A Note on the Albedo of Surfaces

LAWRENCE C. NKEMDIRIM

Dept. of Geography, The University of Calgary, Alberta, Canada

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ABSTRACT

The albedo of a variety of surfaces was measured for a total of approximately 400 hr with Middleton solari-albedometers whose outputs were recorded by a computer-controlled data acquisition system. The albedo for each surface was expressed as a function of solar zenith angle, with strong relationships between the two being obtained for most surfaces. The dependence became stronger, i.e., the correlation coefficient between the two sets of data rose, as the transmissivity increased. All surfaces showed two characteristic albedo zenith angle curves corresponding to AM and PM observations, the PM curves generally being displaced farther from the origin. The feature is explained in terms of the compound effect of solar elevation and haziness. Irrigation increased the albedo during AM periods but showed no significant effect on PM values.

1. Introduction

Albedo as used in this paper is defined as the ratio of reflected to total incident global radiation. Surface albedo plays an important role in the energy because it determines the proportion of insolation which is absorbed by the surface. Its magnitude and variability over various surfaces have been studied by several

investigators. Monteith (1959) established that for most crop surfaces an average albedo of 0.25 can be assumed. Graham and King (1961) showed that albedo increased markedly at low solar elevation but that the diurnal distribution was asymmetrical about noon. They showed that under overcast conditions albedo was slightly smaller. Munn and Truhlar (1963) reported

TABLE 1. The dependence of average albedo on zenith angle and cloudiness.

Zenith angle (deg)	AM Period			PM Period		
	No. of Average hours	Standard albedo	deviation	No. of Average hours	Standard albedo	deviation
a. Transmissivity <0.25 (overcast)						
76-87	2	0.065	0.064	2	0.385	0.117
61-75	3	0.073	0.067	3	0.250	0.040
46-60	4	0.085	0.017	4	0.145	0.033
31-45	4	0.110	0.020	4	0.115	0.053
≤ 30	1	0.120	—	1	0.100	—
Correlation coefficient	0.18			0.972		
b. Transmissivity 0.25-0.50 (intermittent cloudiness)						
76-87	16	0.194	0.128	16	0.417	0.222
61-75	24	0.147	0.059	24	0.266	0.126
46-60	25	0.131	0.033	28	0.155	0.052
31-45	36	0.140	0.031	38	0.138	0.039
≤ 30	11	0.123	0.017	11	0.118	0.018
Correlation coefficient	0.870			0.985		
c. Transmissivity >0.50 (cloudless)						
76-87	19	0.241	0.121	18	0.443	0.178
61-75	34	0.179	0.066	31	0.283	0.069
46-60	25	0.153	0.025	30	0.182	0.029
31-45	42	0.138	0.035	40	0.145	0.026
≤ 30	5	0.106	0.022	5	0.108	0.019
Correlation coefficient	0.981			0.994		

albedo values for afternoon periods that were higher than the forenoon equivalents but made no comment regarding the observation. Stanhill *et al.* (1966) showed that albedo increased markedly with decreasing solar altitude and that the degree of cloud cover had no discernible influence on the values of albedo measured for any of the surfaces over which they conducted their investigation. Impens and Lemeur (1969) also reported a diurnal variation with marked asymmetry about noon. Davies and Buttimor (1969) measured the albedo of leaves plucked from the parent plant and observed that albedo increased as the leaves lost turgidity. The observation may imply that part of the reason for the higher albedos measured in the afternoon is related to the loss of turgidity as a result of moisture withdrawal from the leaves of crops. Coulson and Reynolds (1971) considered that the presence of surface moisture could affect albedo in a marked way.

These works point to the continuing interest in albedo, and the recent controversy as to whether albedo plays an important role in predicting net radiation from global radiation (Idso *et al.*, 1969; Davies and Buttimor, 1969; Gay, 1971, Nkemdirim 1972a) has served to heighten the interest in the subject.

