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Albedo of a Water Surface, Spectral Variation, Effects of Atmospheric Transmittance, Sun Angle and Wind Speed

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Some properties of sea surface albedo have been investigated. (1) With aircraft data of upward and downward hemispheric irradiances in three broad bands of the solar spectrum we have investigated albedo as a function of transmittance (variations in windspeed and solar altitude were small). Transmittance measures the depletion of the solar radiation on its path through the atmosphere. For short solar wavelengths, 0.28–0.53 μm, surface albedo shows little dependence on transmittance, while for longer solar wavelengths, 0.53–2.8 μm, albedo increases with decreasing transmittance. This behavior results from the observation that the short wavelengths are mostly diffuse for all degrees of cloudiness, whereas longer wavelengths become more diffuse with increasing cloudiness. (2) With measurements from broadband pyranometers on a mast over Lake Washington (Seattle, Washington) and from ships in the North Atlantic and the Tropical Atlantic during summer we have investigated the variation of albedo with solar altitude and transmittance. Our results are in general agreement with those of Payne (1972), but some deviations are indicated at high solar altitudes with low transmittances and for solar altitudes below 20°. The effects of wind speed on normalized albedo measured in the Joint Air-Sea Interaction (JASIN) experiment agree with previous findings of Payne (1972) and Simpson and Paulson (1979).

INTRODUCTION

Shortwave irradiance, E_s, dominates the heat budget at the air-sea interface under most conditions. A portion of this incoming solar energy is not absorbed but, by processes of reflection from the surface or scattering from the volume below the surface, is directed upward away from the surface. The ratio of this upwelling shortwave exitance M_s to the irradiance is the albedo α. It is usually integrated over all solar wavelengths, but in this paper we also divide the albedo into three broad bands of the solar spectrum and investigate their dependence on broadband atmospheric transmittance. The terms irradiance and exitance (in units of watts per square meter) imply integration over the hemisphere and include contributions from direct and diffuse light [*Raschke*, 1978].

Daily mean albedo can vary from as low as 0.03 to as high as 0.44 [*Payne*, 1972] making it a significant modifier of the heat budget at the air-sea interface. Backscatter from below the interface can contribute from 0.005 to 0.02 to the total albedo according to *Hollman* [1968] and *Payne* [1972], but *Powell and Clarke* [1936] found backscatter to contribute up to 0.03 to the albedo.

The Fresnel laws of reflection at a water surface predict that the reflectance of a light beam increases with angle of incidence. As solar altitude decreases, the reflectance of the direct beam increases. When the irradiance becomes more diffuse due to cloudiness or haze, the amount of incident radiation from angles other than the solar altitude increases, and the amount of incident radiation from the solar altitude angle decreases. Therefore for high solar altitude, the albedo for cloudy skies will be greater than the albedo for clear skies. For lower solar altitudes the albedo for cloudy skies will be less than the albedo for clear skies. These effects are illustrated in Figures 1*a* and 1*b*. In addition, the incidence angle changes when the reflecting surface is roughened owing to waves. The subsequent change in albedo is illustrated in Figure 1*c*. Examples of calculations of albedo for a rough sea can be found in works by *Kraus* [1972] and *Cox and Munk* [1954].

Upper ocean absorption is a strong function of wavelength [*Jerlov*, 1976; *Paulson and Simpson*, 1977; *Zaneveld and Spinrad*, 1980]. *Simpson and Dickey* [1981] numerically modeled the upper ocean taking this into account. They showed that the turbulent mixing and vertical distribution of current velocity were substantially influenced by the ensuing stratification. This has motivated our study of the spectral distribution of incident and reflected light under various sky conditions.

At least 50% of irradiance reaching the surface in the 0.28- to 0.53-μm wavelength range is diffuse due to Rayleigh scattering, but less than 30% of the energy in the longer wavelengths, 0.53 to 2.8 μm, arrives as diffuse radiation with clear skies [*Jerlov*, 1976]. Since the effect of cloudiness is to make irradiance at all wavelengths more diffuse, we can anticipate that the albedo in the longer wavelengths will show a stronger dependence on cloudiness than the albedo in the shorter wavelengths.

As a quantitative measure of the diffuseness of irradiance, *Payne* [1972] used transmittance in his study of albedo variations with solar altitude and cloudiness. Transmittance τ is defined as the ratio of solar irradiance at the surface, E_0, to irradiance at the top of the atmosphere, E_{s0}, namely, $\tau = E_0/E_{s0}$. E_{s0} can be calculated from knowledge of time and location [*Paltridge and Platt*, 1976].

In this study, we examine the albedo's dependence on transmittance (cloudiness) and solar altitude using observations obtained from aircraft and a ship in the Joint Air-Sea Interaction (JASIN) experiment, from a ship in the GARP Atlantic Tropical Experiment (GATE, where GARP is the Global Atmospheric Research Program), and from an instrumented mast located in Lake Washington (Seattle, Washington). These results are then compared with *Payne*'s [1972].

DATA SOURCES

Aircraft Data

The NCAR Electra carried three upward and three downward looking Eppley Precision Spectral Pyranometers (Eppley

[1] Now at Digitek, Inc., Bothell, Washington.

