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Summary This study is concerned with the evaluation of the isotropic and four anisotropic solar radiation models for inclined surfaces. The evaluation procedure was split in two stages—abbreviated and detailed analysis. Physical reasoning was used in the abbreviated analysis to demonstrate the shortcomings of the older models, while detailed evaluation was carried out for the newer models, using at least one-year's measured hourly data from each of five European sites. Plots displaying the hourly estimated radiation against measured values have been prepared along with computation of the mean bias error and the root mean square error for each slope/azimuth. The isotropic model has been found to perform very poorly and in view of its impact on the thermal energy and daylight related calculations it is not recommended for further use. In this work further refinements have been suggested for the treatment of the background sky-diffuse radiance. The newer models including the presently proposed one have shown good agreement with the measurements.

Solar radiation model for Europe

T Muneer BEng MSc PhD CEng MIMechE
School of Mechanical and Offshore Engineering, Robert Gordon's Institute of Technology, Aberdeen, Scotland

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List of symbols

- b Radiance distribution index (dimensionless)
- D Hourly horizontal diffuse irradiation (Wh m^{-2})
- D_v Hourly vertical surface sky-diffuse irradiation (Wh m^{-2})
- D_β Hourly inclined surface sky-diffuse irradiation (Wh m^{-2})
- E Hourly horizontal surface extra-terrestrial irradiation (Wh m^{-2})
- F Modulating function defined by equation 3 (dimensionless)
- F' Modulating function defined by equation 5 (dimensionless)
- F_1' Function used in Perez model, Reference 4 (dimensionless)
- F_2' Function used in Perez model, Reference 4 (dimensionless)
- G Hourly horizontal global irradiation (Wh m^{-2})
- i Angle of incidence of sun's rays (radians)
- L_α Luminance of sky at an angle α from the horizon (lux)
- L_z Luminance of sky at the zenith (lux)
- Z Zenith angle of sun (radians)
- α Solar altitude (radians)
- β Inclination of the sloped surface (radians)

1 Introduction

Over the past 10 years or so building energy analysis software has become detailed and refined and therefore requires more precise estimation of solar radiation. A good solar radiation model is also useful in obtaining daylight estimates[1]. For these reasons, accurately knowing the amount of solar radiation incident on inclined vertical surfaces is important.

The incident solar radiation on a slope is evaluated as the sum of direct beam, sky-diffuse and ground-reflected components. The main difference between solar radiation models is the treatment of the sky-diffuse component. In the European climate this component is often the largest source of estimation error. The author has in previous communications surveyed the historical development of sky-diffuse and ground-reflected radiation models[2,3]. Historically, both the sky-diffuse and ground-reflected components have been treated as isotropic and in spite of the findings of several authors, revealing the anisotropic nature of these components[2,4], the use of the isotropic model[5] is common.

In previous work[3,6–8] the author has evaluated the validity of the models which were then available for sky-diffuse irradiation. The strengths and limitations of the isotropic, Hay[9] and Klucher[10] models have been discussed and an anisotropic model was developed which satisfactorily described the radiance distribution of six locations in the United Kingdom. In the present study the isotropic, Muneer's[7] and Perez[4] models have been evaluated against data from five European sites and a new, more detailed model is presented. I would like to point out here that, with the advent of a single European market in the year 1992, a validated solar radiation model for Europe would be of significant importance to HVAC engineers and architects. It would also be a responsibility of the relevant institutions, such as CIBSE, to collate information on a Europe-wide basis rather than within the present national scope of its Guides.

2 The database

The database for the present work is as follows:

(*a*) One complete year's data (1983) for Easthampstead (51.4°N, 0.8°W) in England. The data consisted of hourly global irradiations on vertical surfaces facing North, East, South and West and an inclined surface (slope = 51.4°) facing South together with horizontal global and diffuse values. The data were obtained from the Meteorological Office in Bracknell.

(*b*) One year's data (July 1986–June 1987) for Geneva (46.2°N, 6.1°E) in Switzerland. The data consisted of hourly global irradiations on the four principal vertical surfaces (facing North, East, West and South) and three inclined surfaces facing due South (slopes = 30°, 45° and 60°) including horizontal global and diffuse measurements. The data were obtained from the Physics Department of the University of Geneva.

(c) One-and-a-half year's data (April 1985–October 1986) for Eindhoven (51.4°N, 5.5°E) in the Netherlands. The data, once again, contained hourly horizontal global and diffuse irradiations, and corresponding values for the four principal vertical surfaces. The data were furnished by the Institute of Applied Physics in Eindhoven.

(d) One year's hourly data (1988) for Friburg (48°N, 7.9°E), in West Germany, consisting of global irradiation for the four principal vertical surfaces, a South-facing inclined (slope = 45°) surface and the horizontal surface. There was no diffuse irradiation measurement carried out for this period in Friburg and hence this quantity has been estimated using a correlation developed for Camborne, England (50.2°N) by the author[9]. Also, contrary to the normal practice of excluding the ground-reflected radiation in such measurements the inclined surface sensor due South included this component. The reflected radiation has therefore been accounted for in the estimation process. The data were furnished by the Fraunhofer Institute for Solar Energy Systems in Friburg.

(e) One year's (April 1977–March 1978) data for Vaerloese (55.8°N, 12.3°E) in Denmark consisting of global irradiation on a horizontal surface and the four principal vertical surfaces, and diffuse irradiation (uncorrected) on the horizontal and an inclined surface (slope = 60°) due South. These data were obtained from the Thermal Insulation Laboratory of the Technical University of Denmark.

3 Evaluation of models: Abbreviated analysis

In this section some of the well-known slope solar radiation models will be evaluated in an abbreviated manner. The models examined here are the isotropic, Hay[9], Klucher[10], Muneer[7] and Perez[4]. A brief description of the models is appropriate at this stage.

The isotropic model assumes uniform sky-diffuse radiance distribution. Hourly sky-diffuse irradiation on a surface of slope β is given by

$$D_\beta = D\cos^2(\beta/2) \tag{1}$$

Hay's model[9] combines two components of the sky radiance, a circumsolar and an isotropic background-sky component. The two components are mixed via a modulating function F.

$$D_\beta = D\left[F\left(\frac{\cos i}{\sin\alpha}\right) + (1-F)\cos^2(\beta/2)\right] \tag{2}$$

$$F = (G-D)/E \tag{3}$$

Klucher's model[10] is based on the principle that overcast skies tend to be isotropic while clear skies show strong horizon brightening. It is expressed mathematically as:

$$D_\beta = D\cos^2(\beta/2)\left[1 + F'\sin^3(\beta/2)\right] \times \left[1 + F'\cos^2 i\sin^3 Z\right] \tag{4}$$

$$F' = 1-(D/G)^2 \tag{5}$$

Muneer's model[7] treats the shaded and sunlit surfaces separately and further distinguishes between overcast and non-overcast conditions of the sunlit surface. In this model the slope diffuse irradiation for surfaces in shade and sunlit surfaces under overcast sky is computed as

$$D_\beta = D\left[\cos^2(\beta/2) + \frac{2b}{\pi(3+2b)} \times (\sin\beta - \beta\cos\beta - \pi\sin^2(\beta/2))\right] \tag{6}$$

and a sunlit surface under non-overcast sky as

$$D_\beta = D\left[T(1-F) + F\cos i/\sin\alpha\right] \tag{7}$$

T is the function contained within the square brackets of Equation 6. The parameter b in Equation 6 is termed the radiance distribution index and was introduced by Moon and Spencer[11] to model the luminance distribution of an overcast sky *viz*,

$$L_\alpha = L_z\frac{1 + b\sin\alpha}{1+b} \tag{8}$$

For an isotropic sky, b assumes nil value. On the basis of measured data from five locations in the United Kingdom, Muneer[7] has shown that the sky-radiance distribution is anistropic. Muneer has reported the 'best' values of b as found for Easthampstead data as: $b = 5.73$ (shaded surface); $b = 1.68$ (sunlit surface under overcast sky); $b = -0.62$ (sunlit surface under non-overcast sky).

