MODELLING SOLAR DATA

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The objective of this paper is to present validated mathematical models for estimation of hourly and daily solar irradiation on surfaces of arbitrary orientation and tilt from irradiation on a horizontal plane. Daily irradiation on a surface may still be estimated even if only the hours of sunshine are known. To do this regression equations have been established to estimate the hourly or daily diffuse irradiation, given the corresponding horizontal global irradiation. The sky-diffuse irradiation is treated anisotropically and a semi-empirical model is established which treats the surfaces in shade and sunlit surfaces under overcast and non-overcast skies separately. The work presented here is the result of a three-year programme related to modelling of solar data.

INTRODUCTION

Solar radiation availability of sloped surfaces is required in many sciences. For example building services engineering, daylighting, agricultural meteorology, photobiology and animal husbandry all require irradiation availability on slopes.

The current awareness of the energy consumption in buildings has called for strict conservation measures. The optimal building design from an energy conservation viewpoints demands among other requirements, precise knowledge of solar radiation on windows, walls and roof. The low energy loss, multiple glazed window technology has helped pave the way for a greater use of fenestration. Although, in Winter seasons the fenestrations may be employed for admittance of solar energy they may tend to overheat the building in the Summer. Thus an optimum design would require a year round study of the energy balance: day-gains and nocturnal losses.

Also in the utilization of active or passive solar energy, estimation of the irradiation on collectors of different orientations and tilts is required. The rising cost of electricity has provided the motive for making best use of daylight. Utilization of daylight and solar radiation has led to new architectural developments. Typical design elements include atria, sloping facades and large windows. But although there are new opportunities for making use of daylight, there is lack of information on appropriate calculations. Traditional prediction methods are based on the daylight factor derived for the overcast sky; however, this ignores the effects of orientation and bright days. By incorporation of realistic prediction methods, daylight design can provide reduction in energy costs. The need for prediction methods for daylight is genuine owing to the fact that there is a dearth of measured illuminance data. It is however possible to compute illuminance from irradiation data.

Thus validated solar irradiation models will not only provide information on the interception of total energy (energy in the visible + infra red wave bands) but also on the daylight. Modelling of the energy availability for the above mentioned applications requires knowledge of slope irradiation either on a monthly-averaged, daily or hourly basis depending on how refined the analysis has to be.

In the United Kingdom, hourly diffuse and global irradiation, on a horizontal plane, are recorded by the Meteorological Office for 19 locations. Records for hourly global irradiation alone are available for a further 7 stations. Additionally, daily global and diffuse irradiation are recorded at 30 and 4 stations, respectively. Contrary to this the slope irradiation is recorded at only two stations; Easthampstead (51.4°N, 0.8°W) and Lerwick (60.2°N, 1.2°W). Thus a method is required to estimate irradiation availability of sloped surfaces.

Global irradiation on a slope is the sum of its direct (beam), diffuse and ground-reflected components. If one is starting from horizontal global and diffuse irradiation data, the normal irradiance can be evaluated from the difference of the two and this in turn can be employed for determining the beam irradiation on a slope. The diffuse component, is not so straightforward to evaluate. It may be computed from the angular, radiance distribution of the sky. The distribution of the sky-diffuse radiance, which is anisotropic in nature, depends on the condition of the sky and determination of it is a fairly involved task. Likewise, the ground-reflected component may be computed, given the horizontal diffuse and global irradiation.

The first step in estimating slope irradiation would be to acquire horizontal global, as well as diffuse irradiation data. Therefore, in the first instance, for those locations at which only horizontal global irradiation is recorded, a method is needed to estimate the diffuse component. One way is to study the correlation between the two quantities at locations where appropriate data is available and hence, establish regression equations for the diffuse irradiation. The regression equations obtained from daily based data differ from those based on hourly irradiation data. Having established the hourly and daily regressions for horizontal diffuse irradiation, and a validated model for inclined surface irradiation, it is then possible to estimate slope irradiation for 26 locations on an hourly and 56 locations on a daily basis.

Estimation of Hourly Diffuse Irradiation

Hourly diffuse and global horizontal irradiation data from 11 locations was acquired from the Meteorological Office. These locations, listed in Table 1, were selected in such a manner that they comprehensively covered the range of latitude in the U.K. The raw data had been edited by the Meteorological Office. However, it was further checked for internal inconsistencies such as diffuse irradiation exceeding global irradiation and global irradiation exceeding extraterrestrial irradiation.

The next step was to obtain for each hour, and for each of the eleven locations, the diffuse ratio I_D/I_G (ratio of hourly diffuse to global irradiation on a horizontal surface) and clearness index K_t (ratio of hourly global to extraterrestrial irradiation on a horizontal surface) along with the corresponding fractional sunshine (fraction of the day-length which received bright sunshine). In order to identify any underlying seasonal trends the data was grouped for individual seasons as follows: Winter (1st November - 28th February), Summer (1st May - 31st August) and Spring and Autumn (1st March - 30th April and 1st September - 31st October). The choice of these dates, to classify the seasons, was made to simplify the task of the end user. Regression analysis was carried out for each of the eleven sites, and was then extended to the United Kingdom by pooling data for all sites. Several degrees of fit were tried for each site and in each case the value of R^2 (coefficient of determination) was computed.