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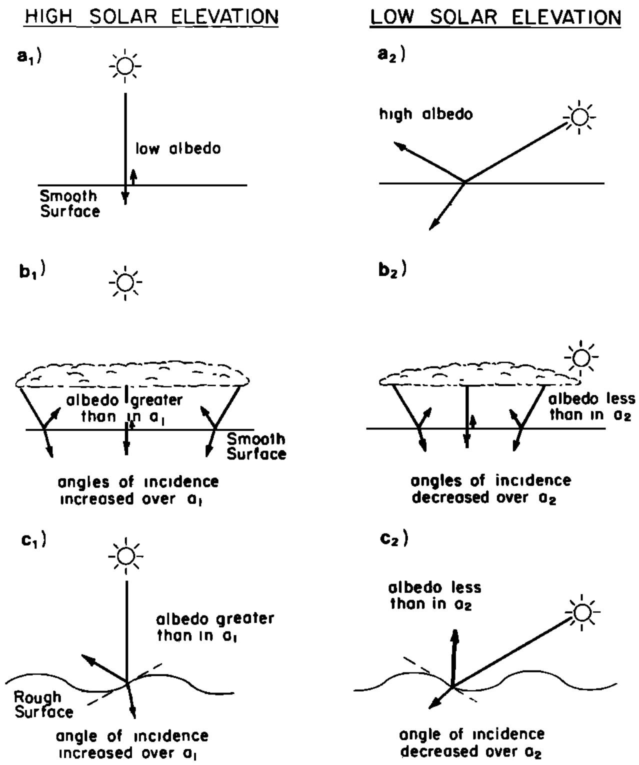

Fig. 1. Schematic illustration showing how angles of incidence are expected to change owing to solar altitude: (a_1, a_2) from consideration of the Fresnel law of reflection for clear skies and smooth surfaces, (b_1, b_2) for cloudy skies and smooth surface, and (c_1, c_2) for clear skies with roughened surface.

PSP) during the JASIN experiment (July to early September 1978). The filtered pyranometers measured radiative flux density (irradiance and exitance) in wavelength bands 0.28–2.8 μm, 0.53–2.8 μ, and 0.7–2.8 μm. Flight data were confined to the JASIN meteorological triangle, 180 × 180 × 220 km, centered near 58°N, 12°W. Details of the experiment such as design, purpose, and available data sources can be found in a work by *Pollard et al.* [1983].

Two types of flight patterns were flown. These were L-shaped and box patterns repeated at several heights. During each "leg" of the pattern, the Electra flew at constant heading and altitude for several minutes, covering 15–20 km. Only legs flown at altitudes of 50–100 m, free from precipitation, were used in the analysis. Reports of precipitation were recorded by an observer aboard the aircraft. The pyranometer data were recorded at 1 Hz. Albedos were calculated using a 60-s averaging time corresponding to a flight distance of about 600 m. All flight data were collected between 1100 and 1400 local time, limiting the range of solar altitude to 38°–42° but allowing comparison between data sets taken under different sky conditions. Winds were between 5 and 10 m s^{-1}.

Surface Data

JASIN–M/V Endurer. During JASIN, the M/V *Endurer* was positioned at the NW corner of the meteorological triangle (60°15′N, 14°30′W). A downward looking Kipp and Zonen (type CM5) pyranometer was gimbal mounted on a 7.5-m-long boom (5 m above water) amidships. An upward looking Kipp and Zonen (type CM5) pyranometer was gimbal mounted high upon the ship. The Kipp and Zonen CM5 pyranometer has rather flat spectral response between 0.3 and 3 μ [*Hinzpeter*, 1980]. Shadows on the sea surface cast by the ship contaminated about 40% of the albedo data. These data were removed from the analysis by calculating solar azimuth and comparing ship headings for the times in question. If the ship shadow was within the hemisphere viewed by the downward looking pyranometer, the data were discarded. The pyranometer signals were sampled at a rate of 33 Hz before recording by an analog to digital conversion system. A microprocessor computed averages for 10-min periods. Subsequent analyses were carried out with these 10-min averaged data. During the late summer period of this experiment, solar altitudes ranged from 0° to 58°, and winds ranged from calm to 12 m s^{-1}.

GATE–R/V Researcher. During Phase III (September 1974) of the GARP Atlantic Tropical Experiment, the R/V *Researcher* was positioned at 7°N, 23°E. A boom extending from the bow housed the gimbaled downward looking Eppley (model 8-48) pyranometer. Shortwave irradiance was measured with an Eppley (model 2) pyranometer. These pyranometers have a rather flat response from 0.1 to 3.0 μm. Data, sampled every 4 s, were processed as 15-min averages. Data used in our analysis were required to contain at least 200 valid samples within each average. Albedo data covered solar altitudes from 0° to 90°, providing albedos beyond the range of observations made by Payne.

Lake Washington field station. A meteorological mast is maintained by the Department of Atmospheric Sciences of the University of Washington on the shore of Lake Washington in water depths of about 5 m. The mast is used primarily to study radiation, atmospheric turbulence, waves, and near surface water temperature profiles. Upward and downward looking Eppley (type CM5) pyranometers were mounted on a boom extending to the south, where water depths decrease rapidly. At the position of the radiometers the water depth was only 1.6 m. Radiation data were sampled at 33 Hz and processed as 5-min averages. Because of the shallowness of the water at the site and owing to vegetation and sediments stirred up by wave action, albedo data are not representative of the open ocean. They are included to demonstrate the magnitudes of such effects.