The Perez model[4] incorporates two components: a geometric description of the sky hemisphere with a circumsolar component and isotropic background, and brightness coefficients F_1' and F_2' expressed as a function of the solar radiation conditions (the sun's zenith angle and insolation parameters). F_1' and F_2' are provided via an 8×6 matrix which gives values of coefficients based on data from two French sites, Trappes (48.8°N) and Carpentras (44.1°N). Among other versions of the model a 'point-source' version has also been presented whose accuracy is comparable with, if not better than, the other versions. This point-source version, which assumes the circumsolar radiation to emanate from a point-source of the solar disk, is selected here for comparison with other models. This version of the Perez model which is given by Equation 9 in Reference 4 is expressed as,

$$D_\beta = D\left[\cos^2(\beta/2)(1-F_1') + F_1'\frac{\cos i}{\sin\alpha} + F_2'\sin\beta\right]$$

F_1' and F_2' are obtained via relationships given in Table 2 of Reference 4. These relationships are too involved to be duplicated here.

4 Evaluation of models for shaded vertical surface

In this case $\beta = \pi/2$; $i \geqslant \pi/2$.

4.1 Overcast conditions ($G = D$)

The following values are predicted by the given models: isotropic model (Equation 1): $D_v = 0.5\,D$; Hay's model (Equation 2): $D_v = 0.5\,D$; Klucher's model (Equation 4): $D_v = 0.5\,D$; Muneer's model (Equation 6): $D_v = 0.36\,D$.

The analysis of the Perez model is not straightforward and further data are required. Muneer[12] has shown that overcast conditions ($D = G$) may occur for a clearness index (G/E) of 0.2. On this basis, and assuming an intermediate $Z = 60°$, it may be shown that the Perez model yields

$$D_v = 0.42\,D$$

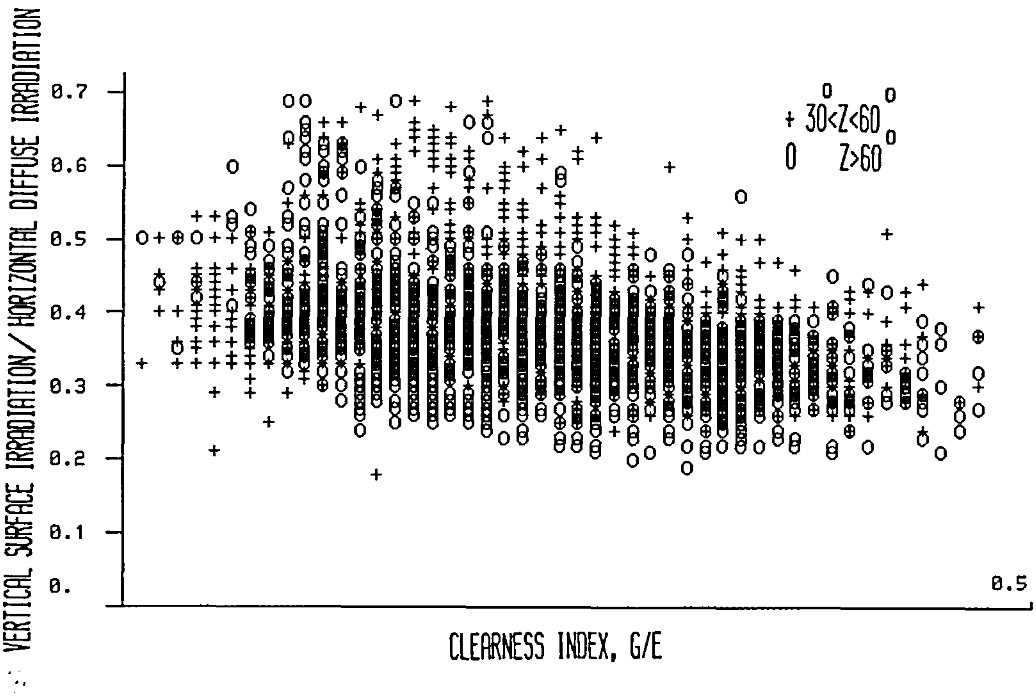

Figure 1 Relationship between shaded vertical surface diffuse fraction and clearness index—Geneva data

The values of F_1' and F_2' were respectively 0.055 and −0.058.

Using measured data Saluja and Muneer[2] have shown that the vertical surface irradiation for a shaded surface receives approximatively a third of the horizontal diffuse irradiation. Figures 1 and 2 which are based on measured data from Geneva and Vaerloese are shown here as a further proof that the isotropic, Hay and Klucher models significantly overestimate for this condition. The overestimation may reach in excess of 40%. For a daylight designer this difference between the estimated and available illuminance may result in a significant overdesign. Perhaps some further observations based on Figures 1 and 2 are forthcoming.

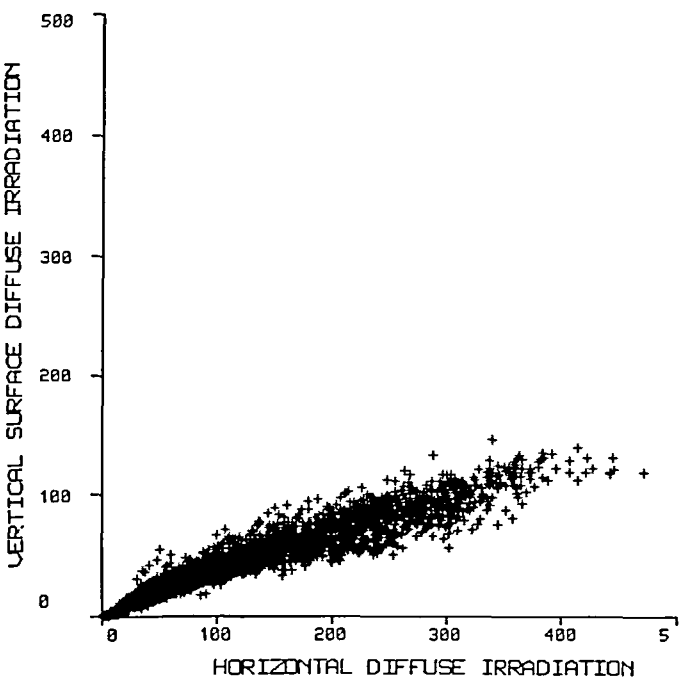

Figure 2 Relationship between shaded vertical surface irradiation and horizontal diffuse irradiation—Vaerloese data

Figure 1 contains two groups of data points with reference to the Zenith angle. There is no particular trend to be noticed and hence the approach of Perez[4] in relating the two quantities does not seem to be fruitful. However, there seems to be some dependence of D_v/D against G/E, though the effect is not so strong. Figure 2 shows the relationship between D_v and D for a north facing surface and the slope of the mean line (slope ≈ 0.3) is in agreement with the findings of Saluja and Muneer[2]. Plots similar to Figures 1 and 2 were obtained for all the five locations. They are not reproduced however, for economy of space.

