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Study of ground-reflected component and its contribution in diffuse solar radiation incident on inclined surfaces over India

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Abstract
To define the diffuse radiation incident on an inclined plane of any orientation and of any tilt angle, we need to know sky diffuse radiation as well as ground-reflected radiation. Here we made a study of ground-reflected component of radiation on inclined surfaces with varying inclination angles for Lucknow (Latitude 26.75^0, Longitude 80.85^0), Mumbai (Latitude 19.12^0 N, Longitude 72.85^0 E), Calcutta (Latitude 22.65^0 N, Longitude 88.35^0 E), and Pune (Latitude 18.53^0 N, Longitude 73.91^0 E) cities of India using isotropic and anisotropic models. We have calculated the data for entire year using these models for all considered stations and obtained the percentage contributions in diffuse radiations. It is found that anisotropic model predict lower values than isotropic and contribution of ground-reflected component in diffuse radiation for isotropic model is more than anisotropic.
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Keywords: Isotropic, Anisotropic, Ground-reflected, Zenith angle, Diffuse radiation.

1. Introduction

The computation of the ground- reflected radiation (albedo) is very important in evaluating the total insolation on a building or on a solar energy collecting device. It is also important in studies dealing with thermal balance in the atmosphere [1]. Though there are many worldwide solar radiation measuring stations, only few of them measure solar radiation components on tilted surfaces and even fewer the reflected component from the ground. Therefore, it is common practice to develop new or use existing algorithms that compute the solar irradiance on tilted surfaces accurately for various applications.

In the last fifteens years, several models have been developed for the transposition of the diffuse radiation from a horizontal surface to an inclined one for arbitrary orientation [2-3]. Most of these models have been tested against measurements in different countries [4-7].

The computation of the ground-reflected radiation plays an important role in estimating solar radiation on an inclined surface. Therefore, some investigators [8-10] have developed an albedo expression as a function of the solar zenith angle, sun-surface geometry, latitude dependent etc. In general, the majority of the models provide acceptable accuracy, although in some cases local weather phenomena and prevailing atmospheric conditions may favour the development of new models or modification of the existing ones.

Our objective of the present study is to analyze the behaviour of isotropic and anisotropic models for predicting ground-reflected radiation data and observe the contribution of ground-reflected component in diffuse radiation on inclined surfaces with different angle of inclination. This study has been made using these two models for four prominent locations of India viz. Lucknow (Latitude 26.75^0, Longitude 80.85^0), Mumbai (Latitude 19.12^0 N, Longitude72.85^0 E), Calcutta (Latitude 22.65^0 N, Longitude 88.35^0 E), and Pune (Latitude 18.53^0 N, Longitude 73.91^0 E).

2. Estimation methodology

For estimation of ground-reflected radiation, we consider two particular cases: (1) perfectively diffuse reflection, called isotropic reflection; and (2) imperfectly diffuse reflection, called anisotropic reflection.

2.1 Isotropic reflection

The daily amount of ground-reflected radiation incident on an inclined plane can be obtained using following relation [1]:

$$H_r = \tfrac{1}{2} H\rho(1-\cos\beta) \tag{1}$$

where H, ρ and β are the monthly mean daily total radiation on horizontal surface, albedo and tilt angle respectively.

2.2 Anisotropic reflection

Under the clean and cloudless skies, global radiation is composed primarily of direct radiation. When the ground is covered with a layer of water or with plants having glossy leaves, the reflection of such radiation is usually anisotropic. Temps and coulson [11] recommended that under these conditions for estimating the anisotropic hourly ground-reflected radiation, the isotropic radiation $I_r = \tfrac{1}{2} I\rho(1-\cos\beta)$ should be multiplied with the following factor:

$$[1+\sin^2(\theta_z/2)](|\cos\Delta|) \tag{2}$$

where Δ is the azimuth of the tilted surface with respect to that of the sun; this angle reduces to ω for surface tilted toward the equator. θ_z is the solar zenith angle (deg.). Consequently, the anisotropic hourly ground-reflected radiation incident on an inclined surface under clear skies can be estimated with following relation [1]:

$$I_r = \tfrac{1}{2} I\rho(1-\cos\beta)[1+\sin^2(\theta_z/2)](|\cos\Delta|) \tag{3}$$

Since daily amount of ground-reflected radiation incident on an inclined surface can not be expressed in terms of the daily horizontal global radiation, therefore it is expressed in terms of hourly ground-reflected radiation as follows.

$$H_r = \sum^{day}[\tfrac{1}{2} I\rho(1-\cos\beta)[1+\sin^2(\theta_z/2)](|\cos\Delta|)] \tag{4}$$

To define the reflective properties of the bare ground ρ, an average value of 0.2 is used for calculation.