ANALYSIS PROCEDURE AND RESULTS

Aircraft. Since aircraft do not fly in a perfectly horizontal attitude, corrections were applied to exitances and irradiances to account for aircraft pitch and roll according to the procedures of *Albrecht and Cox* [1977]. It was found that exitances were occasionally less than zero, of the order of 10 W m^{-2}, implying a negative bias. A possible cause for the bias is a change in the calibration of the instruments over the course of the experiment. However, preexperiment and postexperiment calibrations were very similar, indicating insignificant change. Side by side intercomparison flights of the Electra aircraft with the British C-130 were made, but the agreement between the irradiances measured by the Electra and by the C-130 was found to be poor, mostly owing to variable cloudiness during the comparison flights. Unfortunately, the only consistency in the comparison is a lower average measured by the Electra [*Slingo et al.*, 1982]. Since a bias-error correction could not be determined directly, an alternative method of determining the corrections to the pyranometers was derived. The primary goal of the correction method was to eliminate the negative bias while still maintaining the same ratios between the instruments. Details of how the biases were determined and their values can be found in Appendix B of *De-*

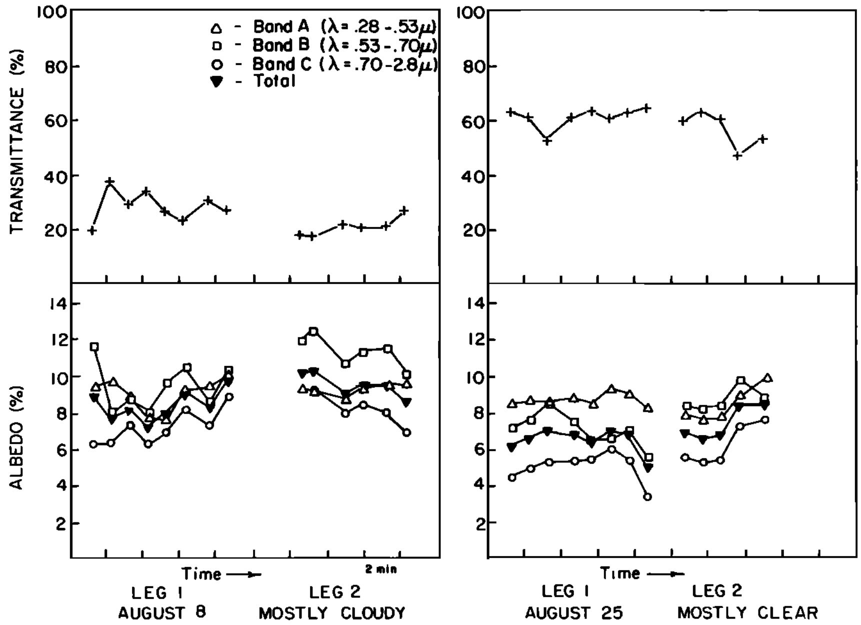

Fig. 2. Time series of broadband transmittance (top), albedo in three spectral bands, and total albedo (bottom) obtained from 1-min averages of NCAR Electra data collected on August 8 and 25, 1978. On both days the aircraft flew at a height of 50 m. The August 8 flight was below a uniform stratocumulus deck with solar altitude of 38°, and the August 25 flight took place under clear skies with a solar altitude of 42°.

Vault and Katsaros [1983]. These bias corrections were applied to the data before albedo calculations were made.

Three spectral bands, A (0.28–0.53 μm $\pm$.01), B (0.53–0.70 μm $\pm$.01), and C (0.70–2.8 μm $\pm$.01), were obtained by subtracting one pyranometer output from another for both existence and irradiances. Albedos in each band and the total albedo were calculated and then averaged to obtain 60-s mean spectral and total albedos. Transmittances of the broadband solar irradiance for the same 60-s periods were calculated and ranged from 0.2 to 0.7. The relatively short averaging time period was chosen because often the aircraft was flying under conditions of variable cloudiness and it was desirable to try to separate the times of clear and cloudy skies. However, 3-min albedos were calculated and the results were the same as the 1-min averaged albedos (not shown here). The averaging times for the ship data, on the other hand, were longer because the sky conditions do not change as fast when viewed from a ship as they do when viewed from an aircraft.

Samples of time series of transmittance and spectral albedos are show in Figure 2 for overcast (August 8) and clear (August 25) skies. These time series, with different sky conditions and similar solar altitudes, demonstrate that total albedo increases with transmittance as shown in Figure 1. August 8 was characterized by uniform stratocumulus, whereas August 25 was mostly clear.

Albedos in bands A, B, and C and total albedo are shown as functions of total transmittance in Figure 3. Albedos for band A are nearly constant over all transmittances and average 0.07. Albedos for bands B and C and the total albedo increase as transmittance decreases. The total albedo ranges from 0.10 to 0.06 when the transmittance ranges from 0.2 to 0.7. Albedos computed for transmittances less than 0.2 are not included because of possible contamination due to haze, low cloudiness, or precipitation not reported by the observer aboard the aircraft.

The percentages of radiant energy before attenuation by the atmosphere contained within bands A, B, and C are 27%, 22%, and 51%, respectively [*Johnson*, 1954]. After attenu-