Figures 1 and 2 show the plots of I_D/I_G (ratio of hourly diffuse to global irradiation) against K_t (ratio of global to extraterrestrial irradiation) for Camborne and Stornoway respectively. Plots for all eleven locations were obtained, however since the plots were similar in appearance only two are shown here as examples. A correlation between the two parameters under discussion is apparent. For values of K_t close to zero I_D/I_G assumes a constant value owing to the fact that under overcast skies I_D becomes equal to I_G. For $K_t < 0.3$, and for each increment of 0.C?, the corresponding values of I_D/I_G were averaged. A plot of I_D/I_G versus K_t showed an increase up to a K_t of 0.2. For $K_t < 0.2$ the averaged values of I_D/I_G were constant. Hence in the regression analysis only the data points with $K_t > 0.2$ were considered. Regression analysis was carried for I_D/I_G on K_t. Several degrees of fit were tried for each site, and the coefficient of determination (R^2) calculated in each case. It was found that a cubic fit was the best throughout. In order to investigate the seasonal effect on the regression I_D/I_G was plotted against K_t, separately, for Winter, Summer and Spring/Autumn. Figs 3-5 show the trends for Camborne. While the correlation seems strong during Summer and Spring/Autumn a large scatter is to be noticed for Winter. The significantly higher scatter for Winter was observed for all remaining locations as well.

Table 1 shows the values of regression coefficients and of R^2 for a cubic equation obtained by the least-square method,

$$I_D/I_G = a_0 + a_1 K_t + a_2 K_t^2 + a_3 K_t^3;\ K_t > 0.2 \qquad (1)$$

$$I_D/I_G = 0.98;\ K_t < 0.2 \qquad (2)$$

The lower values of R^2 in Winter for most locations are due to higher scatter which may be explained as follows:

(i) "the most serious source of systematic error of the solarimeter in Winter is usually the failure of cosine response at low solar elevations, leading to underestimation of intensity; but overestimation is known to occur when the outer glass dome is covered with water droplets or frost", as stated by Monteith (1).

(ii) the itensity of diffuse irradiation is to a certain degree a function of the albedo (reflectance) of the ground; a high surface albedo, which could be the result of fresh snow cover, results in higher reflections of solar irradiation back to the sky some of which is in turn reflected back to the ground as additional diffuse irradiation. This factor is enhanced under partly cloudy skies when K_t assumes an intermediate value.

Further refinement of the Winter diffuse irradiation model may be achieved by incorporating the influence of the multiple reflections between the earth's surface and atmosphere. Hay (2) has shown that there is some potential in this approach especially under conditions of high surface reflectivity.

Figure 6 shows the plot of diffuse ratio against clearness index for Camborne. While data points for Winter and Spring are close to each other, those for Summer are significantly and distinctly lying higher up. This could be explained to the higher turbidity of atmosphere during Summer season as reported by Souster (3). Plots similar to the one shown in Fig. 6 were obtained for all the eleven locations considered in this study. For each of the remaining stations the trend was a repeat of those shown for Camborne, i.e. Summer and Winter data points at the top and bottom respectively and Spring/Autumn data points lying in between.

The trend of the regressed curves for different stations is shown in Figs. 7 and 8. The station numbers are arranged in a decreasing order of latitude. Three points are noticeable.

Firstly there is some bearing of latitude on the data points. Secondly the scatter in Winter is more widespread than in Summer and, thirdly the data points for Lerwick have a distinct character, higher diffuse ratio for all values of K_t. This phenomenon could be attributed to the geographical location of Lerwick, an island detached from the mainland UK and lying at a high latitude.

Following the identification of Lerwick possessing a unique character due to its geographical position, the data points computed from regression equations for Lerwick and Stornoway (both Coastal locations on small islands and close to each other in latitude) were plotted separately. Figures 9 and 10 display these results for Winter and Summer respectively. The closeness of the data points for the two locations is marked.

A single regression equation was attempted for the entire United Kingdom by pooling data for all mainland locations separately for Summer and Winter/ Spring/Autumn (Lerwick and Stornoway having a different behaviour were excluded from this analysis). For each location the data points for Winter, Spring and Autumn were enjoined due to the closeness of the respective data points. The regression equations for the UK are shown in Table 1. Further details of the correlation between hourly diffuse and global irradiation may be found in Refs. (4) and (5).

Estimation of Daily Diffuse Irradiation

The estimation of daily diffuse irradiation is carried out by the same process as is the hourly diffuse fraction. A relationship between monthly-averaged daily diffuse and global irradiation has been developed by Page (6). Rodgers et al (7) have extended this work to predict long-term performance of vertical glazings. However, for detailed analysis diffuse and global irradiation have to be evaluated on a day-to-day basis. In this section a relationship between daily diffuse ratio D/G (ratio of daily diffuse to global irradiation on a horizontal surface) and daily clearness index G/E (ratio of daily global to extraterrestrial irradiation on a horizontal surface) is presented.

Daily diffuse and global horizontal irradiation data from five locations in the UK, with a minimum of three-year records, was used in establishing the above relationship. Regression analysis was carried out for each of the five locations and then for the UK by pooling all the data. The data points were plotted for specific ranges of fractional sunshine. In the final analysis, however, the regression curves were found to be independent of the fractional sunshine. Figs. 11 and 12 show the plots for Lerwick and Easthampstead respectively. A stronger correlation is to be noticed at the daily level. A straight line fit, relating the daily diffuse ratio and clearness index, was found to be the optimum:

$$D/G = a_0 + a_1 K_t \; ; \; K_t > d \qquad (3)$$

$$D/G = a_2 \; ; \; K_t \leq d \qquad (4)$$

Table 2 provides the values of the regression coefficients for the five locations and for the UK.