The purpose of this paper is to report on three aspects of the albedo question. These are:

- 1) The relationship between albedo and zenith angle under different sky conditions.
- 2) The relationship between albedo and the period of day—forenoon and afternoon.
- 3) The influence of irrigation on albedo.

The reported results were obtained from 400 hr of measurement of albedo over extensive crop surfaces and bare soil made as part of the energy balance study being conducted at the University of Calgary Experimental Station.

2. Site and instrumentation

The Experimental Station is located to the northwest of the University campus on relatively flat prairie terrain at 51°17'N, 114°W. Elevation is approximately 1080 m MSL. With the nearest obstruction about 500 m away, it is believed that the exposure was adequate and that the hemispherical sky radiation was undisturbed.

The experimental farm (100 m×100 m) was divided into four equal portions. Two of the plots had a potato crop. Irrigation was applied to one of the plots with the potato crop. The plot so treated was separated from the other by plastic-covered plywood boards sunk to a depth of 2.5 m. The rest of the potato crop was watered by rainfall only. The third plot had mixed vegetables grown over it. These included green peas, cabbage and beans. The fourth plot was left bare.

Incident and reflected global radiation were measured with two Middleton solari-albedometers. This instrument consists of two Kipp and Zonen type solarimeters mounted back to back. The upward facing part of the instrument serves as a solarimeter and the other as an albedometer, an arrangement designed to facilitate the task of simultaneous solar and albedo measurements. It is a hybrid instrument containing two thermopiles and sensor plates opposed to each other. Its design includes a gimbal mount that can be turned to any angle and still have the albedo and incoming radiation perfectly aligned. The two thermopiles are made of copper-constantan and each has 82 junctions. The sensitivity and resistance of 0.164 mV per mW cm⁻² and 40 Ω quoted by the manufacturers were checked in the laboratory and found to agree within 2%. The instrument gives separate outputs for insolation and reflected shortwave radiation. Laboratory tests in which the instrument was rotated with respect to a light source in a constant position confirmed that the response follows the cosine law even at low angles of incidence. A temperature compensating circuit utilizing a thermistor probe to monitor ambient temperature was attached to each side of the instrument, and corrections were made to the sensor sensitivity when a temperature difference existed between the two surfaces. When identical ambient temperature was recorded, no correction was made since the ratio between incoming and

FIG. 1. The diurnal distribution of albedo over crop surfaces and bare ground.

reflected radiation was unaffected. For a full discussion on sensitivity and ambient temperature the reader is referred to Drummond *et al.* (1965) and Davies *et al.* (1970).

The instrument was mounted at a height of 1.8 m, a spirit level being used to ensure that the instrument was within $\pm 1^\circ$ of the horizontal. It was estimated through methods outlined by Slatyer and McIlroy (1961) that about 90% of the radiation incident on the lower surface of the instrument came from a circular area with a diameter of approximately 3 m; the instrument was positioned accordingly to ensure as much surface homogeneity as was possible. Efforts were made to minimize shading at low solar elevation by slight adjustment of the mount and rotation of the instrument. However, the shaded area was always less than 0.5% of the effective reflecting surface and no adjustment in albedo values were made to correct for so small an area.

The outputs from the sensors were measured sequentially by an integrating digital voltmeter and the measurements stored by an on-line computer. The computer averaged ten measurements from each sensor per minute and printed 5-min average values of insolation and reflected radiation.

On recalibration of the instruments after four months use in the station, changes of less than 1% were found in the calibration factor. Measurements of the radiation components analyzed in this paper were made for a total of 400 hr in 108 days from June to September 1971. Measurements were made continuously from before sunrise until after sunset over any selected surface. Because only two instruments were available, the sensors were placed over different crops on different days. Similarity theory suggests that if prevailing conditions remain essentially similar, then the dimensionless ratio (albedo) is directly comparable. Prevalent conditions are defined here by equivalence in transmission coefficient and zenith angle.