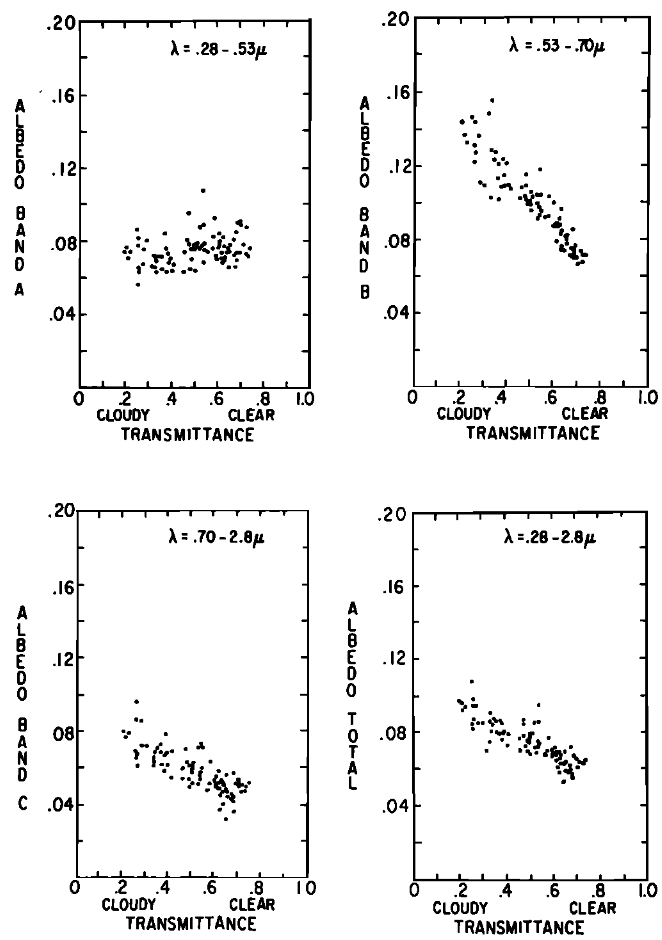

Fig. 3. Total albedo and spectral albedo shown against total transmittance for NCAR Electra flights during JASIN 1978 from flights on July 28 and August 7, 21, 24, and 25. The solar altitudes ranged from 38° to 42°. Note the lack of dependence on band A (0.28–0.53 μm) on transmittance.

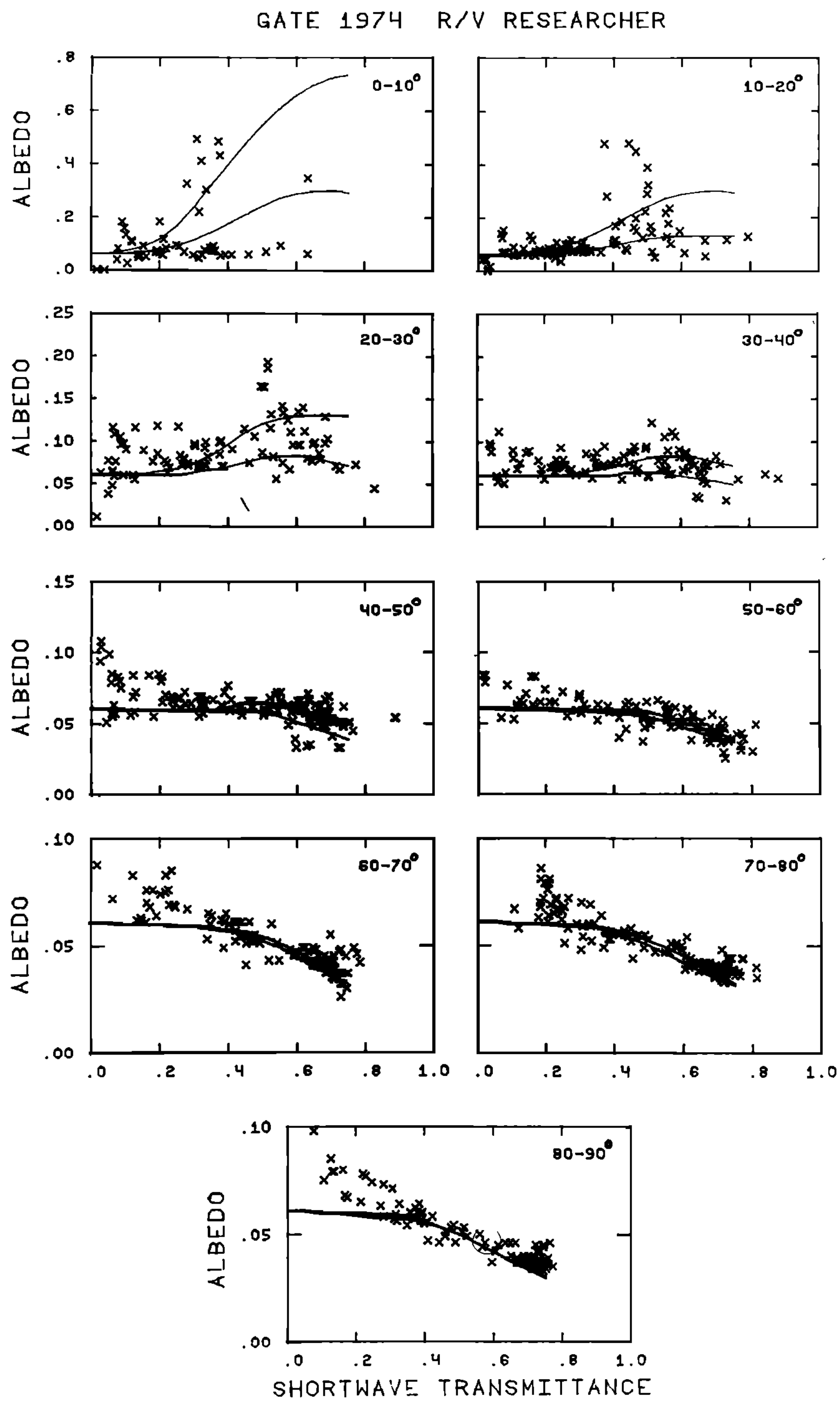

Fig. 4a

Fig. 4. Total albedo shown against total transmittance for 10° bands of solar altitude for (*a*) M/V *Endurer* during JASIN and (*b*) R/V *Researcher* during GATE. Smoothed albedos from *Payne* [1972] for lowest and highest solar altitudes are shown for comparison. Note scale change on the ordinate axis from one plot to the next.

ation by atmospheric constituents these percentages are 26%, 27%, and 47%, respectively.