The effect of latitude is studied once again by plotting, simultaneously, the regression lines for all five locations.

Figure 13 displays the closeness of the regression lines to each other thus justifying the use of a single relationship for the United Kingdom.

Further information on the analysis under discussion are provided in Ref. (8).

Hourly Model for Inclined Surface Irradiation

Given the horizontal diffuse and global irradiation the beam irradiation on an inclined surface is obtained easily by means of solar geometry (9). The corresponding sky-diffuse component is, however, not so straightforward to estimate. It requires validated models which take into account the anisotropic radiance distribution of the sky. Using one-year data for one inclined and four vertical surfaces, for Easthampstead and Lerwick, the isotropic and some other anisotropic models were evaluated for their performance (10, 11). Neither of those models were found to be satisfactory. Hence a new all-sky model was established which treated the surfaces in shade and sunlit conditions separately (10, 11).

Details of this model are as follows:

Three distinct groups of data points were identified for hours in which

(a) the surface is in shade,

(b) the surface faces the sun but under overcast conditions,

(c) the surfaces the sun under non-overcast conditions.

The data points belonging to groups (a) and (b) were plotted separately to obtain relations between measured hourly vertical (I_{DV}) and horizontal diffuse irradiation. A linear trend and subsequent least-squares fit yielded:

$I_{DV} = 0.356\ I_D$, (for Easthampstead) $\quad$ $I_{DV} = 0.357\ I_D$ (for Lerwick) (surface in shade)

and

$I_{DV} = 0.404\ I_D$, (for Easthampstead) $\quad$ $I_{DV} = 0.426\ I_D$ (for Lerwick) (sunlit surface under overcast sky)

Since the isotropic model suggests, for either of the two cases, $I_{DV} = 0.5 I_D$ the above relationships suggest the anisotropic distribution of sky radiance. Moon and Spencer (12) proposed the luminance distribution of an overcast sky as

$$L_\delta = L_z \frac{1 + b \operatorname{Sin} \delta}{1 + b} \qquad (5)$$

with b = 2. L_δ and L_z are, respectively, the luminance of the sky at an angle δ from the horizon and at the Zenith. The values of b (radiance distribution index), for the two cases under discussion, are shown in Table 3.

Once the radiance distribution of the sky is known the diffuse irradiation on a slope ($I_{D\beta}$) may be obtained by integration of Eq.5 as,

$$\frac{I_{D\beta}}{I_D} = \operatorname{Cos}^2 \frac{\beta}{2} + 2b\ \{(3+2b)\}^{-1}\ \{\operatorname{Sin} \beta - \beta \operatorname{Cos} \beta - \pi \operatorname{Sin}^2 \frac{\beta}{2}\} \qquad (6)$$

where β is the slope's angle with the horizontal.

For hours in which the surface faces the sun under non-overcast conditions the sky-diffuse irradiation was modelled as a combination of (i) a circumsolar component, and (ii) the background irradiation which is also anisotropic. The two components are mixed using a modulating function, $F = (I_G - I_D)/I_E$. Thus, the slope irradiation for this case is

$$I_{D\beta} = I_D\ \frac{\operatorname{Cos} i}{\operatorname{Sin} \alpha}\ F + T(1-F) \qquad (7)$$

where T is the tilt factor given by the R.H.S. of Eq. 6, and i is the angle of incidence of sun's rays on any surface. α is the solar altitude. The optimum values of b for Easthampstead and Lerwick are given in Table 3.

Figures 14 and 15 compare the performances of the presently discussed model and the isotropic model using Easthampstead data. Similar plots have been obtained for Lerwick, Aberdeen, Edinburgh and Cardiff data and may be referred (10, 11).

Daily Model for Inclined Surface Irradiation

The horizontal diffuse and global irradiation data can be used to estimate slope irradiation provided R, the ratio of global irradiation on a slope to that on a horizontal surface, is known. R can be expressed in terms of the contribution of the beam and diffuse irradiation:

$$R_B = \frac{B_\beta}{B} \qquad (8)$$

and

$$R_D = \frac{D_\beta}{D} \qquad (9)$$

where B_β and D_β are, respectively, the daily beam and diffuse irradiation on a slope. R is then given by

$$R = \frac{B}{G} R_B + \frac{D}{G} R_D \qquad (10)$$

The angular correction for the beam component may be evolved analytically by using the principles of solar geometry (12). The procedure involves the integration of beam irradiation on an inclined surface and on a horizontal surface

$$R_B = \int_{w_s'}^{w_s} \cos i \, dw \Big/ \int_{w_s'}^{w_s} \sin \alpha \, dw \qquad (11)$$

Equations of R_B for vertical and inclined surfaces are provided in Ref. (12).

In the isotropic model R_D (refer Eqs. 9 and 10) is given as

$$R_D = \cos^2 (\beta/2) \qquad (12)$$

The data used for evaluating the daily isotropic and an anisotropic model was the same as described in the previous section. Fig. 16 shows the plot of the isotropic model for Easthampstead.