3. Results and discussion

Keeping in mind the variation in slope and different seasonal and atmospheric conditions, the study is made for entire year at four different locations (Lucknow, Mumbai, Calcutta and Pune) of India. We have calculated the ground-reflected radiation with isotropic and anisotropic models using eqs.(1) and (4) respectively on inclined surface with inclination angle varying from 15º to 60º. The station wise variation of ground-reflected data with inclination angles are shown through tables 1 to 4. It is observed from the tables that ground-reflected radiation increases with the increase of inclination angles i.e. increasing slope of surfaces for both the isotropic and anisotropic models. However, the ground-reflected radiation increases from winter to summer (January to June months) and then decreases from summer to winter (June to December) with isotropic model at all inclination angles for all stations, while reverse is observed with anisotropic model. Further anisotropic model predicts lower ground-reflected radiation than isotropic. It may be because of the fact that anisotropic model developed for clear sky conditions. The maximum values with isotropic model for May at 60º inclination angle are 320.46, 280.55, 347.63 and 358.60 Wh. m^{-2}. day^{-1} respectively for Lucknow, Mumbai, Calcutta and Pune stations. We have also calculated the diffuse radiation on tilted surfaces from measured data of horizontal surface and then evaluated percentage contribution of ground-reflected radiation in diffuse radiation for above both models for all inclination angles and shown through Tables 1 to 4.

Table 1. The ground reflected radiation (Wh. m $^{-2}$. day $^{-1}$) using isotropic and anisotropic model and its contribution (in percentage) in diffuse solar radiation at different slopes for Lucknow, India.

Month	Reflected component								% reflected component in Diffuse radiation				% reflected component in Diffuse radiation			
	Isotropic				Anisotropic				Using Isotropic				Using Anisotropic			
	15 ^{0}	30 ^{0}	45 ^{0}	60 ^{0}	15 ^{0}	30 ^{0}	45 ^{0}	60 ^{0}	15 ^{0}	30 ^{0}	45 ^{0}	60 ^{0}	15 ^{0}	30 ^{0}	45 ^{0}	60 ^{0}
JAN	13.58	53.51	116.99	199.65	13.51	53.25	116.43	198.69	0.884	3.101	6.205	10.26	0.879	3.086	6.175	10.211
FEB	16.66	65.67	143.59	245.04	14.83	58.44	127.79	218.07	0.873	3.352	6.827	11.569	0.777	2.983	6.076	10.295
MAR	19.44	76.62	167.53	285.88	14.01	55.22	120.73	206.03	1.114	4.013	8.284	13.729	0.803	2.892	5.969	9.894
APR	20.92	82.46	180.31	307.7	11.11	43.78	95.72	163.34	0.964	3.756	8.04	13.359	0.511	1.994	4.268	7.091
MAY	21.79	85.88	187.79	320.46	7.21	28.39	62.09	105.97	0.937	3.491	7.754	13.676	0.31	1.154	2.564	4.522
JUN	24.13	95.1	207.95	354.87	10.31	40.59	88.76	151.46	0.921	3.639	7.972	14.021	0.393	1.553	3.402	5.984
JUL	23.23	91.54	200.16	341.56	7.51	29.56	64.62	110.28	0.819	3.221	6.691	12.58	0.264	1.04	2.16	4.061
AUG	20.84	82.13	179.58	306.45	9.23	36.37	79.52	135.69	0.737	2.922	6.503	11.544	0.326	1.294	2.879	5.111
SEP	20.39	80.37	175.73	299.88	13.22	52.12	113.96	194.47	0.939	3.449	6.821	11.162	0.609	2.236	4.423	7.239
OCT	16.84	66.36	145.09	247.6	14.08	55.49	121.33	207.05	0.879	3.226	6.719	10.989	0.735	2.697	5.619	9.189
NOV	12.53	49.39	107.99	184.29	12.18	48.02	104.99	179.18	0.724	2.683	5.591	9.44	0.704	2.609	5.436	9.178
DEC	11.75	46.26	101.16	172.62	12.13	47.8	104.52	178.37	0.753	2.688	5.544	8.986	0.778	2.778	5.728	9.285

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Table 2. The ground reflected radiation (Wh. m^{-2}. day^{-1}) using isotropic and anisotropic model and its contribution (in percentage) in diffuse solar radiation at different slopes for Calcutta, India.

