Article

The importance of correct albedo determination for adequately modeling energy received by tilted surfaces

INEICHEN, Pierre, PEREZ, R, SEALS, R

Abstract

The aim of this work is to demonstrate the importance of correct estimation of the radiation reflected by the ground and perceived on a tilted surface. A good evaluation of the reflected radiation is an essential complement to any diffuse radiation and daylight transposition model.

Reference

INEICHEN, Pierre, PEREZ, R, SEALS, R. The importance of correct albedo determination for adequately modeling energy received by tilted surfaces. *Solar Energy*, 1987, vol. 39, no. 4, p. 301-305

DOI : 10.1016/S0038-092X(87)80016-6

Solar Energy Vol. 39, No. 4, pp. 301–305, 1987
Printed in the U.S.A.

0038-092X/87 $3.00 + .00

THE IMPORTANCE OF CORRECT ALBEDO DETERMINATION FOR ADEQUATELY MODELING ENERGY RECEIVED BY TILTED SURFACES

PIERRE INEICHEN
University of Geneva, Group of Applied Physics, Geneva, Switzerland

RICHARD PEREZ and ROBERT SEALS
State University of New York at Albany, Atmospheric Science Research Center, Albany, NY, U.S.A.

Abstract—The aim of this work is to demonstrate the importance of correct estimation of the radiation reflected by the ground and perceived on a tilted surface. A good evaluation of the reflected radiation is an essential complement to any diffuse radiation and daylight transposition model.
Résumé—Le but de ce travail est de montrer l'importance de la détermination correcte du coefficient d'albédo lors de l'utilisation et de la validation de modèles de transposition du rayonnement diffus et de l'éclairage naturel, d'un plan horizontal sur un plan incliné.

1. INTRODUCTION

A proper knowledge of the incident radiation is essential for effective use of solar radiation for heat production, electricity generation or daylighting. While more and more is known about horizontally received radiation, the same is not true of radiation or natural daylight reaching an inclined plane. Several models for the transposition of the diffuse radiation from a horizontal plane to a directional and inclined plane have been developed in various countries based on various databanks[1–6]. The critical point for these models lies in validation using radiation measurements made in other climates and different geographical conditions. The aim of this work is to demonstrate the importance of the radiation reflected by the ground and received by the inclined plane, to assess the effect of the close and distant horizon in estimating this radiation and therefore, to point out the error which may be caused by an over- or underestimation of the albedo.

2. MEASUREMENTS

A *one-year measurement program* is now being conducted in Geneva by the Group of Applied Physics of the University of Geneva to supplement the previous four years of measurements[4]. The measurements are made on a University building in the City of Geneva and concern the global and diffuse radiation on a horizontal plane, the global radiation on the north, south, east and west vertical planes and the global radiation on three south-facing planes inclined at 30°, 45° and 60°. All the measurement planes are fitted with artificial horizons preventing the radiation reflected by the ground from reaching the measuring cell. The reflected radiation is measured by other instruments on the same planes. The direct radiation is measured by a normal incident pyrheliometer (Eppley NIP) to make it possible precisely to determine the diffuse radiation on all the planes. All the measuring instruments are Kipp & Zonen CM 11 thermopile pyranometers. Recorded data are six-minute averages. Some other daylight parameters are also measured and will be analyzed in a further work. The results given here are preliminary ones based on the first three-month period covering May, June and July, 1986.

3. METHODS OF COMPARISON

The data available for demonstrating the importance of a correct estimate of the albedo coefficient are the diffuse radiation measured on various planes with an artificial horizon (a black horizontal plane masking the radiation reflected by the ground) and that measured on a full hemisphere viewed by the inclined plane (diffuse radiation from the sky and radiation reflected by the ground). Various assumptions have been used to obtain the graphs and tables below. In every case, a "calculated" reflected diffuse radiation (the product of the albedo coefficient and the global radiation measured on a horizontal plane, weighted by the solid angle seen by the inclined plane) has been subtracted from the diffuse hemispherical radiation measured. The result is a "calculated" diffuse celestial radiation which is then compared to the "measured" value.