There are three groups of points towards which attention is drawn. The group containing points almost all of which lay above the 45°-line were identified as those belonging to the south facing surfaces (one vertical and the other tilted at the local latitude angle). The second group of points, which clustered just below the 45°-line and having low values of irradiation, were identified as those belonging to the north oriented surface. A third group of points, which were scattered on either side of the line, were those belonging to the east and west surfaces. It is apparent that the isotropic model consistently under predicts and over predicts for south and north facing surfaces respectively.

In the development of a daily anisotropic model for slope irradiation the approach of hourly model was adopted. However, it should be noted that, while at an hourly level it is straightforward to determine whether the given surface is in shade, this is not the case on a daily basis. The surface may be under shade for a fraction of the day-length (the period between astronomical sunrise and sunset). The procedure to determine the fraction of the time the sloped surface is under shade is described in detail in Ref. (12).

The fraction of the time, during a day, a surface is under shade (F_{shade}) is obtained as

$$F_{shade} = 1 - F_{sun} \qquad (13)$$

where F_{sun} is the fraction of day-length the surface is sunlit.

For any sloped surface facing south

$$F_{sun} = \omega_s'/\omega_s \qquad (14)$$

where ω_s' is obtained from

$$\omega_s' = \min \begin{vmatrix} \omega_s \\ \arccos(-\tan(L - \beta)/\tan\delta) \end{vmatrix} \qquad (15)$$

ω_s and ω_s' are the sunset hour angles on the horizontal and inclined surfaces respectively, L is the locality's latitude and δ is the sun's declination.

The sun's motion in the northern hemisphere is symmetric about the south. Hence for either of the two cases - vertical surfaces facing east or west,

$$F_{sun} = 0.5 \qquad (16)$$

The daily anisotropic model may be written as

For overcast days (i.e. when G = D)

$$G_\beta = D^* \, [F_{shade} * T_{shade} + F_{sun} * T_{overcast}] \qquad (17)$$

The "tilt factors" T_{shade} and $T_{overcast}$ are the ratios of the diffuse irradiation on a slope to that on a horizontal surface. The values of these factors depend upon the tilt of the surface and the radiance distribution of the sky for the respective case. Equations for T_{shade} and $T_{overcast}$ were reported in the previous section.

For non-overcast days (i.e. when G > D)

$$G_\beta = (G - D)R_B + D * \; (R_B{*}F + T_{non-overcast}^{*(1-F)}) \, F_{sun} + T_{shade} * F_{shade} \qquad (18)$$

where $T_{non-overcast}$ is the tilt factor for the sunlit surface under non-overcast conditions, and F is the modulating function which "mixes" the diffuse circumsolar and background sky irradiation. F is given by,

$$F = (G - D)/E \qquad (19)$$

Table 4 displays the values of the three tilt factors.

Figures 17 and 18 display the results for the anisotropic model for the south and the east and west facing surfaces for Easthampstead. Similar plots were obtained for Lerwick. It is to be noted that the points for east and west lie in pairs in exact verticality (this becomes evident if the pairs of point to the extreme right are observed closely). The reason for this phenomenon may be attributed to the fact that the model does not differentiate between east and west facing surfaces, both having the same orientation with respect to the south. However, the measured values of irradiation of the two surfaces may be different due to changing weather conditions during the day. A pair of points, one belonging to the east and other to the west facing surface, lie close to each other if the cloud condition throughout the day remains unchanged. However, they become separated, sometimes widely, if the cloud conditions fluctuate during the day, resulting in uneven irradiation received by the horizontal surface during the two half day-lengths around the solar noon.

The irradiation on north facing surface was plotted separately against horizontal irradiation. A straight line regression was identified, the slope being equal to 0.4 both for Easthampstead and Lerwick data. Thus the irradiation on the north facing vertical surface has been modelled as

$$G_\beta = 0.4 * G \qquad (20)$$

This result is in agreement with the study carried out by CIBSE (13). CIBSE findings were based on two consecutive years data for Kew.

Figure 19 shows the performance of the model for the north facing surface for Easthampstead data. The same pattern was noted for Lerwick data (12).

<u>Use of Daily Sunshine Data</u>

Cowley (14) has presented a relationship to estimate daily horizontal global irradiation from data for daily sunshine. Since sunshine data is recorded by the Meteorological Office at 231 stations, Cowley's relationships may be effectively used for estimating global irradiation for all these sites in the United Kingdom. The models presented herein may then be used to estimate daily slope irradiation for the above sites.

Conclusions

A method has been presented which enables estimation of the hourly and daily solar irradiation on inclined surfaces, given the horizontal irradiation. The method involves, in the first instance, estimation of horizontal diffuse irradiation where such data are not recorded. Inclined surface irradiation is then calculated using an anisotropic model for sky-diffuse irradiation.

The method can be used to obtain good estimates of hourly slope irradiation for 26 locations in the United Kingdom. Correspondingly, if estimates of daily slope irradiation are required these may be obtained, with significant accuracy, for 56 locations where horizontal irradiation is recorded or for 231 locations, with reasonable accuracy, where sunshine measurements are carried out.

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TABLE 1 - Regression co-efficients for hourly irradiation stations.