Ships. For each data set, solar altitude, azimuth, top of atmosphere irradiance, and transmittance were computed over each averaging period (10-min average for the M/V *Endurer* and 15-min average for the *Researcher*). Data from the M/V *Endurer* were required to be clear from shadowing by the ship, as mentioned previously. The black hull of the M/V *Endurer* occupied a portion of the hemisphere viewed by the downward looking pyranometer, reducing measured exitances. Corrections were made to measured exitances assuming reflection of E_s from the hull to be zero. The ship also blocked diffuse irradiance from the area of ocean viewed by the downward looking pyranometer. These effects were taken into account as follows. We define the exitance from the sea measured from the boom as M_{s_b}. The fraction of the hemispheric solid angle not blocked by the ship's hull below the boom is estimated to be 0.82. The fraction of the skyward hemisphere over the area

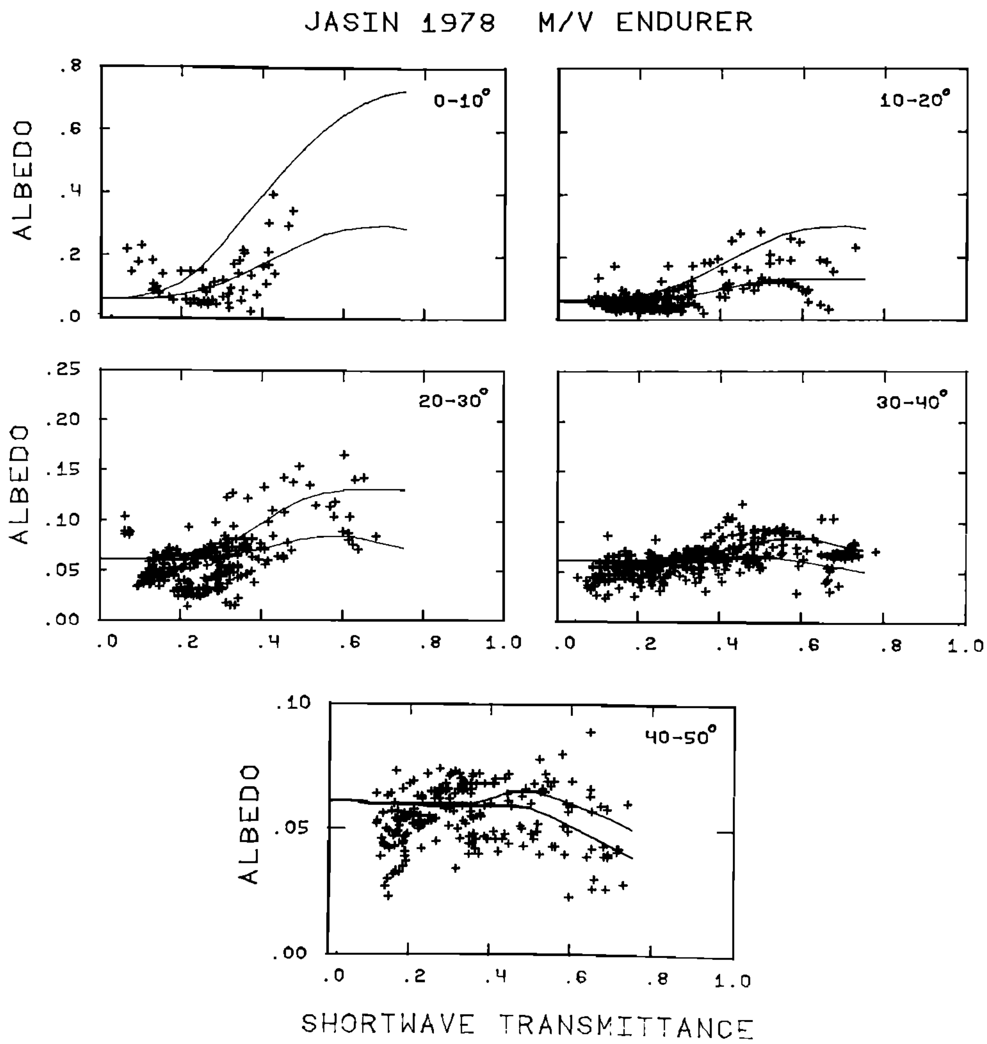

Fig. 4*b*

viewed by the downward looking pyranometer and not blocked by the ship is estimated to be 0.78. Corrections to the backscattered exitance due to the fraction of hemispheric solid angle occupied by the ship (above and below the waterline), 0.36, were also made. This correction, according to *Hollman* [1968], is equal to 0.005 × 0.36 E_s. Equation (1) summarizes these corrections to measured exitances:

$$M_s = \frac{1}{0.78} \times \frac{1}{0.82} M_{s_b} + 0.005 \times 0.36\, E_s \qquad (1)$$

These corrections to the observations assume isotropy, although isotropy is known not to apply. However, these estimates give an indication of the severity of measurement errors induced by a large object in the field of view of the instruments. The correction factor due to the first term in (1) is 1.56. Lost exitance due to backscattered irradiance, the second term in (1), is about 1.5 W m^{-2} for clear skies during JASIN. Roughness changes, due to the presence of the ship, are likely, but no attempt was made to correct for this effect.

The R/V *Researcher* is a white ship, and anticipated corrections would be in the opposite sense. Radiation instruments were mounted from a boom on the bow, making the solid angle subtended by the ship substantially less. However, the effect of an object with a higher albedo, perhaps 0.50, in the field of view on a measurement of a relatively low albedo is potentially just as large. This reflected irradiance from the hull is probably higher than the irradiance lost by the ship blocking diffuse irradiance. Indeed, the uncorrected albedo observations presented below appear a bit high compared to Payne's and our other results. No attempt was made to correct these data, since we obtained the data from the GATE archives and are not familiar with the exact deployment of the sensors.