The following assumptions were made:

(a) The albedo coefficient is 0.2 (Liu and Jordan assumption), a figure which is widely accepted and used in most applications where measurements are lacking.

(b) The use of a single albedo coefficient for all the planes, obtained by measuring the radiation reflected by the ground under a horizontal plane; the coefficient is an average one for the entire three-month measuring period.

(c) The same coefficient as above but averaged over a day period.

(d) A differentiated albedo coefficient for each direction (N, E, S and W) obtained by the measurement of the radiation reflected on the four vertical planes and averaged over the entire three-month measuring period.

(e) The same coefficients as above, but averaged over a day period.

(f) Differentiated albedo coefficients over N, E, S and W planes and for the two half-days (one for the morning and one for the afternoon), making eight different coefficients; they are averaged over the three-month measuring period.

Figures 1(a) to 1(f) show the average relative bias (calculated-measured, in [%]) arising during the assessment of the diffuse radiation from the sky for each of the above assumptions and plotted against the measured diffuse celestial radiation (expressed in hourly figures [Wh/m^{2}h]). Each point is surrounded by plus/minus one relative root mean square deviation (RRMS). The histogram of the fre-

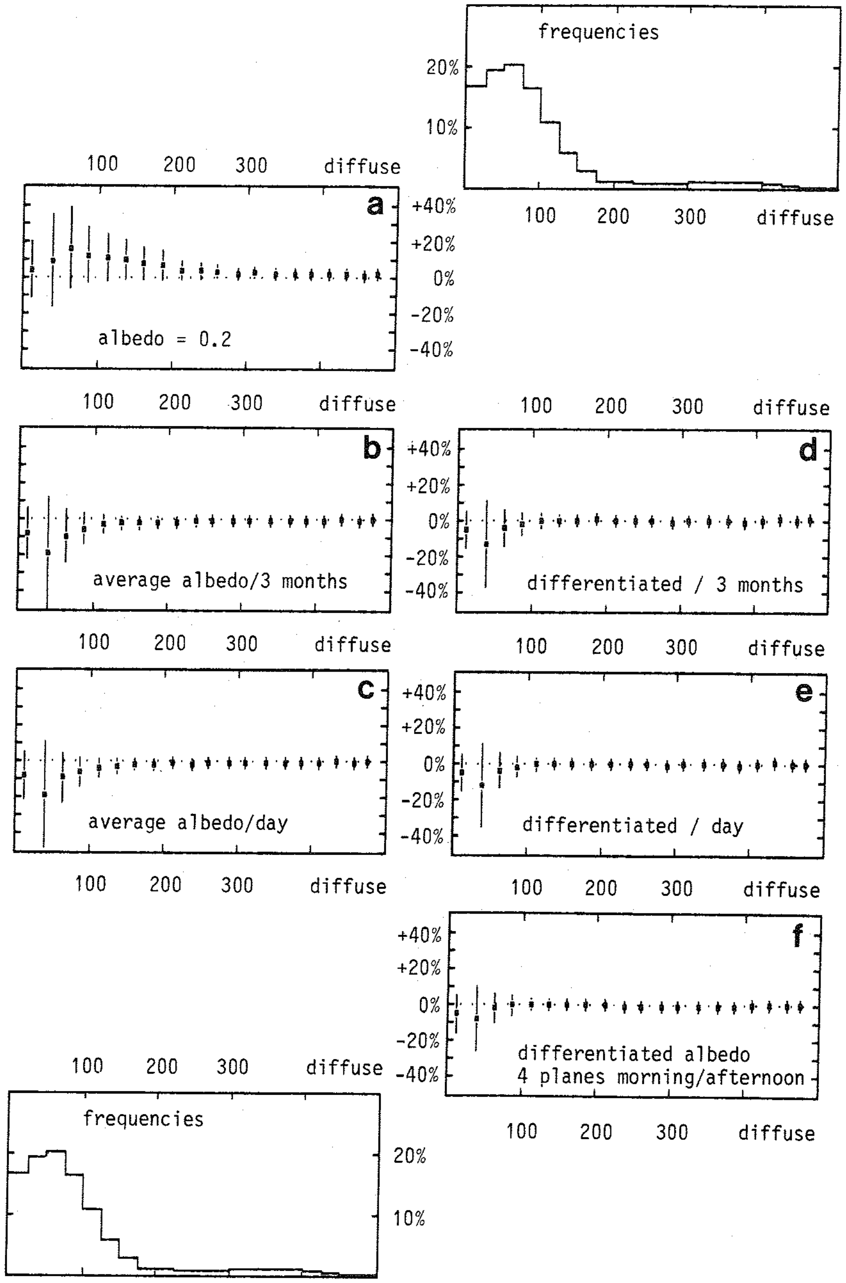

Fig. 1. Average relative bias arising during the evaluation of the diffuse radiation for the described albedo assumptions (see text) plotted against the measured diffuse celestial radiation [Wh/m^{2}h].

Table 1. Average albedo coefficients over the three-month period of measurement

Albedo	horizontal	North	East	South	West
horizontal	0.134				
differentiated		0.147	0.155	0.138	0.148
morning		0.139	0.143	0.143	0.157
afternoon		0.160	0.172	0.131	0.135