4.2 Non-overcast conditions ($G > D$)

For completely clear skies, Muneer[12] has shown that $G/E \approx 0.8$ and $D/G \approx 0.2$. Thus $D/E = 0.16, F = 0.64$ and $F' = 0.96$. Under these conditions the following values are predicted by the candidate models: isotropic model: $D_v = 0.5\,D$; Hay's model: $D_v = D[(1 - F) \times 0.5] = 0.18\,D$; Klucher's model: $D_v = D \times 0.5 \quad (1 + 0.35 \times F') = 0.67\,D$; Muneer's model: $D_v = 0.36\,D$.

Once again, for the Perez model, Z is typically assumed as 60°. The model yields $D_v = 0.53\,D$. The values of F_1' and F_2' were respectively 0.442 and 0.255.

The United Kingdom data have shown that for this condition, as well as the one discussed in the previous section, the vertical surface received only a third of the horizontal diffuse irradiation[2].

Figures 1 and 2 show that the isotropic, Klucher and Perez models overestimate while Hay's model underestimates for this condition. Another feature to be noticed in Figure 1 is that, if anything, the ratio D_v/D decreases with increasing clearness index and does not increase as suggested by the Klucher and Perez models.

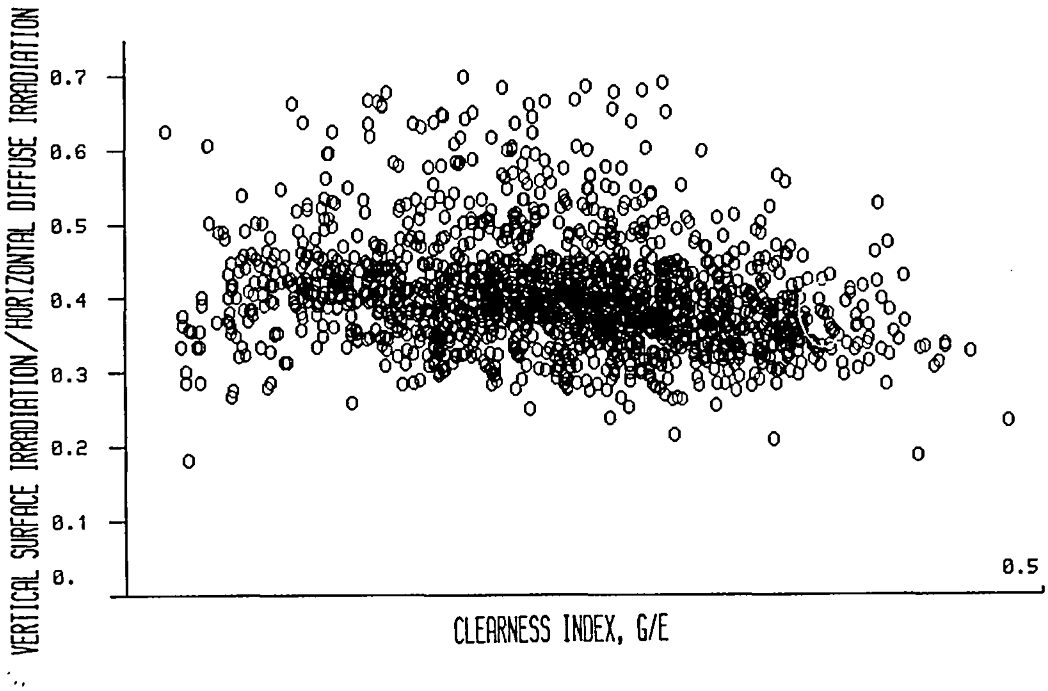

Figure 3 Relationship between sunlit vertical surface diffuse fraction and clearness index for overcast sky—Eindhoven data

5 Evaluation of models for sunlit vertical surface

In this case $\beta = \pi/2$ and $i < \pi/2$.

5.1 *Overcast conditions* ($G = D$)

For this condition the models examined yield the following estimates: isotropic model: $D_v = 0.5\,D$; Hay's model: $D_v = 0.5\,D$; Klucher's model: $D_v = 0.5\,D$; Muneer's model: $D_v = 0.4\,D$.

Once again for the Perez model, taking $Z = 60°$, F_1' and F_2' are evaluated as 0.055 and −0.058 respectively. The model yields $D_v = 0.51\,D$.

Figure 3 shows that the average D_v/D ratio is lower than 0.5, closer to the value suggested by Saluja and Muneer[2]. A further point to be noticed in Figure 3 is that although there is a slight decrease in the ratio D_v/D with an increasing clearness index, the relationship is not very strong.

5.2 *Non-overcast conditions* ($G > D$)

The insolation conditions in this case are taken as identical to the ones in Section 4.2. Fortunately there are measured slope diffuse irradiation data available for Vaerloese in Denmark. The measurements were carried out for a 60° slope ($\beta = \pi/3$) facing the South. Hence this configuration is presently considered: isotropic model: $D_{\pi/3} = 0.75\,D$; Hay's model: $D_{\pi/3} = 1.3\,D$; Klucher's model: $D_{\pi/3} = 0.82\,D$; Muneer's model: $D_{\pi/3} = 1.4\,D$; Perez model: $D_{\pi/3} = 1.4\,D$.

The estimates of the models are now compared against measured data. Figure 4 shows that for clear skies, with the clearness index approaching a value of 0.8, the isotropic model significantly underestimates. The other four models are however in agreement with the experimental findings.

Let us now examine the assumptions of Hay and Klucher, i.e. that the background sky-diffuse radiance is isotropic. Perhaps this point needs some clarification. While Hay's model superimposes a circumsolar component, Klucher's model imposes additional horizon brightening on a uniform sky. These models are not to be confused with the isotropic model which is a single component model.

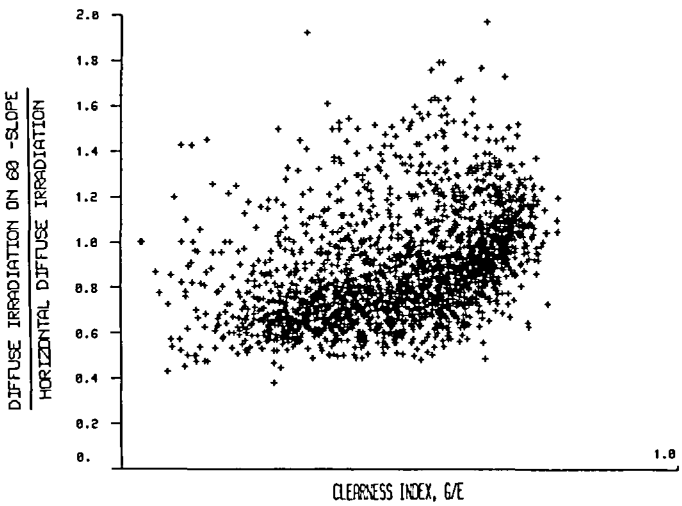

Figure 4 Relationship between sunlit sloped surface diffuse fraction and clearness index for all-sky conditions—Vaerloese data

Figure 5 shows the variation of the background sky-diffuse irradiation expressed as a fraction of the horizontal diffuse irradiation. The former component was obtained via subtraction of the diffuse circumsolar component from the total diffuse irradiation on a vertical surface. Hay's background isotropicity suggests a constant value of 0.5 for the Y-axis which is obviously grossly exceeded, particularly for the clear skies, by the experimental values. Plots similar to Figure 5 were obtained for Geneva and Eindhoven, each showing the same trend. Averaged curves for the variation of the normalised background sky-diffuse irradiation are shown in Figure 6. Equations fitted for the radiance distribution index b against the modulating function F are given in Table 1. Table 2 presents the comparisons of the above models against measured results.