Station	Latitude Deg	Latitude Min	Period	No of Hours	WINTER a_o	WINTER a_1	WINTER a_2	WINTER a_3	WINTER R^2	SUMMER a_o	SUMMER a_1	SUMMER a_2	SUMMER a_3	SUMMER R^2	SPRING a_o	SPRING a_1	SPRING a_2	SPRING a_3	SPRING R^2
LERWICK	60	08	Jan '81 - Dec '83	12701	0.617	3.668	-11.197	8.352	0.49	0.304	5.768	-14.271	8.840	0.81	0.685	3.143	-9.510	6.184	0.79
STORNOWAY	58	12	Oct '82 - Dec '83	5263	0.539	4.513	-13.254	9.695	0.63	0.524	4.056	-10.106	5.766	0.88	0.576	4.030	-11.701	7.951	0.81
SHANWELL	56	26	Jan '82 - Dec '83	9396	0.456	5.237	-15.718	11.469	0.76	0.721	2.722	-7.903	4.614	0.84	0.579	4.148	-12.576	8.767	0.82
ESKDALEMUIR	55	19	Jan '81 - Dec '83	12723	0.559	4.032	-11.715	7.818	0.72	0.638	3.228	-9.102	5.621	0.80	0.755	2.379	-7.429	4.609	0.78
ALDERGROVE	54	39	Jan '81 - Dec '83	14107	0.644	3.090	-9.220	5.938	0.69	0.513	3.793	-9.739	5.745	0.82	0.679	2.800	-8.396	5.279	0.79
AUGHTON	53	33	Jan '82 - Dec '83	8144	0.758	2.660	-8.839	6.162	0.56	0.777	2.142	-6.224	3.317	0.83	0.786	2.186	-6.891	4.062	0.79
FINNINGLEY	53	29	Nov '82 - Dec '83	5116	0.312	6.614	-19.263	14.472	0.76	0.744	2.386	-6.796	3.718	0.84	0.572	4.034	-11.966	8.311	0.80
HEMSBY	52	51	Jan '82 - Dec '83	9006	0.487	5.055	-14.896	10.476	0.80	0.787	2.073	-6.198	3.340	0.83	0.790	2.139	-6.922	4.111	0.83
ABERPORTH	52	08	Jan '81 - Dec '83	11937	0.579	4.093	-12.006	8.058	0.76	0.681	2.821	-7.650	4.260	0.80	0.741	2.628	-8.162	5.088	0.79
EASTHAMP-STEAD	51	23	Jan '81 - Dec '83	14058	0.349	6.085	-17.438	12.387	0.80	0.857	1.570	-5.608	3.271	0.82	0.784	2.396	-8.306	5.558	0.83
CAMBORNE	50	13	Jan '82 - Dec '83	9109	0.514	4.644	-13.539	9.389	0.80	0.632	3.211	-8.730	5.167	0.80	0.804	2.145	-6.977	4.198	0.84
UNITED KINGDOM	-	-	-	111552	0.629	3.549	-10.651	7.098	0.79	0.651	3.050	-8.460	5.006	0.81	-	-	-	-	-

TABLE 2 - Regression co-efficients for daily irradiation stations.

Station name	Latitude Deg (North)	Latitude Min (North)	Longitude Deg (West)	Longitude Min (West)	Regression coefficients: Intercept a_0	Slope a_1	Value of a_2	R^2-value	Value of 'd'	Number of days used
Lerwick	60	08	01	11	1.382	-1.561	0.967	0.792	0.266	777
Eskdalemuir	55	19	03	12	1.299	-1.428	0.938	0.818	0.253	956
Aldergrove	54	39	06	13	1.288	-1.395	0.963	0.842	0.233	1043
Aberporth	52	08	04	34	1.333	-1.489	0.973	0.812	0.242	780
Easthampstead	51	23	00	47	1.316	-1.513	0.944	0.838	0.246	1081
UK	-	-	-	-	1.320	-1.472	0.937	0.811	0.260	4637

TABLE 3 - Values of 'b' for Easthampstead and Lerwick.

Case	Lerwick	Easthampstead
Surface in shade	5.49	5.73
Sunlit surface under overcast sky ($I_G = I_D$)	1.04	1.68
Sunlit surface under non-overcast sky ($I_G > I_D$)	-0.73	-0.62

TABLE 4 - Tilt factors for Easthampstead and Lerwick.

Case	Easthampstead $\beta = 90°$	Easthampstead $\beta = 51.4°$	Lerwick $\beta = 90°$	Lerwick $\beta = 60.1°$
Surface in shade (T_{shade})	0.356	0.719	0.357	0.638
Sunlit surface under overcast sky (G = D) ($T_{overcast}$)	0.404	0.750	0.426	0.691
Sunlit surface under non-overcast sky (G > D) ($T_{non\text{-}overcast}$)	0.628	0.895	0.672	0.883

