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A TWO-PARAMETER DESCRIPTION OF THE SKY HEMISPHERE

Richard Perez
Ronald Stewart
Jon T. Scott

Atmospheric Sciences Research Center
State University of New York at Albany
1400 Washington Avenue
Albany, New York 12222

1. INTRODUCTION

The isotropic assumption for diffuse radiation has been observed to generate non-negligible errors in the computation of energy received by inclined surfaces (Stewart, 1980; Hay, 1978). Several studies have been undertaken in the last few years in order to account for the directionality of diffuse radiation (e.g., Robinson, 1966; Temps, 1977). Most authors have used only one parameter to describe the degree of directional scattering occurring in the atmosphere. This parameter is generallly an expression of the amount of direct radiation received at the earth surface (e.g., Hay, 1978; Klucher, 1978).

The present paper shows the importance of a secondary parameter, describing the brightness of the sky dome for the characterization of a given solar event and the determination of the degree of diffuse radiation directionality. This determination is performed by describing the sky radiance as constant throughout the dome, except for two zones (circumsolar region and horizon), where radiance can be enhanced.

2. METHODS

One minute solar events in Albany, NY, described by global and direct radiation records (SEMRTS-II, 1980), are classified for five categories of solar incidence angle (θh), according to two parameters: (1) Dh, defined as diffuse radiation received by the horizontal, and (2) ε, defined as the sum of direct radiation and Dh divided by Dh. Table 1 illustrates the Dh and ε intervals selected for this study. The five categories of solar incidence angle are: (1) $\theta h < 35^o$; (2) $35^o < \theta h < 45^o$; (3) $45^o < \theta h < 55^o$; (4) $55^o < \theta h < 65^o$ and (5) $\theta h > 65^o$. Thus a total of 210 possible sky descriptions is generated.

Five one minute events are analyzed for each hour of the months of February 1980, April 1980 and June 1980. In order to determine the degree and the type of directional scattering occurring in the atmosphere, a framework is developed to describe the sky dome. This is shown in Figure 1, where L, F1 x L and F2 x L are the radiances originating respectively from the main portion of the dome, the circumsolar region and near the horizon. Such a configuration was decided upon in order to account for the two main zones of anisotropy observed in the atmosphere (Temps, 1977).

Table 1. Description of Dh and ε categories.

Dh (KJ/mn) interval #	lower bound	upper bound	ε interval #	lower bound	upper bound
I	0	3	1	1	1.003
II	3	6	2	1.003	1.03
III	6	10	3	1.03	1.1
IV	10	15	4	1.1	1.5
V	15	20	5	1.5	2.5
VI	20		6	2.5	5
			7	5	

From simple geometrical considerations, it is possible to express the amount of diffuse radiation, Dc, received by a sloping plane, as a function of this value on the horizontal (Perez, 1983).

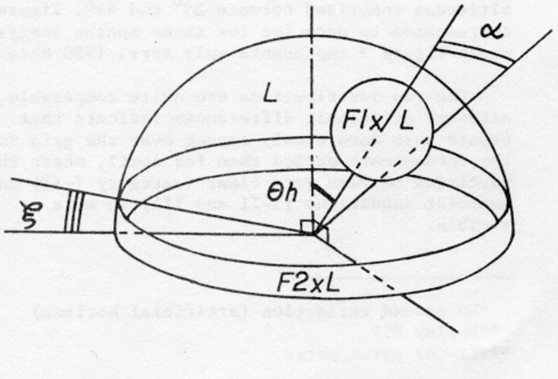

Fig. 1. Description of the sky hemisphere used for the analysis.

This is given by,

$$Dc = Dh \times \left\{ \frac{(1 + \cos s)/2 + 2(1 - \cos \alpha)(F1 - 1)\ Zc + \ldots}{1 + 2(1 - \cos \alpha)(F1 - 1)\ Zh + \ldots} \cdots \frac{2\ \xi\ \sin \xi'\ (F2 - 1)/\pi}{(1 - \cos 2\xi)(F2 - 1)/2} \right\}, \quad (1)$$

where s is the tilting plane's slope, α is the half angle sustended by the circular solar region, ξ is the angular thickness of the horizon zone, ξ' is the altitude of its apex with respect to the sloping plane, and Zc and Zh are respectively the fractions of circumsolar region seen by the sloping plane and the horizontal. Values of 15^o and 6.5^o are assumed for α and ξ respectively. F1 and F2 are the two radiance enhancement terms within the circumsolar and the horizon region respectively.

The values of radiance within the two zones are established statistically from the analysis of the total radiation* recorded by seven tilting pyranometers for each considered solar event. These are (1) 33^o tilt south facing**, (2) 43^o tilt south facing**, (3) 53^o tilt south facing**, (4) vertical south facing***, (5) vertical east facing***, (6) vertical west facing***, and (7) vertical north facing*** pyranometers.