Albedos from the two ships, grouped into 10° solar altitude bands, are plotted against transmittance in Figures 4*a* and 4*b*. Smoothed albedos from *Payne* [1972] representing lowest and highest solar altitudes in the range are also shown.

R/V *Researcher* albedo data extend over all possible solar altitudes, allowing comparison with calculations of Payne for solar altitudes greater than 72°. Payne did not make observations beyond 70° solar altitude but extrapolated albedo values by adding emergent irradiance (0.005) to *Saunders*'s [1967] calculated reflectances for $\tau = 1.0$ and wind speed of 7.5 knots (13.9 km/h). He then extended his smoothed albedo curves to $\tau = 1.0$ with zero slope. Measured albedos from the R/V *Researcher* and Payne's calculated albedos compare well for these high solar altitudes except at low transmittances.

Figure 5 shows averaged albedo differences from Payne's table values over 2° increments of solar altitude. This was done by averaging the difference between each 10- or 15-min albedo observation and the Payne albedo corresponding to

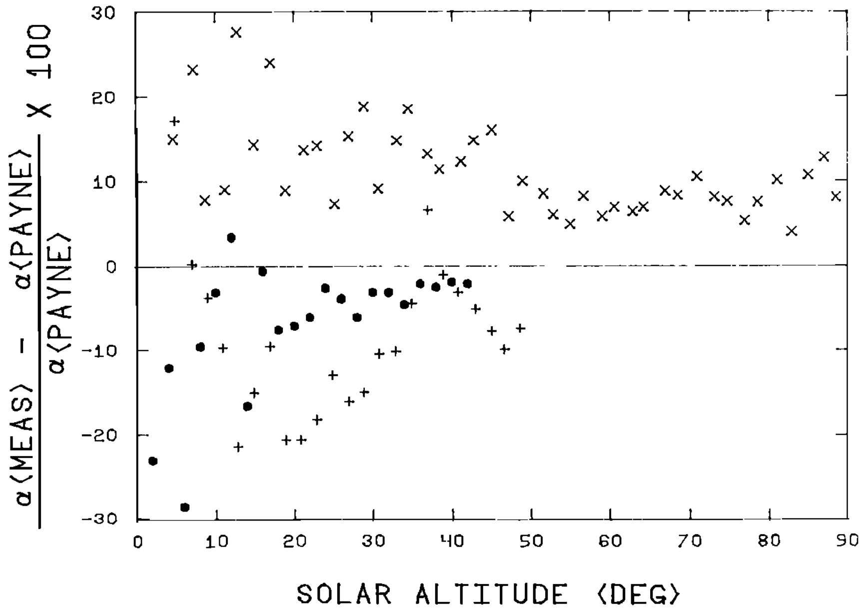

Fig. 5. Average deviations of measured albedo for the M/V *Endurer* (+) and the R/V *Researcher* (X) from *Payne*'s [1972] curves as a function of solar altitude. Results from *Simpson and Paulson* [1979] (solid circles) are also shown.

the same solar altitude and transmittance. Differences between R/V *Researcher* albedos and Payne's values are positive. This could be due to not correcting for the effect of the white ship. Differences between the M/V *Endurer* and Payne are mostly negative, indicating that corrections made assuming isotropy were not accurate enough or that the radiance distribution during JASIN was different from those of Payne's observations. Differences found by *Simpson and Paulson* [1979] between measurements made at 35°N, 155°W and Payne's curves are shown for comparison.

Few albedo measurements are available for high winds (>10 m s^{-1}), as conditions are too severe for conventional boom-mounted instrumentation from ships. Theoretical relationships between wind speed and albedo in clear skies were presented by *Payne* [1972]. Using a theory from *Saunders* [1967], Payne expected to see little change in albedo with change in water roughness for clear sky conditions and solar altitudes greater than 30°.

M/V *Endurer* albedo data were selected for clear skies and sorted by wind speed into 2 m s^{-1} bands and 2° solar altitudes. Winds of up to 12 m s^{-1} were experienced during JASIN. These albedos were normalized by mean clear sky albedos in the same 2° solar altitude range and averaged over each 2 m s^{-1} band. These points are shown plotted as a function of wind speed in Figure 6. Results from *Simpson and Paulson* [1979] are also shown, as is Payne's relationship for solar altitudes from 17° to 25°.