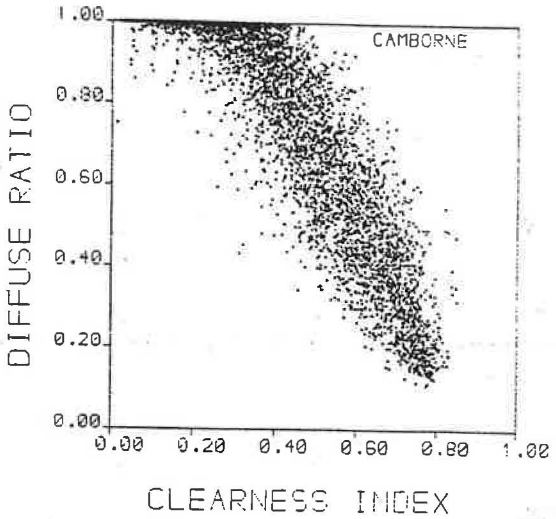


Figure 1 Hourly diffuse ratio against clearness index - all year

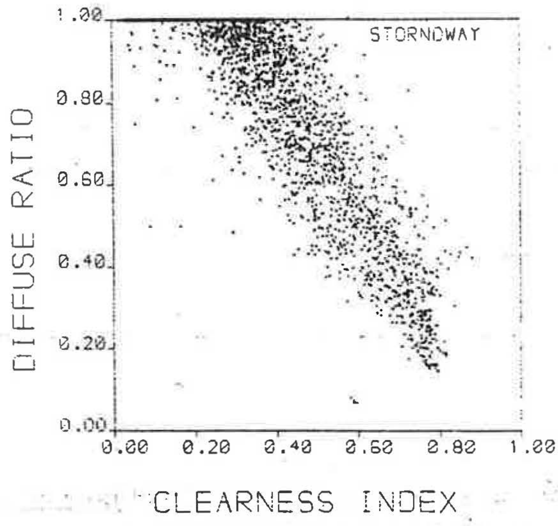


Figure 2 Hourly diffuse ratio against clearness index - all year

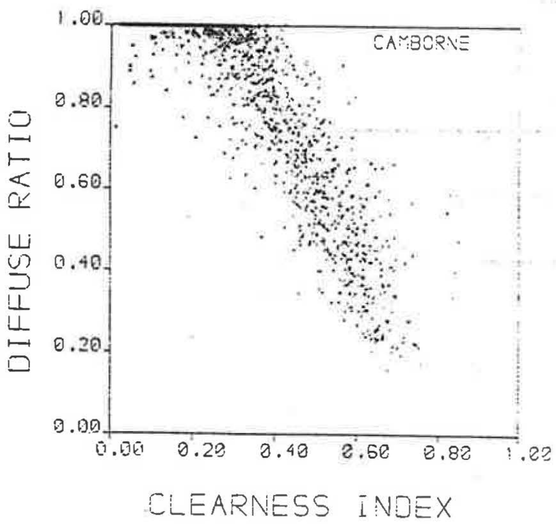


Figure 3 Hourly diffuse ratio against clearness index - Winter

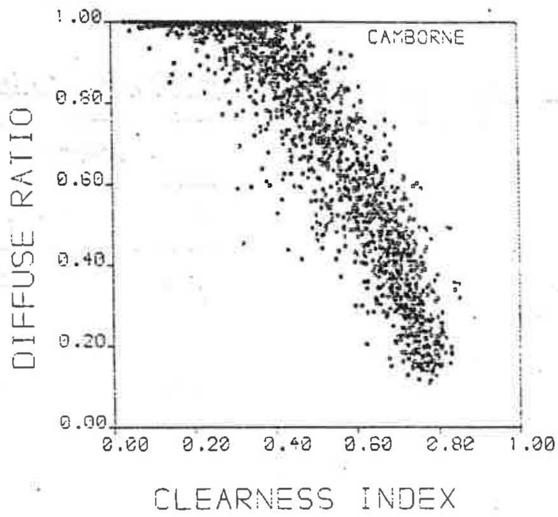


Figure 4 Hourly diffuse ratio against clearness index - Spring/Autumn

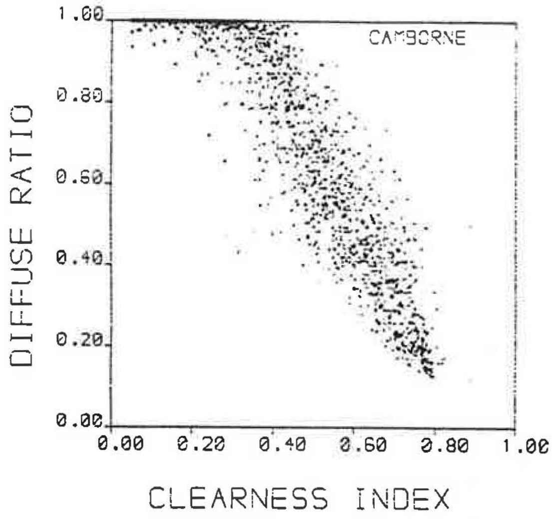


Figure 5 Hourly diffuse ratio against clearness index - Summer

