frac{\sum_{i=1}^{N}\alpha_iD_i}{\sum_{i=1}^{N}D_i}=\frac{\sum_{i=1}^{N}\alpha_ie^{-am_i}\left[\int_0^{15}(S\sin\theta/\gamma^2)dt\right]_i}{\sum_{i=1}^{N}e^{-am_i}\left[\int_0^{15}(S\sin\theta/\gamma^2)dt\right]_i}. \tag{A13}$$

REFERENCES

Anderson, E. R., 1952: Energy-budget studies. Water-loss investigations: Vol. I—Lake Hefner studies. *U. S. Geol. Survey Circ.*, No. 229, 71–88.

Budyko, M. I., 1963: *Atlas of Heat Balance*, 2nd ed. Moscow Akad. Nauk. U. S. S. R. (1st ed., 1956, Leningrad, Main Geophys. Obs.)

Burt, W. V., 1954: Albedo over wind-roughened water. *J. Meteor.*, **11**, 283–290.

Grischenko, D. L., 1959: Dependence of the albedo of the sea upon solar height and roughness of the sea surface. *Tr. Gl. Geofiz. Observ.*, No. 80.

Hollman, R., 1968: Studies on the albedo of the sea surface. Ph.D. dissertation, New York University.

Kimball, H. H., and I. F. Hand, 1921: Sky-brightness and daylight-illumination measurements. *Mon. Wea. Rev.*, **49**, 481–488.

Kondratyev, K. Ya., 1969: *Radiation in the Atmosphere.* New York, Academic Press, 912 pp.

Kuzmin, P. P., 1957: *Physical Properties of Snow Cover.* Leningrad, Gidrometeoizdat.

Lauscher, P., 1955: Sonnen und Himmelstrahlung im Meer und in Gewassern. *Handbuch der Geophysik* Vol. 7, Berlin, Springer, 723–768.

Monahan, E. C., 1971: Oceanic whitecaps. *J. Phys. Oceanogr.*, **1**, 139–144.

Moon, P., and D. E. Spencer, 1942: Illumination from a non-uniform sky. *Illum. Eng.*, **37**, 707–726.

Neumann, G., and R. Hollman, 1961: On the albedo of the sea surface. *Union Geod. Geophys. Intern., Monogr.*, **10**, 72–83.

Payne, R. E., 1971: Albedo of the sea surface. Ph.D. dissertation, University of Rhode Island.

——, 1972: Sensitivity stability of Eppley model 6-90 pyranometers. *J. Geophys. Res.* (in press).

Richardson, R. A., and E. O. Hulburt, 1949: Sky-brightness measurements near Bocaiura, Brazil. *J. Geophys. Res.*, **54**, 215–227.

Saunders, P. M., 1967: Shadowing on the ocean and the existence of the horizon. *J. Geophys. Res.*, **72**, 4643–4649.

Ter-Markariantz, N. E., 1959: On calculation of albedo of water surface. *Tr. Gl. Geofiz. Observ.*, No. 80.