Lake Washington. Because of terrain surrounding Lake

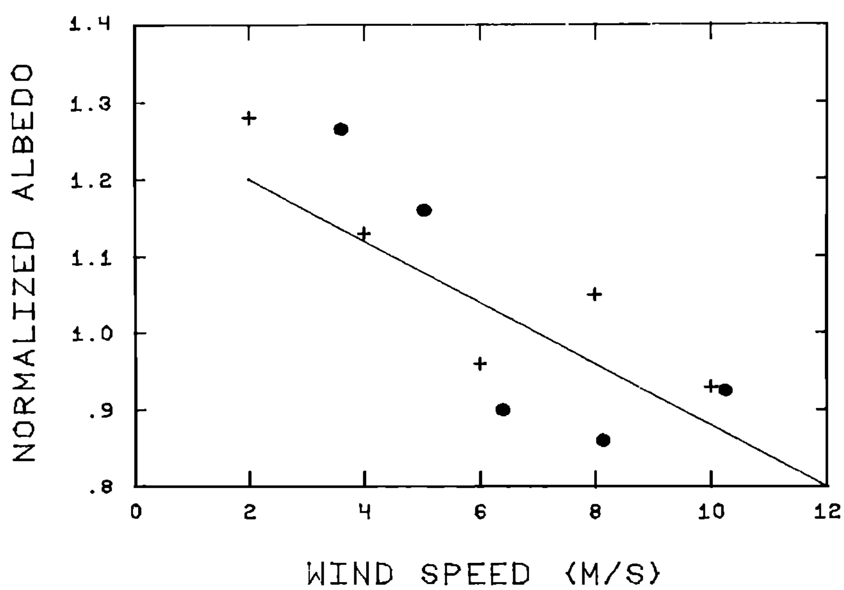

Fig. 6. Normalized albedo versus wind speed for clear sky cases and solar altitudes less than 30°. Data is from the M/V *Endurer* (+) during JASIN. The line is from *Payne* [1972] for solar altitudes from 17° to 25°. Results from *Simpson and Paulson* [1979] (solid circles) are also shown.

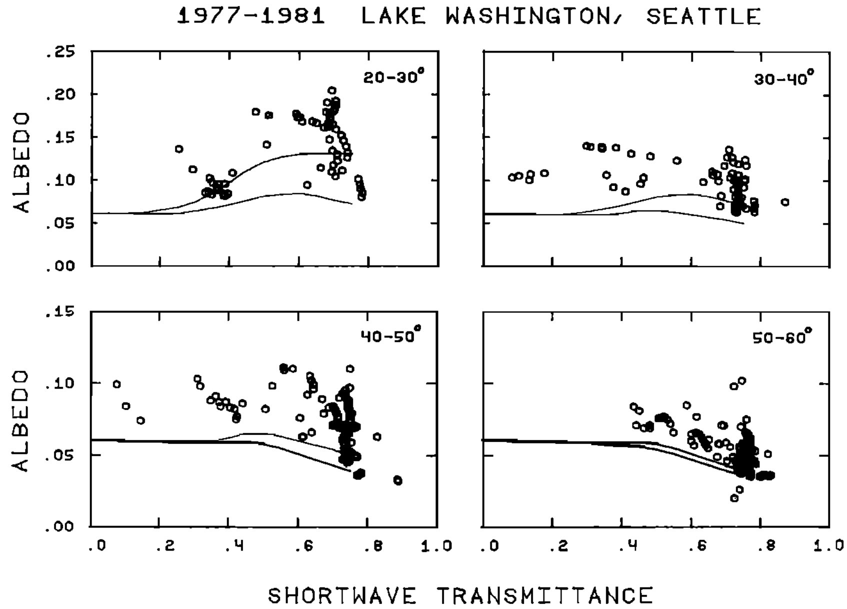

Fig. 7. Total albedo as a function of total transmittance for 10° bands of solar altitude for data from a near-shore mast over Lake Washington, Seattle. Smoothed albedos from *Payne* [1972] for lowest and highest solar altitudes are shown for comparison.

Washington, the horizon is not at 0° altitude. For this reason, only data for solar altitudes greater than 20° were selected. Albedos from Lake Washington are shown in Figure 7 and discussed later.

DISCUSSION OF RESULTS

Aircraft. Since surface roughness and sun angles were nearly constant and are not variable parameters in the aircraft data, we have isolated the effect of transmittance on spectral albedo. We encountered a wide range of cloud conditions including several missions with scattered clouds. For some flights, transmittances had intermediate values due to either thin uniform stratus or a combination of clear and cloudy regions.

As explained in the introduction, cloudy conditions create diffuse incoming irradiance which causes the albedo to be higher than it would be for clear skies for relatively high solar altitude (see Figure 1*b*). This trend is evident in both Figure 2 and Figure 3. The total albedo curve in Figure 2 shows lower values on August 25, when the sky was mostly clear, and higher albedos on August 8, when the sky was mostly cloudy. The plot of total albedo versus transmittance in Figure 3 also shows increasing albedo with decreasing transmittance (solar altitude was near 40°, winds averaged 10 m s^{-1}).

The spectral albedos shown in Figures 2 and 3 also behaved as expected; albedo of band A showed little dependence on transmittance, and albedos of bands B and C increased as transmittance decreased. This is due to how the percentage of diffuse light within each of the bands changes with transmittance. Even when the sky is clear, at least 50% of the irradiance in band A comes as diffuse light from the sky [*Jerlov*, 1975, Figure 29] so the effect of cloudiness on albedo in band A is small. However, about 20% of the irradiance in band B and 10% in band C is diffuse under clear skies. As transmittance decreases, the percentage of diffuse light in bands B and C increases, so that the albedo also increases. This is clearly seen in Figure 3. The total albedo exhibits behavior similar to that of bands B and C, since about 75% of the total irradiance resides in these bands. Note that the total albedo for a certain transmittance is the weighted sum of the albedo in each band, the weights being the percentage of irradiance in each band. These percentages vary with transmittance, e.g., for band C the percentage decreases as transmittance decreases, since longer solar wavelengths are absorbed by clouds.

Surface data. For solar altitudes greater than 20°, the midlatitude data from JASIN and the tropical data from GATE as well as the Lake Washington data generally support *Payne*'s [1972] curves. Some scatter in the results at intermediate values of transmittance is evident. This can be expected, since an intermediate value of transmittance can result from a uniform cloud deck or from variable cloudiness. Therefore two periods with the same transmittance may have very different albedos owing to the irradiance distribution.

For the high sun angles of the tropical midday, albedos from R/V *Researcher* data support Payne's extrapolations to these conditions for all except the very lowest transmittances, which may have been contaminated by precipitation. Precipitation and fog render the radiative environment nearly isotropic, and observed albedos will be artificial and appear greater than they would otherwise.