3. Analysis

a. Cloudiness, average albedo, zenith angle and period of day

Initially the data were divided according to crops for three ranges of cloudiness. The transmissivity obtained by dividing the global radiation received at the surface by the global radiation incident at the top of the atmosphere was used as an index of cloudiness. The latter quantity was calculated from the basic

FIG. 2. Albedo and zenith angle over bare ground and peas.

formula for computing the amount of solar radiation reaching a unit horizontal area at the top of the atmosphere (List, 1958). Three transmissivity ranges selected were less than 0.25, 0.25–0.5, and greater than 0.5. These transmissivities corresponded approximately to overcast conditions, intermittent cloudiness and cloudless conditions, respectively. Average albedo over all surfaces for zenith angle classes were found under each atmospheric condition. The results are broken into AM and PM periods and are presented in Table 1. An examination of each set of data showed the relationship between albedo and zenith angle to be approximately exponential, and subsequent plotting of the two variables (Figs. 1–3) showed that this assumption was valid. Coefficients of curvilinear correlation between the variables were computed using the exponential transformation of the data in Table 1. The results of the computation are listed in the bottom row of each data set. Differences in mean value between AM and PM albedos were tested for each transmissivity range using the student “t” test, and these differences were found to be statistically significant at the 0.05

significance level.¹ Analysis of variance of all six groups in Table 1 also showed statistical significance at the same level. Because of the strong differences shown by forenoon and afternoon albedos in their relation to zenith angle, a plot of mean albedo of various surfaces vs zenith angle was made (Fig. 1). Two distinct curves are evident, the upper representing the PM data and the lower AM. The two curves converge at about noon.

b. Albedo and zenith angle

The relationship between average albedo for each surface and zenith angle was sought by regressing the former on the latter. Strong exponential relationships were obtained for most of the surfaces (r curvilinear >0.9). It was only in the case of bare soil which showed little sensitivity to the solar path during the AM period

¹ The full range of data rather than the grouping shown in the table was used when the test was made. It is emphasized that the inferential answer provided above is only approximate because the transformed log distribution was only approximately normal. The same caution applies to all statistical test carried out in this paper.

FIG. 3. The effect of irrigation on the diurnal variation of albedo.

(Fig. 2) that a poor correlation was found. The PM curve showed a more sensitive relationship. Each relationship was adequately expressed by a least square equation of the form $\alpha = ae^{bz}$, where α is the surface albedo, z the zenith angle (in degrees), e the base of natural logarithm, and a and b are constants. The values of a and b are listed in Table 2 along with the correlation coefficient and standard error of estimate expressed as a percentage of mean albedo for each group. Except for the non-irrigated potato plot the differences in the AM and PM values of a for each surface were found to be statistically insignificant. This was interpreted to mean that the a coefficients represent a crop factor. However, statistically significant differences were obtained for the b values. In general, the slope factor b is higher for PM than for AM periods as a result of the more rapid rate of increase in albedo values during afternoon hours.

c. Irrigation and albedo

Irrigation was applied to a portion of the potato crop at different times of the day at a frequency of once a day. The average albedo values for the irrigated and

non-irrigated crops are plotted as a function of azimuth angle in Fig. 3. All periods in which rain fell were excluded from the analysis. The usual AM and PM statistically significant differences can be observed from the figure (see also Table 2), but while irrigation increased albedo values during AM periods, no significant differences were observed between the albedo of irrigated and non-irrigated crops during PM periods.

4. Errors

There are three main sources of error in measuring radiation: the instrument, its mounting, and the measurement of its output. Hamilton and Collingbourne (1967) have indicated that errors in the measurement of radiation by pyranometers are caused by the dependence of their output on temperature and on the solar azimuth and zenith angles, as well as by their inherent non-linearity. In the case of albedo measurements, errors due to temperature are considered insignificant since both sides of the solari-albedometer are at the same temperature. The measurements of radiation could not be corrected for the cosine and azimuth response, since only total global radiation was

TABLE 2. Dependence of average albedo on zenith angles and period of day.