6 Evaluation of models: Detailed analysis

In the previous section it was demonstrated that in three out of four cases the models of Hay and Klucher are in

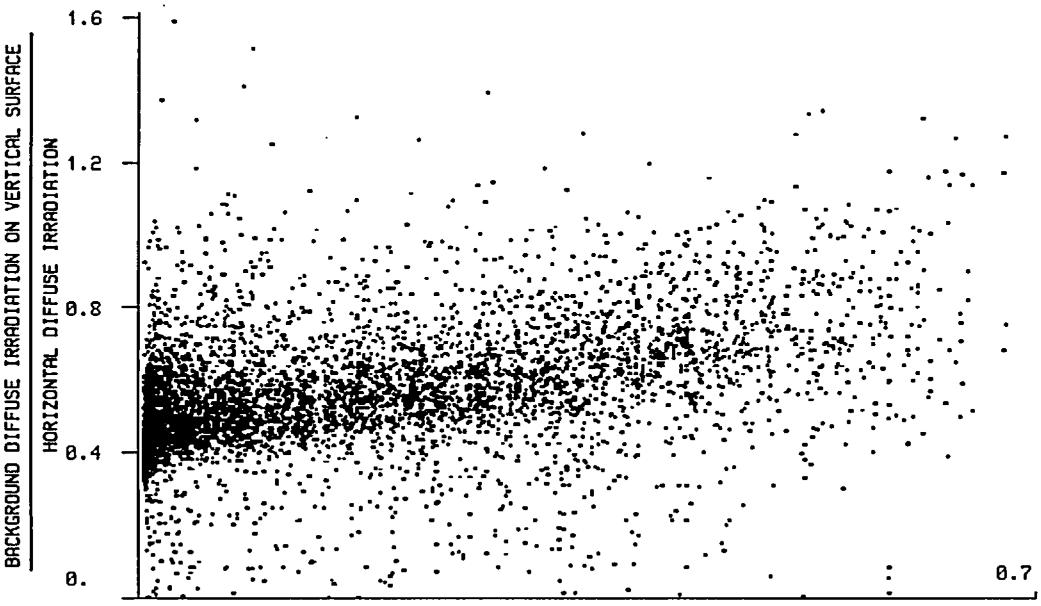

Figure 5 Relationship between vertical-sunlit background sky-difuse fraction and modulating function—Easthampstead data

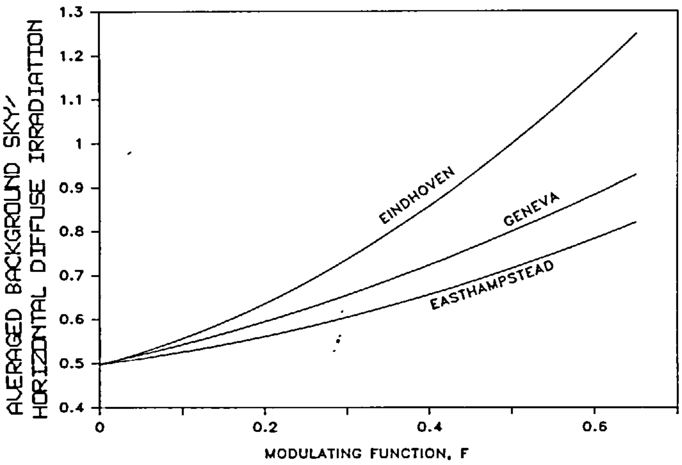

Figure 6 Averaged background sky-diffuse fraction for three European sites

Table 1 Parameters for the background sky-diffuse irradiation† function $2b/\pi(3+2b) = a_0 - a_1F - a_2F^2$

Location	a_0	a_1	a_2
Easthampstead	0.003 33	0.415 0	0.698 7
Geneva	0.002 63	0.712 0	0.688 3
Eindhoven	0.005 45	0.866 4	1.785 7

† Background irradiation =

$$D(1-F)\left[\cos^2(\beta/2) + \frac{2b}{\pi(3+2b)}\left(\sin\beta - \beta\cos\beta - \pi\sin^2(\beta/2)\right)\right]$$

disagreement with the experimental findings. These analyses reconfirm the results reported in References 2 and 7 in which the Hay and Klucher models have been analysed against long-term measurements. Furthermore, for the fourth case of sunlit surface under non-overcast conditions it was shown

Table 2 Abbreviated evaluation of selected diffuse solar radiation models against measured data. Unless stated otherwise, vertical surfaces are considered

Model	Ratio of slope irradiation/horizontal radiation for given sky condition			
	Lighting			
	Shaded		Sunlit	
	Overcast sky	Non-overcast sky	Overcast sky	Non-overcast sky
Isotropic	0.5	0.5	0.5	0.75†
Hay	0.5	0.18	0.5	1.13
Klucher	0.5	0.67	0.5	0.82
Muneer	0.36	0.36	0.4	1.4
Perez	0.42	0.53	0.51	1.4
Measured data for European sites	0.33	0.33	0.38	1.25

† Slope of the surface is 60°

via Figures 5 and 6 that the isotropic condition does not apply, even for the background radiance.

In the subsequent analysis, therefore, the models due to Hay and Klucher are not included. In any case these models are now dated since Muneer's and Perez models are further refinements of the latter models. Also, new work is emerging which further supports the findings being reported here[13]. In the remaining part of this study the isotropic model, in spite of its shortcomings, is evaluated owing to its 'classical' nature and also due to the fact that it still is in widespread use as pointed out earlier.

In Muneer's model[7] a constant anisotropic radiance distribution was used and in the present work functions have been fitted to allow its variability (Table 1). This modification of Muneer's model is hereafter called the 'Modified Muneer's model'. Figures 7–10 display the results of the four models being examined herein for Geneva. Geneva data proved to be extremely useful due to its high accuracy (first class sensors), the number of recording sensors (four vertical and three inclined) and the geographic location of the site (mid-latitude for Europe). Figure 7 shows the limitations of the isotropic model—predominant overestimation for surface in shade and sunlit surface under overcast sky, and