quencies for each diffuse radiation section is also given and shows for which diffuse radiation the precise estimation of the albedo coefficient is important.

The use of an albedo coefficient of 0.2 should be completely abandoned (Fig. 1(a)). Here, the reflected radiation is very clearly overestimated throughout the diffuse radiation range where a large proportion of the observed cases lies. For diffuse radiation ranging between 70 and 100 [Wh/m^{2}h] (corresponding to the peak of the observations distribution), the overestimate reaches 20%, and the RRMS deviation may reach 40%.

When using an average albedo coefficient measured on a horizontal plane (Fig. 1(b)), the diffuse radiation is underestimated by 10% for a diffuse radiationof 70–100 [Wh/m^{2}h], with an RRMS deviation which may reach 25%. The improvement over case 1(a) is considerable for the 50–250 [Wh/m^{2}h] radiation range, despite the fact that the bias between measurement and calculation has changed sign.

When the albedo coefficients are differentiated by planes for the four main directions (N, E, S and W), the underestimate of the radiation is reduced to about 3% for the same radiation range as above. Here, the RRMS deviation may reach 15% (cf. Fig. 1(d) and 1(e)).

For the Geneva horizon, nearby buildings and light-coloured mountainous cliffs lie south-eastwards of the measuring station and considerably affect the radiation reflected during the second half of the day. An additional morning/afternoon differentiation makes it possible to quantify this effect and reduce the bias to about 1% and the RRMS deviation to under 10% (Fig. 1(f)).

Table 1 gives the average albedo coefficients described above obtained over the three-month period

Table 2. Relative mean bias error and relative root mean square deviation resulting from the evaluation of the diffuse radiation with the four models described in the Appendix