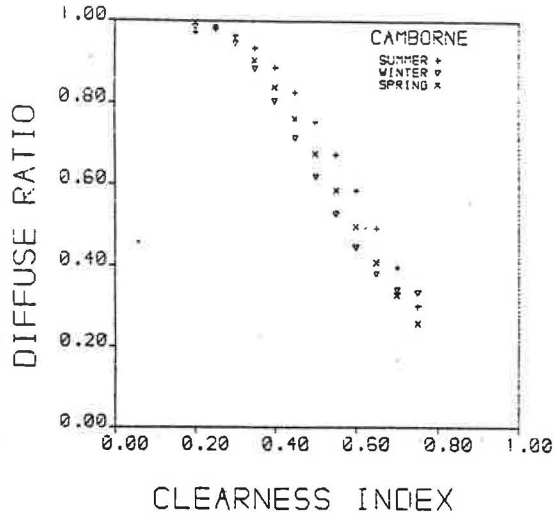


Figure 6 Averaged diffuse ratios

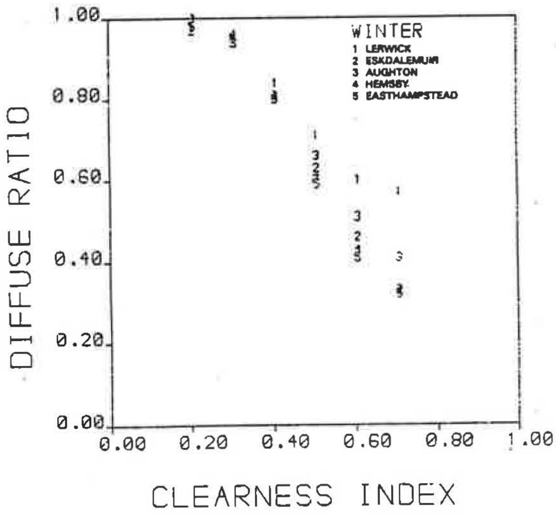


Figure 7 Averaged diffuse ratios for Winter

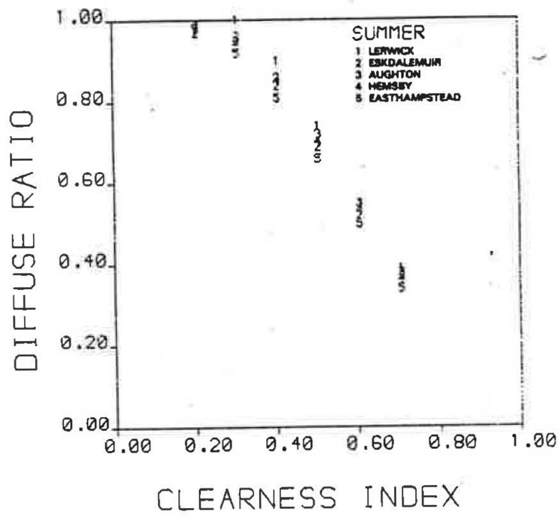


Figure 8 Averaged diffuse ratios for Summer

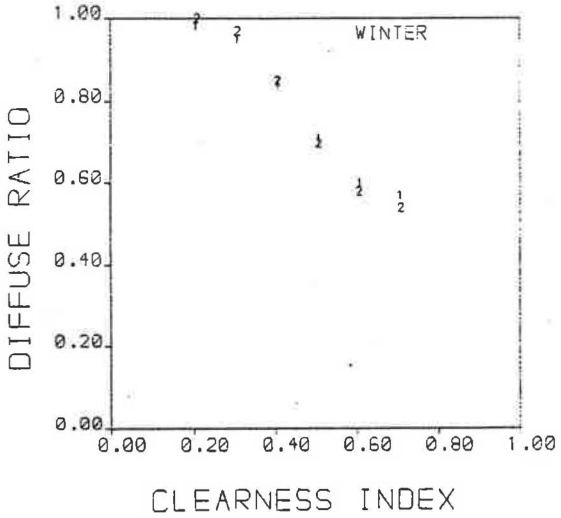


Figure 9 Averaged diffuse ratios for Winter. 1 - Lerwick
2 - Stornoway

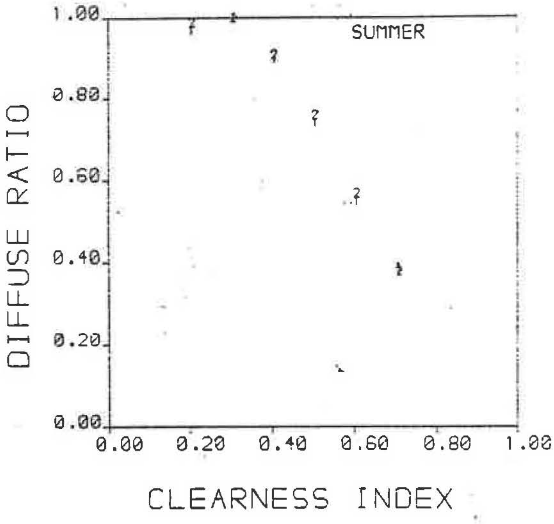


Figure 10 Averaged diffuse ratios for Summer. 1 - Lerwick
2 - Stornoway

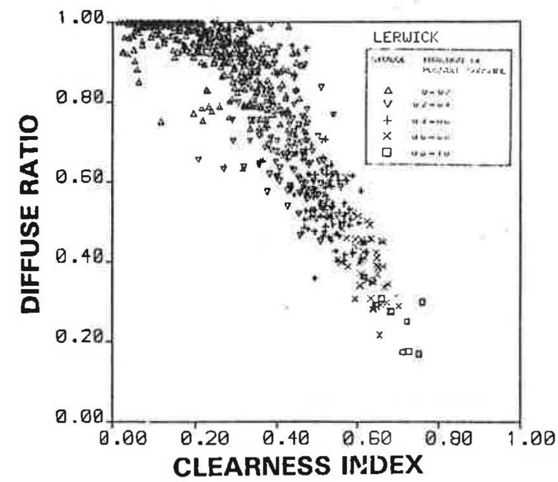