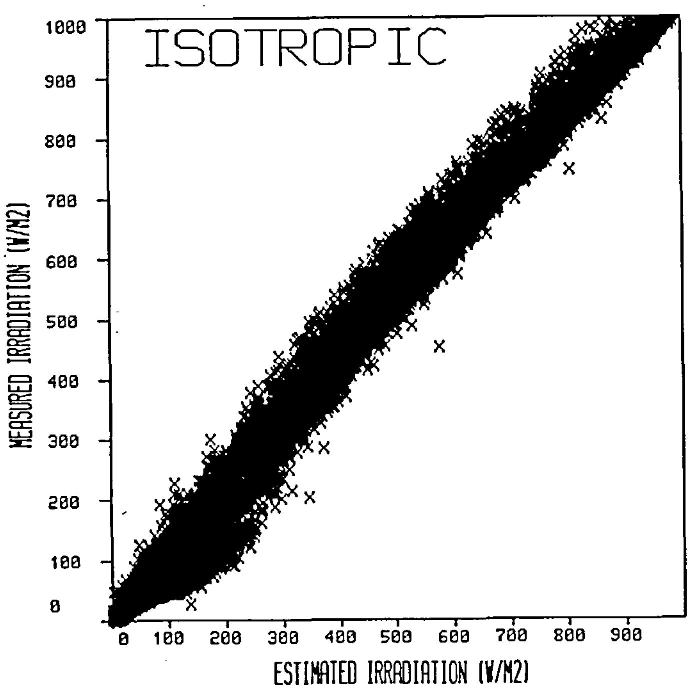

Figure 7 Performance of the isotropic model—Geneva data

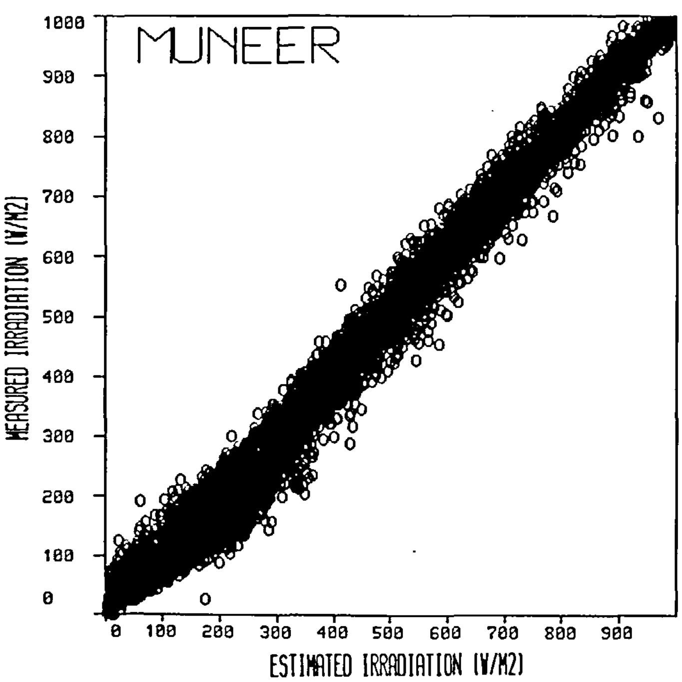

Figure 8 Performance of the Muneer's model—Geneva data

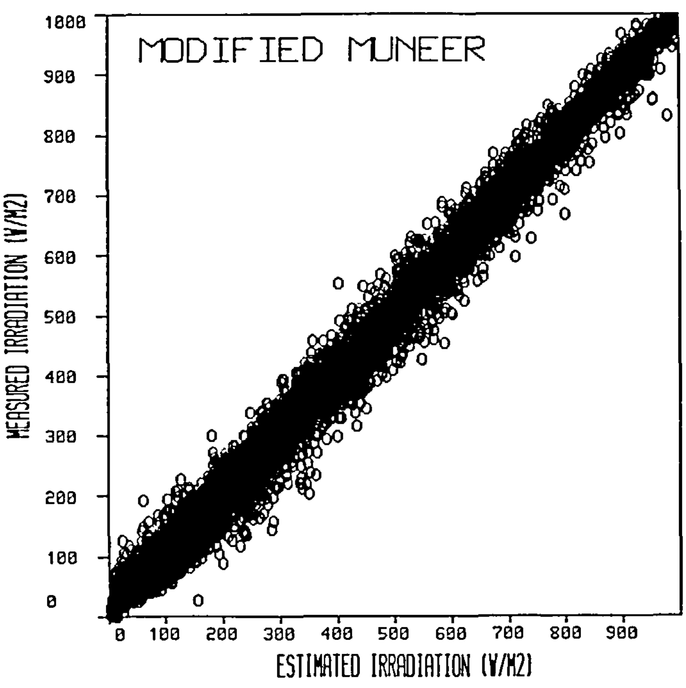

Figure 9 Performance of the modified Muneer's model—Geneva data

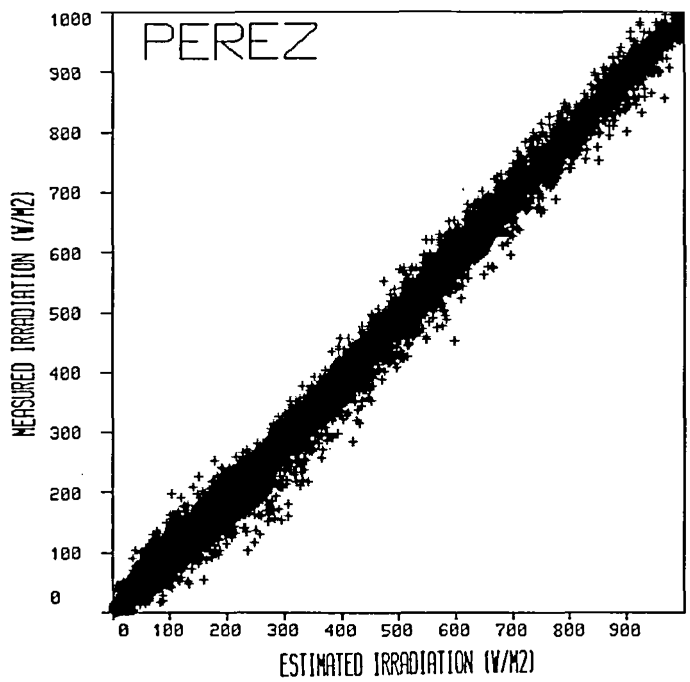

Figure 10 Performance of the Perez model—Geneva data

Table 3 Performance of slope irradiation models for Geneva (46.2°N), 1 July 1986–30 June 1987 (Wh m^{-2})

Model		Azimuth, slope of surface						
		South, 30°	South, 45°	South, 60°	South, 90°	East, 90°	West, 90°	North, 90°
Isotropic	Mean bias error	−21	−26	−31	−19	−3	−4	17
	Root mean square error	37	46	54	42	40	40	29
Muneer	Mean bias error	−2	−3	−7	−3	1	−1	0
	Root mean square error	14	17	23	24	23	21	14
Perez	Mean bias error	5	6	3	6	9	7	5
	Root mean square error	15	16	18	18	22	20	13
Modified Muneer	Mean bias error	−2	−3	−6	−2	−2	0	−1
	Root mean square error	15	17	21	20	20	18	13

consistent underestimation for sunlit surface under non-overcast conditions.

The bulge at the lower end of Figure 8 has been traced to overprediction on the part of Muneer's model under part-cloudy conditions. This phenomenon has been addressed by the modification incorporated in Muneer's model (Figure 9). Both the modified Muneer's model and the Perez model agree quite well with the measured data. To enable further insight in the performance evaluation of the models the mean bias errors (MBEs) and the root mean square errors (RMSEs) have been obtained for all slopes. These parameters are defined as:

$$\mathrm{MBE} = \frac{\Sigma(G_{\mathrm{estimated}} - G_{\mathrm{observed}})}{\text{number of observations}} \tag{10}$$

$$\mathrm{RMSE} = \left(\frac{\Sigma(G_{\mathrm{estimated}} - G_{\mathrm{observed}})^2}{\text{number of observations}}\right)^{1/2} \tag{11}$$

MBE provides an insight for the predominant trend of the model and the magnitude of this trend whereas RMSE gives a measure of the order of the scatter-high RMSE value associated with large scatter.

Table 3 shows the results for Geneva. A negative sign indicates underestimation of solar irradiation by the model. The results quantify the deductions which have been made earlier. An important point to be noted here is that the MBEs and RMSEs on their own are not sufficient to qualify a concrete judgement. Neither are they indicative of the trends in different regimes (low, mid or high values) of irradiation which cover the overcast, part-cloudy and clear sky conditions. An 'optimum' procedure may therefore be to use the type of plots produced herein with complementing MBE or RMSE values. Figures 11–13 compare the performance of the isotropic, Muneer's and modified Muneer's models for Eindhoven data. A plot similar to the Figures 12, 13 was also obtained for Perez model but is not included here for space economy. Figure 11 shows the shortcomings of the isotropic model, the model even further underestimates the global irradiation on the three vertical surfaces (North-facing surface hardly ever receives direct radiation around noon). The results for Eindhoven were somewhat surprising as the data showed exceptional sky clarity as evidenced by Figures 6 and 11. Notice that in Figure 6 the higher proportion of the background diffuse radiation for Eindhoven is distinct from the corresponding values for the other sites.