	Albedo	30°	45°	60°	North	East	South	West	
Isotrope model	Art.	10.9	12.7	15.0	56.7	53.2	15.3	51.5	RRMS
	hor.	−5.6	−6.3	−6.0	+35.2	−3.0	+1.3	+7.9	RMBE
	0.2	9.7	9.2	11.4	78.1	58.8	23.6	63.2	RRMS
		−4.5	−2.9	0.0	+53.8	+4.6	+17.0	+18.4	RMBE
	NESW	10.6	11.8	13.5	55.9	52.0	14.7	53.5	RRMS
	diff.	−5.6	−5.7	−4.8	+34.3	−4.2	+1.2	+7.0	RMBE
Perez model	Art.	5.4	4.8	7.2	15.2	13.9	8.9	15.4	RRMS
	hor.	0.0	+0.3	0.0	−2.5	+1.1	−1.6	+1.5	RMBE
	0.2	5.4	6.3	10.3	22.7	17.8	20.9	24.8	RRMS
		+0.7	+2.9	+5.2	+12.0	+9.5	+12.1	+13.8	RMBE
	NESW	5.1	5.0	7.8	16.1	15.7	11.6	17.8	RRMS
	diff.	−0.1	+1.2	+1.2	−2.8	−0.2	−1.6	+1.1	RMBE
Hay model	Art.	7.5	8.4	11.7	38.7	32.0	19.8	33.5	RRMS
	hor.	−3.4	−4.1	−5.2	+2.9	−6.3	−6.8	−3.4	RMBE
	0.2	6.8	6.8	10.0	49.4	33.5	22.4	39.3	RRMS
		−2.6	−1.2	+0.3	+20.3	+2.7	+7.6	+9.5	RMBE
	NESW	7.2	7.9	11.0	39.2	32.3	20.5	34.8	RRMS
	diff.	−3.4	−3.6	−4.0	+2.4	−7.5	−6.8	−3.9	RMBE
Klücher model	Art.	7.5	7.7	10.8	85.2	53.3	27.2	59.0	RRMS
	hor.	+1.7	+2.0	+4.6	+61.6	+22.0	+22.2	+32.8	RMBE
	0.2	7.5	8.5	14.5	110.7	63.4	47.8	74.8	RRMS
		+2.8	+5.4	+10.7	+83.3	+31.4	+40.0	+45.4	RMBE
	NESW	7.2	7.3	11.0	84.3	52.0	27.9	60.0	RRMS
	diff.	+1.6	+2.6	+5.9	+60.8	+20.4	+22.1	+32.0	RMBE

of measurements. It is interesting to note that the albedo recorded with the instrument facing downward is smaller than the mean of that recorded vertically in four azimuthal directions. This indicates that the ground is indeed less reflective in the immediate vicinity of the site (roof top) than away from it.

4. APPLICABILITY OF THE TRANSPOSITION MODELS

We validated four diffuse radiation transposition models (models to evaluate the diffuse radiation reaching any tilted surface using horizontal global and diffuse radiation measurements) on the Geneva data taking account of the assumption set out above. The models are the isotropic and those of Perez[2, 3], Hay[1] and Klücher[6]. They are described in the Appendix. The indicators used are the relative mean bias error (model-measurement deviation normalized on the measurement: RMBE) representing the systematic deviation resulting on the application of the model and the relative root mean square deviation (RRMS) describing the short-term fluctuation around the average bias.

A look at Table 2 gives rise to the following remarks:

- For the isotropic model, the relatively considerable deviations on all the planes are only slightly affected by the various albedo coefficients.
- Perez's model, which separately parametrises the circumsolar diffuse radiation and the horizon effect, is highly sensitive to the quality of the measurements on which it is validated; the RRMS deviation on certain planes may be doubled by using an albedo coefficient of 0.2 (south plane).
- For Hay's model, the anisotropy of the diffuse radiation is described by only one single parameter: the circumsolar radiation; the result is that the model's underestimate for most of the planes is offset by an overestimate of the reflected radiation, and, therefore, the model is in this case not affected by an overestimate of the albedo; matters would probably be different if the albedo were underestimated.
- Klücher's model, which can be used only on southwardly directed planes, despite the high bias and RRMS deviation figures, gives some of these values doubled depending on the albedo coefficient used.

These Tables show that extreme prudence is required in the validation of models for calculating radiation or natural daylight depending on the method of measurement used in drawing up the databanks used (measurement of direct or diffuse radiation, measurement with or without an artificial horizon, measurement or not of reflected radiation). The conclusions which may be drawn from a validation of two types of data may be diametrically opposed.