Month	Reflected component								% reflected component in Diffuse radiation				% reflected component in Diffuse radiation			
	Isotropic				Anisotropic				Using Isotropic				Using Anisotropic			
	15^0	30^0	45^0	60^0	15^0	30^0	45^0	60^0	15^0	30^0	45^0	60^0	15^0	30^0	45^0	60^0
JAN	10.945	42.817	93.361	160.967	10.621	41.859	91.528	156.19	0.818	3.287	7.495	13.717	0.794	3.216	7.358	13.365
FEB	14.789	57.853	126.146	217.493	12.638	49.81	108.914	185.86	0.804	3.233	7.377	13.516	0.688	2.796	6.434	11.782
MAR	17.301	67.68	147.573	254.437	11.731	46.237	101.101	172.53	0.77	3.101	7.087	13.018	0.523	2.139	4.966	9.213
APR	18.378	71.891	156.756	270.27	8.103	31.937	69.833	119.17	0.662	2.675	6.149	11.392	0.293	1.206	2.836	5.365
MAY	19.077	74.625	162.718	280.547	4.783	18.852	41.223	70.346	0.615	2.487	5.73	10.656	0.154	0.64	1.516	2.904
JUN	14.94	58.444	127.435	219.716	4.282	16.878	36.907	62.981	0.537	2.177	5.038	9.429	0.154	0.638	1.513	2.897
JUL	14.572	57.004	124.293	214.299	3.507	13.822	30.224	51.577	0.516	2.096	4.856	9.104	0.124	0.516	1.226	2.353
AUG	13.892	54.343	118.493	204.299	4.891	19.276	42.149	71.927	0.502	2.039	4.728	8.874	0.177	0.733	1.734	3.314
SEP	13.571	53.087	115.755	199.577	8.195	32.301	70.629	120.53	0.549	2.227	5.151	9.63	0.332	1.367	3.207	6.046
OCT	11.843	46.327	101.013	174.161	9.601	37.84	82.741	141.2	0.669	2.7	6.205	11.489	0.543	2.216	5.14	9.522
NOV	13.363	52.274	113.982	196.522	12.657	49.885	109.078	186.14	0.863	3.47	7.893	14.394	0.817	3.317	7.579	13.738
DEC	11.54	45.144	98.436	169.717	11.63	45.838	100.229	171.04	0.822	3.305	7.533	13.782	0.828	3.354	7.66	13.875

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Table 3. The ground reflected radiation (Wh. m $^{-2}$. day $^{-1}$) using isotropic and anisotropic model and its contribution (in percentage) in diffuse solar radiation at different slopes for Mumbay, India.

Month	Reflected component								% reflected component in Diffuse radiation				% reflected component in Diffuse radiation			
	Isotropic				Anisotropic				Using Isotropic				Using Anisotropic			
	15^0	30^0	45^0	60^0	15^0	30^0	45^0	60^0	15^0	30^0	45^0	60^0	15^0	30^0	45^0	60^0
JAN	15.734	61.548	134.202	231.382	14.682	57.864	126.523	215.91	1.043	4.161	9.378	16.878	0.973	3.922	8.889	15.929
FEB	19.021	74.404	162.234	279.714	16.058	63.287	138.382	236.15	1.255	4.978	11.101	19.679	1.062	4.266	9.626	17.139
MAR	21.316	83.381	181.809	313.463	14.04	55.335	120.995	206.48	1.117	4.449	9.989	17.882	0.739	2.997	6.877	12.544
APR	23.044	90.142	196.55	338.879	8.582	33.822	73.954	126.2	1.111	4.426	9.941	17.804	0.417	1.708	3.988	7.464
MAY	23.639	92.469	201.625	347.629	6.26	24.673	53.948	92.062	1.041	4.155	9.365	16.857	0.278	1.144	2.69	5.096
JUN	16.527	64.651	140.968	243.049	7.352	28.975	63.355	108.11	0.621	2.51	5.781	10.746	0.277	1.141	2.684	5.083
JUL	13.042	51.019	111.244	191.8	5.235	20.633	45.115	76.988	0.494	2.005	4.651	8.734	0.199	0.821	1.94	3.699
AUG	13.911	54.418	118.655	204.578	3.96	15.607	34.126	58.235	0.484	1.964	4.558	8.567	0.138	0.571	1.355	2.598
SEP	14.506	56.745	123.73	213.327	8.403	33.117	72.412	123.57	0.555	2.248	5.197	9.712	0.322	1.324	3.108	5.865
OCT	17.453	68.271	148.863	256.66	13.628	53.71	117.441	200.41	0.836	3.359	7.649	13.981	0.654	2.661	6.134	11.262
NOV	15.498	60.624	132.188	227.91	16.314	64.298	140.592	239.92	1.042	4.159	9.374	16.872	1.096	4.4	9.911	17.605
DEC	13.713	53.642	116.963	201.661	15.397	60.681	132.682	226.42	0.927	3.711	8.414	15.273	1.039	4.178	9.438	16.832