Crop	Period	Zenith angle (deg)	No. of hours	Average albedo	Standard deviation	Regression equation	Correlation coefficient	Standard error of estimate
Non-irrigated potatoes	AM	76-87	8	0.303	0.192	$\alpha = 0.613e^{0.181z}$	0.9581	8.21%
		61-75	13	0.207	0.104			
		46-60	13	0.131	0.038			
		31-35	18	0.131	0.026			
		≤ 30	4	0.108	0.025			
	PM	76-87	9	0.476	0.076	$\alpha = 0.0460e^{0.0269z}$	0.9794	8.05%
		61-75	13	0.278	0.054			
		46-60	15	0.159	0.031			
		31-45	17	0.126	0.032			
		≤ 30	4	0.110	0.024			
Irrigated potatoes	AM	76-87	5	0.190	0.051	$\alpha = 0.0896e^{0.0084z}$	0.9691	8.72%
		61-75	7	0.150	0.030			
		46-60	8	0.134	0.020			
		31-45	11	0.127	0.017			
		≤ 30	4	0.115	0.017			
	PM	76-87	5	0.446	0.328	$\alpha = 0.0453e^{0.0271z}$	0.9638	8.73%
		61-75	6	0.322	0.151			
		46-60	10	0.144	0.043			
		31-45	13	0.125	0.023			
		≤ 30	4	0.110	0.014			
Bare ground	AM	76-87	4	0.143	0.054	$\alpha = 0.1247e^{-0.0003z}$	-0.0526	26.3%
		61-75	7	0.104	0.040			
		46-60	5	0.108	0.037			
		31-45	9	0.129	0.020			
		≤ 30	3	0.133	0.015			
	PM	76-87	5	0.414	0.162	$\alpha = 0.0626e^{0.0216z}$	0.9839	5.61%
		61-75	5	0.256	0.072			
		46-60	8	0.176	0.033			
		31-45	10	0.144	0.024			
		≤ 30	3	0.123	0.031			
Peas	AM	76-87	3	0.300	0.053	$\alpha = 0.0842e^{0.0134z}$	0.8884	12.3%
		61-75	6	0.172	0.044			
		46-60	3	0.157	0.040			
		31-45	9	0.163	0.043			
		≤ 30	2	0.120	0.0			
	PM	76-87	3	0.703	0.067	$\alpha = 0.0559e^{0.0287z}$	0.9800	5.62%
		61-75	4	0.335	0.078			
		46-60	3	0.230	0.04			
		31-45	7	0.179	0.028			
		≤ 30	2	0.130	0.0			

measured and not the direct beam above. Stewart (1971) has estimated the maximum effect of these errors and found that for a solar zenith angle of 80° , the error in the albedo lies between $+0.01$ and -0.003 , and for an angle of 30° between 0.000 and -0.001 . The non-linearity error probably produces an error of up to $+0.003$ in the albedo at the smallest zenith angles. A departure of 0.1° from the horizontal mounting of the solari-albedometer would produce an error of ± 0.002 in the albedo at a solar zenith angle of 80° , becoming negligible at smaller angles. A single measurement of the solarimeter emf by the digital voltmeter is accurate to $\pm 20 \mu V$ which is equivalent to $\pm 0.13 \text{ mW cm}^{-2}$ by our calibration. Half the error is systematic due to error in internal digital voltmeter and the other half random due to the uncertainty in the last figure of the readings. Only the random component introduces an

error into the measurement of albedo, and this component decreases as the number of measurements used to obtain mean radiation values increases. Since up to 120 measurements were used to obtain the mean for this analysis its random error was less than $\pm 0.01 \text{ mW cm}^{-2}$. Consequently, this produced an error in the albedo of ± 0.005 at low radiation levels and much less at higher radiation levels. The probable error in calculated albedo as a result of all these effects is ± 0.005 at a solar zenith angle of 80° decreasing to ± 0.001 at 30° . Part of the larger variation at high zenith angles is probably due to this error.