5. CONCLUSIONS

These preliminary results based on a three-month measurement period in Geneva demonstrate some important points for the measurement of diffuse radiation on inclined planes and for the use of diffuse radiation measurements to validate models:

- The use of a figure of 0.2 for the albedo coefficient is unrealistic in a geographical situation such as Geneva (light-coloured buildings, trees and mountains on the near horizon); it is too high.
- The effect of the near horizon is highly important with an urban horizon for modeling natural daylight. Here, it is essential to know the local albedo coefficient.
- The variation in the albedo coefficient seems not to be very sensitive to the weather conditions over this three-month period of measurement (which included a wide variety; bright skies, cloudy skies, mist, stormy days and very heavy clouds).
- The advantage obtainable from the use of an anisotropic ground radiation reflection model (e.g.[7, 8]) seems very small.
- It is easy to measure an albedo coefficient, whether differentiated or not, on a given site; it requires no long period of measurement, it is necessary and could be adequate to determine the radiation and available daylight. A differentiated albedo coefficient for the four main planes is preferable.
- A databank where the measurements have been made with an artificial horizon (and a measurement of the direct radiation) is essential for validating diffuse radiation transposition models. Otherwise, an increase in the model's inherent error by a factor of two may be expected.

Acknowledgement—This work is financially supported by the Ernst and Lucie Schmidheiny Foundation, the Société Académique de Genève and Geneva's Department of Public Economy. It is made in collaboration with research projects conducted in the United States and sponsored by the Sandia National Laboratories and the New York State Energy Research and Development Authority (NYSERDA).

REFERENCES

1. J. F. Hay, Calculation of the solar radiation incident on a inclined surface. *Proceedings, 1st Canadian Solar Radiation Data Workshop,* April 17–19, Toronto, Canada (1978).
2. R. Perez, R. Stewart, C. Arbogast, R. Seals and J. Scott, An anisotropic hourly diffuse radiation model for sloping surfaces: description, performance validation, site dependency evaluation. *Solar Energy* **36,** 481 (1986).
3. R. Perez, Performance improvement and structural simplification of Perez diffuse irradiance model. Sandia National Laboratories Intermediate Report #2, contract #56-5434. SNL, Albuquerque, NM (1986).
4. P. Ineichen, Quatre années de mesures d'ensoleillement à Genève. Printed by Group of Applied Physics, University of Geneva, Switzerland (1983).
5. O. Guisan, P. Ineichen and A. Razafindraibe, Solar ra-

diation in Geneva: validated models and correlations. *Proceedings, Ninth Biennal Congress of the ISES,* pp. 2483–2487, 23–29 June, Montreal, Canada (1985).
6. T. M. Klücher, Evaluation of models to predict insolation on tilted surfaces. *Solar Energy* **23,** 111 (1979).
7. R. C. Temps and K. L. Coulson, Solar radiation incident upon slopes of different orientations. *Solar Energy* **19,** 179 (1977).
8. C. Gueymard, Radiation on tilted planes: a physical model adaptable to any computational time-step. *Proceedings, Ninth Biennal Congress of the ISES,* pp. 2463–2467, 23–29 June, Montreal, Canada (1985).

APPENDIX: MODEL'S DESCRIPTION

- Isotropic model:

$$D_c = D_h\{0.5(1 + \cos i)\},$$

where i = tilt angle of the plane.

- Perez's model:

$$D_c = D_h \cdot \{0.5(1 + \cos i)(1 - f1) + (a/c)f1 + f2 \sin i\},$$

where

$f1$ = circumsolar diffuse fraction;
$f2$ = horizon diffuse fraction;
a/c = geometrical incidence factor for the circumsolar radiation, normalized to the horizontal plane.

- Hay's model:

$$D_c = D_h\{K(\sin h_i/\sin h + 0.5(1 - K)(1 + \cos i)\}$$

where

K = clearness index for the direct (= B_n/I_o);
h = solar elevation angle;
h_i = solar incidence angle on the tilted plane.

- Klücher's model:

$$D_c = D_h \cdot \{0.5(1 + \cos i)\}[1 + F \sin^3(i/2)] \cdot [1 + F \sin^2 h_i \cos^3 h],$$

where $F = 1 - (D_h/G_h)^2$.

- Radiation reflected by the ground:

$$D_{ir} = \alpha G_h\{0.5(1 - \cos i)\},$$

where

D_{ir} = diffuse radiation reflected by the ground and perceived by the inclined surface;
α = differentiated or not albedo coefficient.