The observations made at Lake Washington show consistently higher albedos than Payne's curves. This is attributed to reflection from the lake bottom and to the higher turbidity of the lake water.

At low solar altitudes, albedos from the M/V *Endurer* are lower than Payne's for all transmittances but more so at lower transmittances. For the R/V *Researcher*, the differences are in the opposite sense and are largest at low transmittances. Part of these differences could be associated with the fact that the cosine response of the radiometer makes measurements of albedo at solar altitudes of ≤10° questionable. This study is in agreement with *Simpson and Paulson*'s [1979] work, which may indicate that Payne's curves for low solar altitudes should be tested further. Simpson and Paulson argued that their differences were within measurement error, while Payne explained that the radiance distribution has the largest effect on mean albedos for low solar angles. Payne's mean albedo estimates have error bars of the order of 25% for solar altitudes of 50°. The presence of the large ships in the observations used for this study certainly makes measurement error a possible explanation in this case as well.

The trend of increasing albedo with decreasing transmittance is larger in the aircraft data than in the ship data. The total albedo calculated from aircraft increased from 0.06 to 0.10 as the transmittance decreased from 0.7 to 0.2. The solar altitude was near 40°. The M/V *Endurer* data showed only minimal increase of albedo at solar altitudes of 40°–50°. The R/V *Researcher* data indicated that the albedo increased slightly from 0.05 to 0.08 as transmittance decreased from 0.8 to 0.1 at solar altitudes of 40°–50°. These differences could be due to several factors. Corrections were applied to all the data sets, so that possibly the data were over corrected or under corrected. At low transmittance, rain or clouds between the aircraft and the ocean surface could cause the albedo to be artificially greater. Therefore a higher dependence of albedo on transmittance in the aircraft data could result. However, note that the R/V *Researcher* results for solar altitudes greater than 50° indicate a definite trend of increasing albedo with decreasing transmittance of similar magnitude, as do the aircraft data.

For the wind speed effect on albedo all three data sets obtained by different instrumentation in different locations are in agreement. This gives some confidence that the effects of wind speeds <12 m s^{-1} on albedo for solar altitudes $<30°$ can be generalized. The effect of wind speed on normalized albedo is found to be of the order of -3.6% per m s^{-1} of wind speed change with clear sky and solar altitudes less than 30°. At higher solar altitudes, albedo is not affected by wind speed (sea state) in the range of wind speeds encountered, i.e., up to 12 m s^{-1}. For higher wind speeds, albedo due to whitecapping, foam, bubbles, and spray must be considered. The effects of the diffuseness of the irradiance and of roughened seas on albedo are additive, since they both act to reduce albedo at low sun angles (Figure 1), but our data set is not sufficient to subdivide the data with respect to sun angle, transmittance and wind speed.

Summary. Albedo calculations for solar altitudes of 38°–42° made from aircraft data indicate that total albedo and albedo of spectral bands B and C increase as transmittance decreases. Albedo of spectral band A has little dependence on transmittance. Albedo calculations from the ship and lake data generally agree with Payne's curves. However, at low solar altitudes, the M/V *Endurer* albedos are less than Payne's curves, and the R/V *Researcher* albedos are greater than Payne's curves. The differences are especially evident at low transmittances. The dependence of albedo on transmittance is greater in the aircraft results than in the ship and lake results. However, the differences are not outside the range of scatter within each category of measurement. Since albedo measurements are difficult to make, the differences can be attributed in part to errors due to the different observing platforms. Further research at low solar altitudes and low transmittance is needed, with particular care paid to the linearity of the sensors and the accuracy of the measurements. The albedo calculations evaluated from the lake data are consistently higher than Payne's values owing to reflection from the lake bottom and water turbidity. For higher solar altitudes, Payne's smoothed observations and extrapolations appear adequate. That the true albedo can vary substantially from Payne's mean value because of varying radiance distribution over the sky dome should, however, be remembered.

COMMENTARY

The measurement of the albedo of the sea is a difficult proposition, since it requires finding the ratio between a small and a large number very accurately. Another problem is that hemispheric instruments must be mounted horizontally from a stable or gimbaled platform. The platform typically shades the skyward hemisphere as well as the oceanic one. Our observations from the M/V *Endurer* appear a bit low, possibly because our exitance measurements were affected more by the ship's presence than we have estimated.

Rather low values of albedo were also seen on a white ship (R/V *Meteor*) during JASIN in 1 day's data reported by *Gube et al.* [1980] (see also comment by *Cogley* [1980]). Ship data, even with gimbal-mounted instruments, experience height changes from sea conditions that lower the instrument, so that it only views the sunlit or shadowed portion of the swell. The effect of vertical ship motion is not linear, making measurements at low solar altitudes difficult. The use of aircraft measurements, therefore, seems to be most sensible for precise determination of albedos at low solar altitudes. There is virtually no interference with the field of view, and aircraft attitude is monitored, thus allowing corrections. Unfortunately, during JASIN the aircraft only flew early in the day on one occasion (September 1), and the sky conditions were not uniform. The bias problem encountered in this study could be remedied by regular tests for a "dark bias," by covering the instruments in flight with a tight-fitting lid and by intercomparison with stationary well-calibrated equipment during several flybys under uniform cloud conditions.

The dependence of albedo on sea state has not been determined for higher wind speeds when breaking waves, foam, and bubbles in wind streaks as well as airborne spray may have significant effects. Using aircraft as the measurement platform appears to be the only possible method for these circumstances.

Since the ocean's albedo is especially large at low solar altitudes and therefore particularly important for high-latitude oceans, careful attempts to determine the mean albedo for low sun angles should be made.

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