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Table 4. The ground reflected radiation (Wh. m $^{-2}$. day $^{-1}$) using isotropic and anisotropic model and its contribution (in percentage) in diffuse solar radiation at different slopes for Pune, India.

Month		Reflected	component						% reflected component in Diffuse radiation				% reflected component in Diffuse radiation			
		Isotropic				Anisotropic			Using		Isotropic		Using		Anisotropic	
	15 ⁰	30 ⁰	45 ⁰	60 ⁰	15 ⁰	30 ⁰	45 ⁰	60 ⁰	15 ⁰	30 ⁰	45 ⁰	60 ⁰	15 ⁰	30 ⁰	45 ⁰	60 ⁰
JAN	15.573	60.92	132.832	229.021	14.644	57.715	126.198	215.36	1.032	4.12	9.291	16.734	0.971	3.912	8.868	15.894
FEB	19.729	77.175	168.276	290.131	15.498	61.081	133.559	227.92	1.301	5.154	11.467	20.264	1.025	4.124	9.321	16.642
MAR	22.317	87.297	190.347	328.185	13.377	52.721	115.278	196.72	1.169	4.648	10.409	18.565	0.704	2.86	6.574	12.023
APR	23.677	92.617	201.947	348.185	8.354	32.926	71.995	122.86	1.141	4.542	10.186	18.204	0.406	1.664	3.886	7.281
MAY	24.385	95.388	207.989	358.601	5.71	22.503	49.205	83.967	1.074	4.281	9.632	17.297	0.253	1.044	2.46	4.669
JUN	17.613	68.899	150.232	259.021	6.661	26.253	57.404	97.959	0.661	2.67	6.138	11.372	0.251	1.035	2.438	4.628
JUL	15.054	58.888	128.402	221.383	4.302	16.953	37.07	63.259	0.57	2.308	5.33	9.947	0.164	0.675	1.599	3.06
AUG	14.553	56.93	124.133	214.022	3.814	15.033	32.87	56.091	0.506	2.053	5.981	8.928	0.133	0.55	1.657	2.505
SEP	15.63	61.141	133.316	229.855	7.747	30.534	66.764	113.93	0.598	2.418	6.966	10.386	0.297	1.222	3.614	5.433
OCT	17.689	69.195	150.876	260.132	13.476	53.11	116.128	198.17	0.847	3.402	8.433	14.143	0.647	2.632	6.619	11.15
NOV	17.179	67.2	146.527	252.632	14.075	55.473	121.295	206.99	1.154	4.59	10.135	18.366	0.947	3.819	8.539	15.564
DEC	15.998	62.582	136.457	235.271	13.242	52.191	114.118	194.74	1.079	4.303	9.52	17.376	0.895	3.615	8.088	14.827

One can observe that with the increase of inclination angle the contribution of ground-reflected radiation in diffuse solar radiation increases with both models. The contribution of ground-reflected radiation in diffuse radiation at 60 º inclinations for Lucknow, Mumbai, Calcutta and Pune are ranging 8-14%, 8.87-14.39%, 8.56-19.68% and 8.92-20.26% respectively with isotropic model and 4-10%, 2.35-13.87%, 2.59-17.60% and 2.5-16.64% respectively with anisotropic model. The maximum contribution of ground-reflected radiation in total radiation is 9% for isotropic model however 4.6% for anisotropic.

4. Conclusion

The behaviour of isotropic and anisotropic models for ground-reflected radiation is studied for Indian locations. Though the data predicted by anisotropic model are lower than isotropic, the trend of predicting data by both models for different slops is same. However if we look over month wise data for entire year, the behaviour of models in predicting data is just reverse. The contribution of ground-reflected radiation in diffuse radiation is quit significant particularly for isotropic case. Further the merits and demerits of model can be tested on the availability of measured ground-reflected radiation data.

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