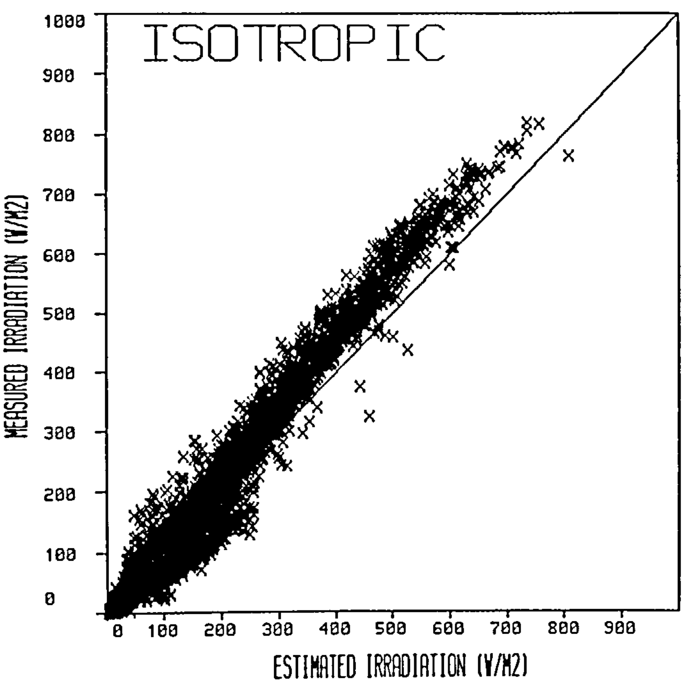

Figure 11 Performance of the isotropic model—Eindhoven data

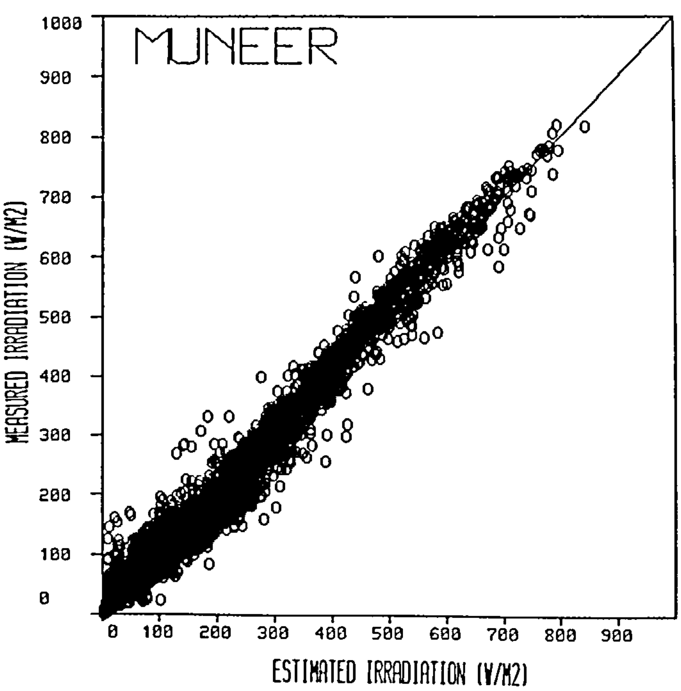

Figure 12 Performance of the Muneer's model—Eindhoven data

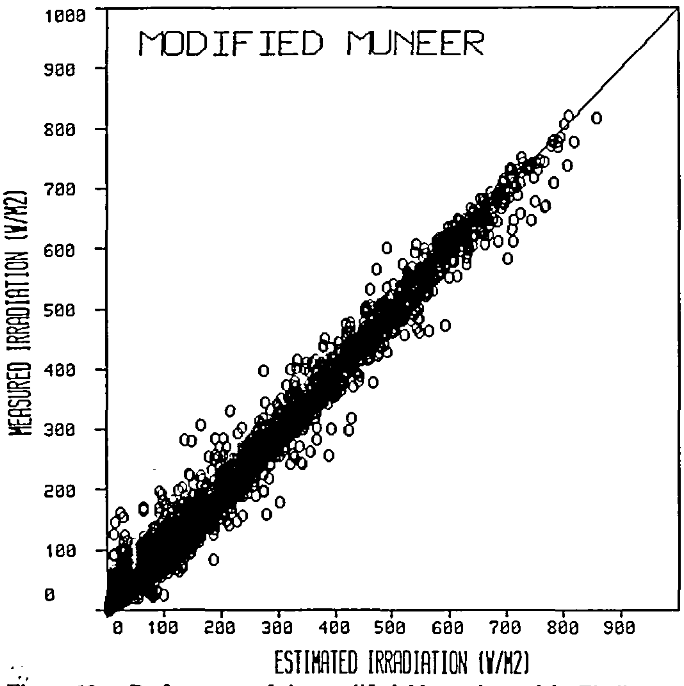

Figure 13 Performance of the modified Muneer's model—Eindhoven data

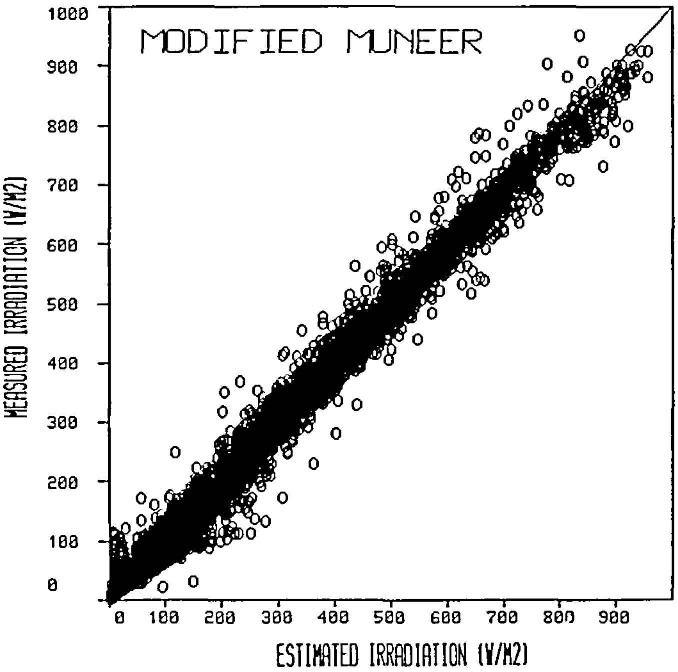

Figure 15 Performance of the modified Muneer's model—Easthampstead data

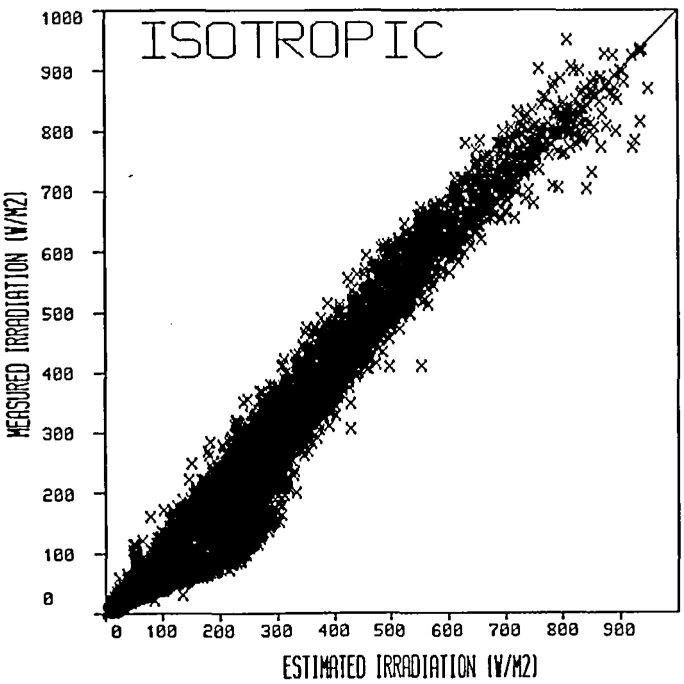

Figure 14 Performance of the isotropic model—Easthampstead data

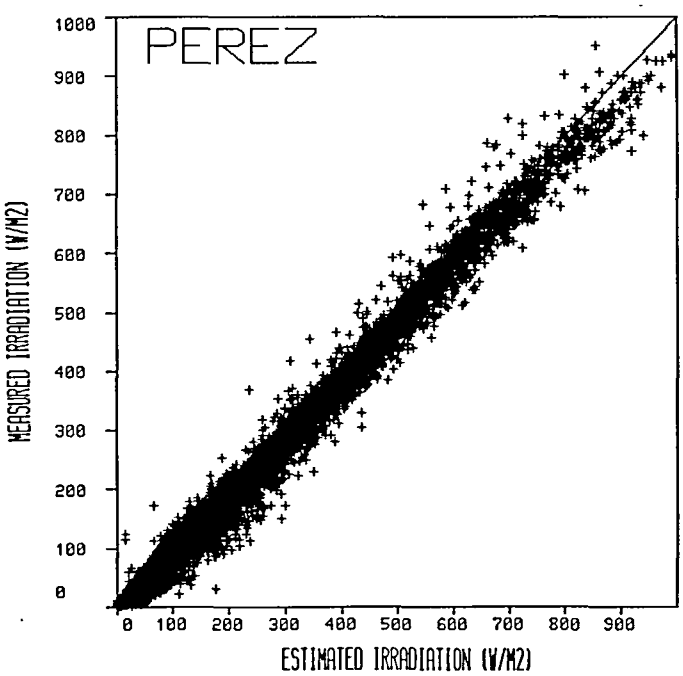

Figure 16 Performance of the Perez model—Easthampstead data

Table 4 Performance of slope irradiation models for Eindhoven (51.4°N) 1 April 1985–31 October 1986 ($Wh\,m^{-2}$)

Model		Azimuth, slope of surface			
		South, 90°	East, 90°	West, 90°	North, 90°
Isotropic	Mean bias error	−20	−2	−10	13
	Root mean square error	39	39	47	26
Muneer	Mean bias error	−6	0	−9	−6
	Root mean square error	28	28	29	14
Perez	Mean bias error	−1	6	0	0
	Root mean square error	−24	26	24	12
Modified Muneer	Mean bias error	−2	5	−4	0
	Root mean square error	22	26	27	14

Table 5 Performance of slope irradiation models for Easthampstead (51.4°N) 1 January–31 December 1983 (Wh m^{-2})

Model		Azimuth, slope of surface				
		South, 51.4°	South, 90°	East, 90°	West, 90°	North, 90°
Isotropic	Mean bias error	−14	−10	2	5	18
	Root mean square error	33	31	36	31	28
Muneer	Mean bias error	3	6	1	4	−1
	Root mean square error	23	23	21	19	11
Perez	Mean bias error	11	10	7	11	4
	Root mean square error	27	21	18	21	10
Modified Muneer	Mean bias error	−1	0	−3	1	−2
	Root mean square error	20	16	16	16	10

A further point to be noted is that the coefficients of the Muneer's model, though obtained from Easthampstead data, seem to work reasonably well for Eindhoven. Close comparison of Figures 12 and 13 will reveal that the scatter has been further reduced by the modifications incorporated in Muneer's model. Table 4 quantifies the discussion made in the above paragraphs.

Figures 14–16 and Table 4 present the results for model evaluation for the Easthampstead data. The isotropic model has trends similar to what has been observed earlier on. Muneer's model, for obvious reasons, showed good performance and a plot similar to Figure 15 has been published earlier[2,7]. Table 5 shows that with the refinement the modified Muneer's model shows even better performance. The Perez model however shows a predominance of overestimation as evident by Figure 16 and Table 5. This is not surprising in view of the fact that the Perez model has been fitted against data from Trappes and Carpentras. Neither of these two French sites have a climate which resembles that of west London. Perez *et al.*[4] have also concluded that the local climatic changes may require that the coefficients in their model be refitted. Moreover, the point to be emphasized here is that the greater the complexity of the model