5. Results and discussions

The pertinent results of this experiment may be summarized as follows:

1) The albedo increases as the transmission coefficient increases.

2) The range in albedo decreases with increase in cloudiness.

3) During the forenoon period (AM) the correlation between average albedo and zenith angle was poor for overcast conditions, moderate for days with intermittent cloudiness, and very good for clear sky conditions. The correlation between the two factors was good for afternoon (PM) periods under all sky conditions.

4) The variation in average albedo values for each zenith angle class increases with decrease in cloudiness.

5) The forenoon values of albedo are lower than the afternoon values for similar zenith angles.

6) The variation in average albedo increases with zenith angle.

7) Irrigation increases albedo values over a potato crop in forenoon periods but has no significant effect on afternoon albedos.

Three aspects of these results are taken up in the ensuing discussion:

a. The role of cloud cover

The dependence of albedo on zenith angle is most marked on clear days, while on overcast days very little dependence is observed. The dependence increases with transmissivity as shown in Table 1. A cloud cover tends to mask the direct rays of the sun such that the sky replaces the sun as the effective radiating surface. Under such conditions, albedo response to solar altitude must be negligible. The smaller diurnal range in albedo experienced on overcast days is a consequence of the replacement of the sun by the sky as the effective radiator.

b. The diurnal asymmetry

It is to be expected, if a strong relationship exists between albedo and solar zenith angle, that the diurnal distribution of albedo should be symmetrical about noon. The observed lack of symmetry may be due to a number of factors. It has been shown by Davies and Buttimor (1969) that leaf wilting tends to increase albedo. "Wilting" is a feature prevalent in the afternoon over most crop surfaces due to loss of moisture. Thus, the compound effect of wilting and multiple reflection at low solar elevation (Nkemdirim, 1972b) may be responsible for the higher afternoon albedo values which cause the asymmetry. Similar results obtained for bare ground may also be explained in terms of moisture withdrawal, but the results of Coulson and Reynolds (1971) suggest that in order to explain such large differences, the soil would have to change from completely wet to completely dry from forenoon to afternoon. Such a change was not observed. In fact, soil moisture which was monitored over the

site twice a day (0800 and 1600) did not show such large differences. A third explanation could be based on the spectral quality of sunlight during the two periods. It would appear that the spectral quality of global radiation received at the surface in the afternoon period is substantially different from that received at forenoon period. This may be accounted for by increases in cloud density, airborne particulate and gaseous matter, and water vapor in the afternoon period. It may be that selective attenuation by these substances filters out those wavelengths most susceptible to ground absorption. Because albedo is reflectivity integrated over all wavelengths of radiation (in this case global radiation), the result of this process would be to increase the albedo in the afternoon period. Robertson (1966), in work conducted in Edmonton, found that decreasing solar elevation increased the proportion of red and far red energy in the solar beam and decreased the ultraviolet and blue energy in skylight. He also found that haze had the same effect as decreasing the solar elevation. Tollefson (1971) reported a marked increase in haze in Calgary and attributed this to atmospheric pollution and increasing mixing depth. Following these works, it would appear that while the larger albedo values observed at low solar elevation may be partly due to changes in spectral quality of the incident radiation, the compound effect of haze and spectral quality produce higher afternoon values.

c. Albedo and irrigation

The difference observed between forenoon and afternoon may be due to the fact that reduced evaporation in the forenoon enables water to linger over the leaves long enough for trends in albedo values to be noticeable, while rapid evaporation in the afternoon removes the intercepted water before it shows any noticeable effect on albedo.

6. Conclusion

It is evident from the analysis and results presented that the diurnal variation in albedo is not symmetrical about midday in spite of the observed symmetry in total global radiation. This diurnal variation should be taken into account in energy budget studies if valid estimates of net radiation from global radiation are to be made.

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