Diffuse radiation recorded on the horizontal and the sloping surfaces is obtained by removing the direct component from the global measurements. All radiation comprised within the pyrheliometer field of new (5.7^o aperture) is treated as direct radiation.

For each event, a least square fitting of data on the seven tilting captors is performed by allowing F1 and F2 to vary respectively from 1 to 50 and from 1 to 35 in equation (1). Averages of these two terms are computed for each one of the sky descriptions presented above. These averages are subjected to a final screening procedure described by Perez (1983) in order to obtain the values presented hereafter.

3. RESULTS

As an example of the observed distributions, Figures 2 and 3 illustrate the number of events recorded in each Dh and ε interval for solar altitudes comprised between 35^o and 45^o. Figure 2 corresponds to data for the three months analyzed, while Figure 3 represents only April 1980 data.

The two distributions are quite comparable, although noticeable differences indicate that events were more evenly spread over the grid for the three-month period than for April, where the partition between very clear (category 7-II) and overcast conditions (1-II and III) is more visible.

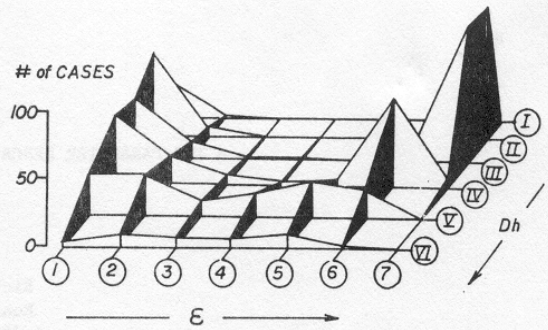

Fig. 2. Number of events analyzed in each (Dh, ε) interval, for $\theta h \in [45^o, 55^o]$ - 3 month survey.

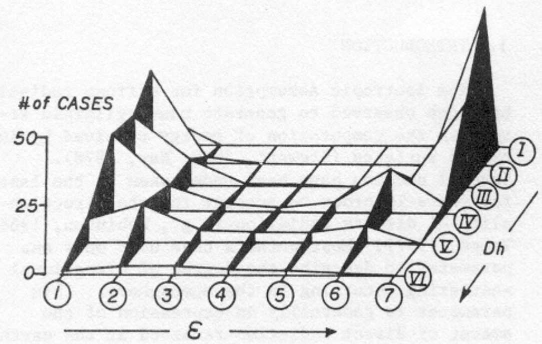

Fig. 3. Number of events analyzed in each (Dh, ε) interval, for $\theta h \in [45^o, 55^o]$ - April 1980.

On both figures, the marked peaks for the highest ε categories reveal the existence of an apparent one to one relationship between the two parameters (i.e., between the direct and diffuse components). This observation confirms that in first approximation, the sole knowledge of global radiation at the earth surface is sufficient to describe a given sky condition. On the other hand for intermediate and lower values of direct solar income, both parameters are necessary to characterize a given event.

However, the role played by the secondary parameter, Dh, becomes more apparent when one looks at Figures 4 (3-month period), and 5 (April 1980). They illustrate the values of F1 and F2 found in each (Dh, ε) interval described by more than three events for the same range of solar altitudes as above.

It is very clear, for low and intermediate solar income, that the description of the sky hemisphere is strongly influenced by the total brightness of the atmosphere. For very luminous sky conditions, the main zone of anisotropy is located around the sun's position, even when there is little or no direct solar income. The horizon brightening becomes intense for very clear skies

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*No ground reflection (artificial horizon)
**Eppley PSP
***Li-Cor pyranometer

(e.g., category 7-II). This character is also exhibited, to a lesser extent in the case of intermediate direct income for less luminous atmospheres (e.g., categories 3-IV, 4-IV and 5-IV). These events are thought to be representative of particular occurrences during variable sky conditions. Indeed, when hourly integrated data are used instead of one minute data, the frequency of these events is found to be different and both F1 and F2 are found to be smaller. This suggests that hourly events belonging to these (Dh, ε) categories are in fact a combination of instances belonging to other categories, and that pertinent information is lost in the process.

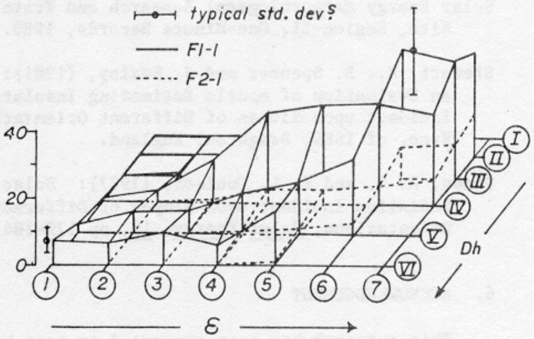

Fig. 4. Value of enhancement terms F1 and F2 found in each (Dh, ε) interval for θh ∈ [45°, 55°] - 3 month survey.