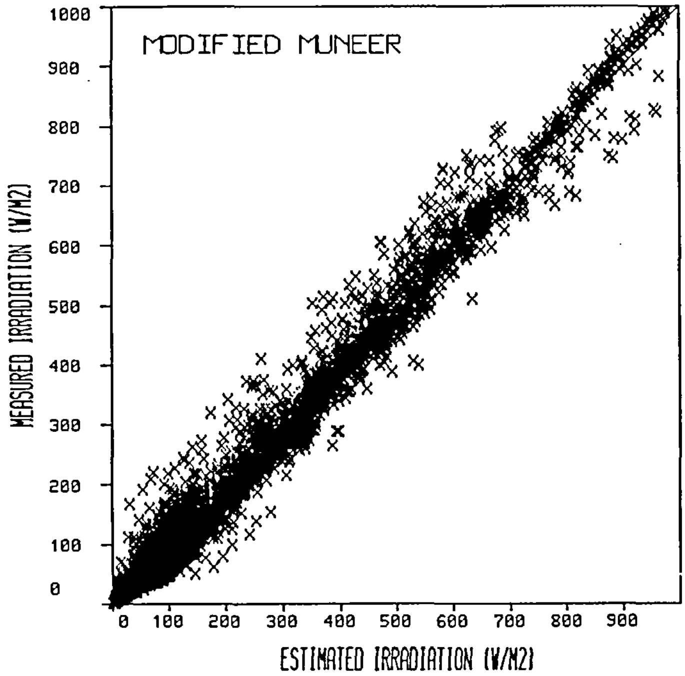

Figure 18 Performance of the modified Muneer's model—Friburg data

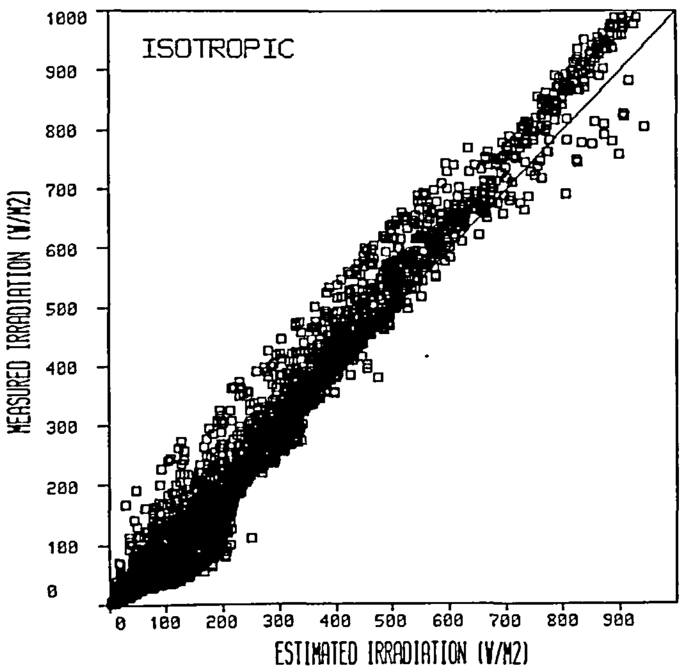

Figure 17 Performance of the isotropic model—Friburg data

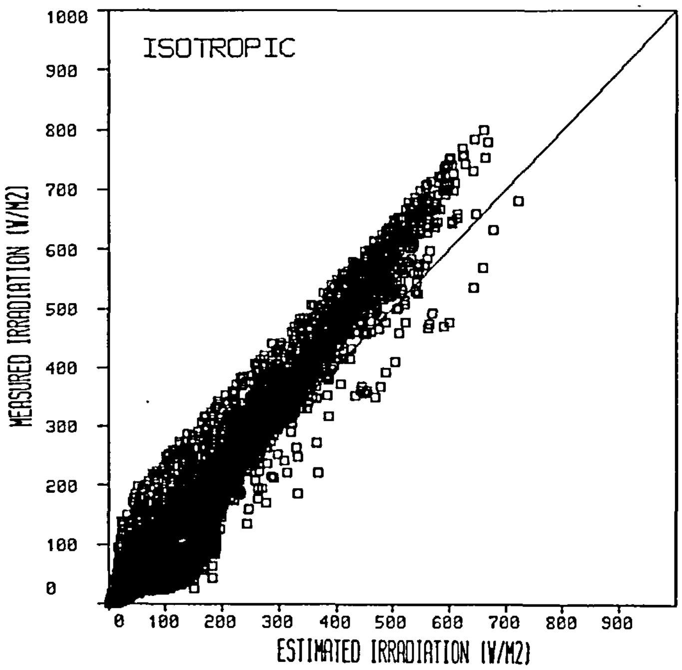

Figure 19 Performance of the isotropic model—Vaerloese data

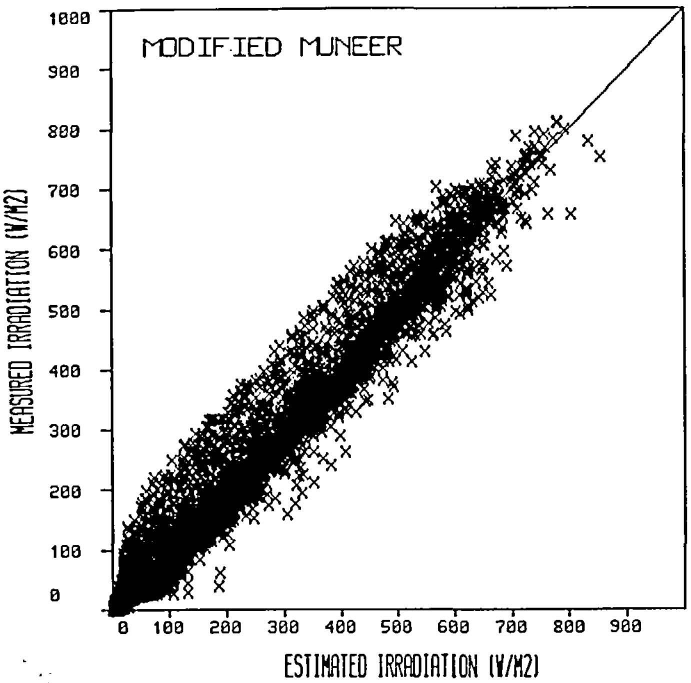

Figure 20 Performance of the modified Muneer's model—Vaerloese data

(Perez model requires an 8 × 6 numerical matrix) the more temporal and spatial limitations it will have. The complexity of Perez model even in its present 'simplified' form is also a constraint of some sorts.

Figures 17–20 and Tables 6 and 7 show the performance of the isotropic and the modified Muneer's model for Friburg (48°N) and Vaerloese (55.8°N). These data provide interesting case studies in solar radiation modelling since no horizontal (corrected) diffuse irradiation data was available and the tilted surface for Friburg additionally received ground-reflected radiation. Thus as a first step the diffuse component of the horizontal irradiation was estimated using correlations for Camborne (50.2°N) for Friburg and Shanwell's (56.5°N) data for Vaerloese(12).

Ground-reflected radiation was modelled according to the albedo values for gravel roof, which was the solar sensor's horizon, given in Reference 3.

Figures 17 and 19 display the limitations of the isotropic model whereas good performance was found for the other three models. An important point to be noted is that although Table 5 shows comparable MBEs for the South, East and West-facing surfaces for all the four models, the isotropic model is clearly inadequate and shows poorer performance when compared to the modified Muneer's model as well as the remaining two models (the plots are not shown here). This phenomenon of the isotropic model could be explained to the overestimation errors in the overcast regime being compensated by underestimation errors under clear skies.

7 Conclusions

Solar radiation estimation on vertical and inclined surfaces is an important step in a building's energy exchange analysis. In view of the fact that daylight calculations are also linked to estimation of solar radiation the latter's precise estimation is very much in order.

In this study two levels of analysis, abbreviated and detailed, were used to evaluate the performance of the isotropic and four anisotropic models. The shortcomings of the two older models namely the isotropic, Hay's and Klucher's have been shown using measured data and abbreviated analysis.

In the next phase data from five European sites have been used to compare the isotropic, Muneer's, the Perez and the modified Muneer's model. The modified Muneer's model describes the background sky-diffuse radiance more appropriately. The isotropic model has shown the poorest performance and it is recommended that its use should now be discontinued. Muneer's model, though originally developed against south-west England's data, showed reasonably good performance for the other four European sites. These sites which cover the range of latitudes between 46°N–56°N lie in central and northern Europe. The Perez model displayed a tendency of being site-specific for some locations. This behaviour is not surprising, however, in view of the large number of coefficients (48) which are required to execute this model. The modification made in the Muneer's model have demonstrated the further refinements which have been achieved in estimating slope irradiation to a high degree of accuracy.

It has also been shown that in the absence of measured horizontal diffuse irradiation, correlations developed for neighbouring sites may be used with good effect. Thus if only the hourly horizontal global irradiation records are available it is possible to obtain good slope irradiation estimates for any azimuth.

Table 6 Performance of slope irradiation models for Friburg (48°N) 1 January–31 December 1988 (Wh m^{-2})

Model		Azimuth, slope of surface				
		South, 45°†	South, 90°	East, 90°	West, 90°	North, 90°
Isotropic	Mean bias error	5	0	10	−13	24
	Root mean square error	32	25	53	72	39
Muneer	Mean bias error	9	9	14	−13	3
	Root mean square error	27	29	36	48	21
Perez	Mean bias error	12	7	16	−9	3
	Root mean square error	26	18	34	41	20
Modified Muneer	Mean bias error	7	8	13	−15	2
	Root mean square error	25	20	34	47	21

† Ground reflected radiation is included in the measurements for this particular azimuth and slope of surface.

Table 7 Performance of slope irradiation models for Vaerloese (55.8°N) 1 April 1977–31 March 1978 (Wh m^{-2})

Model		Azimuth, slope of surface			
		South, 90°	East, 90°	West, 90°	North, 90°
Isotropic	Mean bias error	−31	−14	−13	28
	Root mean square error	56	67	70	43
Muneer	Mean bias error	−3	−8	−5	−8
	Root mean square error	39	45	43	21
Perez	Mean bias error	1	−2	1	13
	Root mean square error	34	38	37	22
Modified Muneer	Mean bias error	0	−7	−4	7
	Root mean square error	38	45	43	21

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