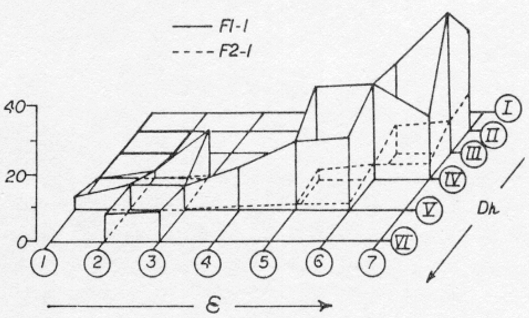

Fig. 5. Value of enhancement terms F1 and F2 found in each (Dh, ε) interval for θh ∈ [45°, 55°] - April 1980.

The similarity between values obtained for the one-month and the three-month period expresses the validity of the proposed sky description since events belonging to identical categories exhibit comparable features. The results are qualitatively consistent with observations (Coulson, 1975), since horizon brightening is found to be maximum for very clear skies (Rayleigh atmosphere), whereas forward scattering is found to dominate for very luminous (turbid) atmospheres.

Of course, the enhancement values F1 and F2 are not to be considered as representing a faithful image of the sky dome. This distorted image is a direct result of the rigid framework shown on Figure 1. However, tests have proven (Perez, 1983) that on a real time as well as on an integrated basis, such a representation explains most recorded insolation values on any one of the 7 tilting captors.

In order to illustrate this last point, Tables II, III and IV show the results of tests performed against February, April and June data. Insolation values obtained using equation (1) and the same F1 and F2 for the three months, are compared to results obtained using the classical isotropic model. The data shown in these tables include the average global radiation, G, and average diffuse radiation, D, recorded by each sensor, the average absolute errors generated by the isotropic model and equation (1), respectively ΔD_1 and ΔD_2, and the accumulated errors generated by both models, respectively δG_1 and δG_2.

Table 2. Results of the test against February 1980 data.

Captor	G dJ/mn	D dJ/mn	ΔD_1 dJ/mn	ΔD_2 dJ/mn	δG_1 %	δG_2 %
south s = 33°	2563	917	203	75	- 7.5	0.9
south s = 43°	2676	918	252	86	- 8.8	1.0
south s = 53°	2716	897	284	100	- 9.6	1.3
north vertical	317	317	101	51	24.3	10.1
east vertical	987	491	173	75	- 9.8	-1.9
south vertical	2269	703	319	103	-13.6	0.8
west vertical	968	455	159	71	- 6.3	0.6

The average standard error for 7 captors in February 1980 is,
(a) 250 dJ/mn, using the isotropic model and,
(b) 96 dJ/mn, using equation (1).

Table 3. Results of the test against April 1980 data.

Captor	G dJ/mn	D dJ/mn	ΔD_1 dJ/mn	ΔD_2 dJ/mn	δG_1 dJ/mn	δG_2 dJ/mn
south s = 33°	2219	846	107	57	- 4.1	0
south s = 43°	2162	826	134	54	- 5.3	-0.3
south s = 53°	2008	746	139	59	- 4.3	1.5
north vertical	343	334	103	45	22	6.7
east vertical	961	460	167	72	- 5.1	0.1
south vertical	1132	448	96	77	- 3.3	4.7
west vertical	990	468	184	85	- 5.6	0.5

The average standard error for the 7 captors in April 1980 is,
(a) 169 dJ/mn, using the isotropic model, and
(b) 80 dJ/mn, using equation (1).

Table 4. Results of the test against June 1980 data.

Captor	G dJ/mn	D dJ/mn	ΔD_1 dJ/mn	ΔD_2 dJ/mn	δG_1 %	δG_2 %
south s = 33°	2305	1036	93	45	-3.2	-0.8
south s = 43°	2149	993	113	56	-4.1	-1.3
south s = 53°	1899	884	100	57	-2.4	0.6
north vertical	548	447	146	52	13	0.2
east vertical	1246	602	234	83	-6.3	-1.7
south vertical	848	535	75	59	-1.4	-1.5
west vertical	1078	602	235	102	-7.3	-2.2

The average standard error for the seven captors in June 1980 is,
(a) 193 dJ/mn, using the isotropic model and,
(b) 81 dJ/mn, using equation (1).

In the quasi totality of the cases, the use of equation (1) results in substantial improvements over the isotropic assumption at both the accumulated and the random error level.

4. CONCLUSION

The main conclusion of this paper is that quality measurements of global and diffuse or direct radiation at the earth surface do provide information which allows for the delineation of specific sky conditions in most instances. The consistency of the pattern between Figure 4 and 5 and the tests' results show that the main features of directional scattering in the atmosphere can be expressed with such measurements. The additional information brought by the second parameter, especially for low values of direct solar income, offers interest on a meteorological as well as on an engineering point of view.

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6. ACKNOWLEDGEMENT

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