Figure 11 Daily diffuse ratio against clearness index

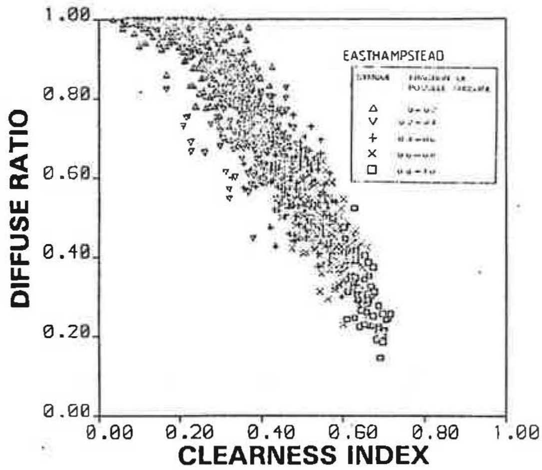


Figure 12 Daily diffuse ratio against clearness index

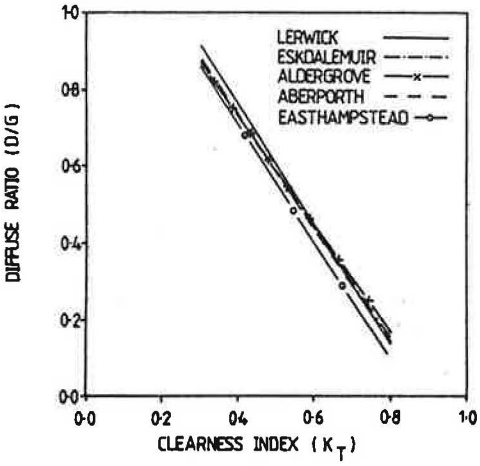


Figure 13 Comparison of the daily regressions

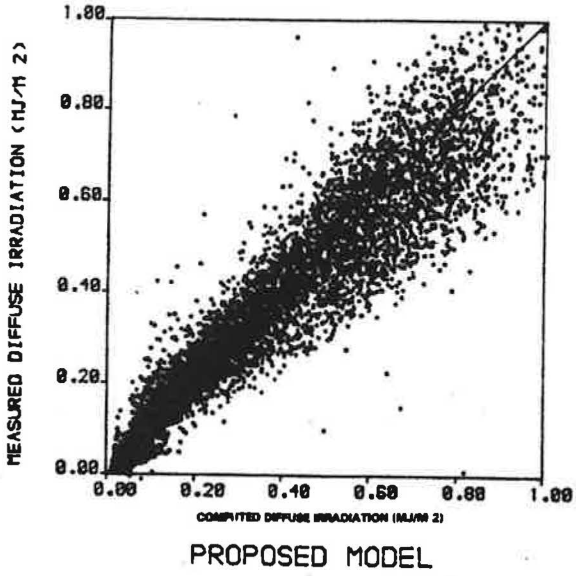


Figure 14 Performance of the hourly anisotropic model

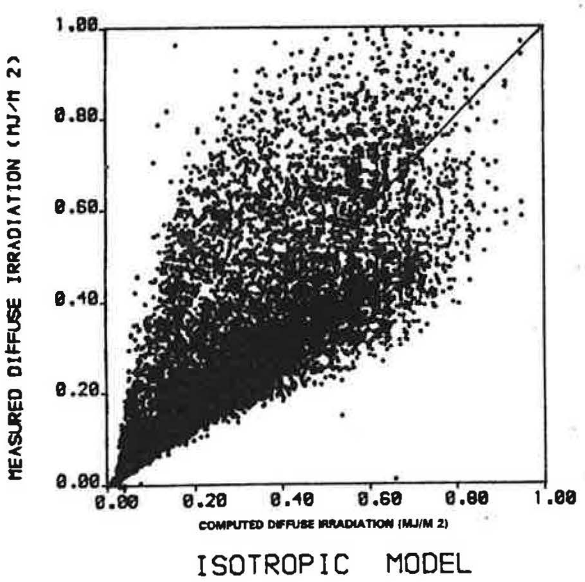


Figure 15 Performance of the hourly isotropic model

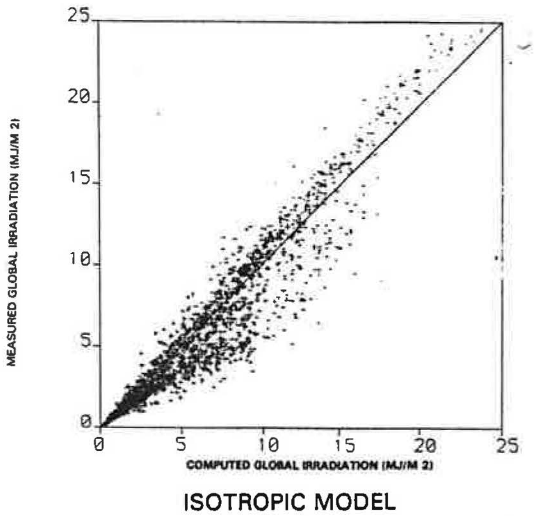
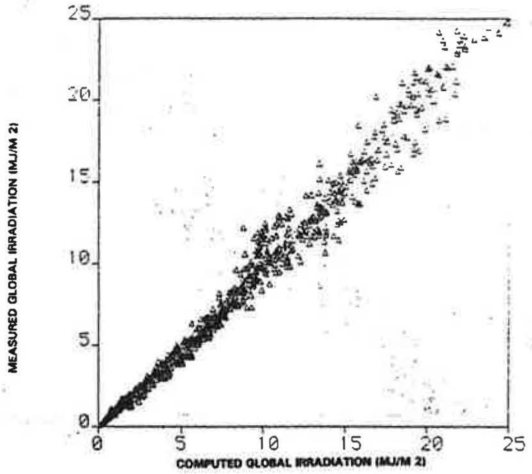
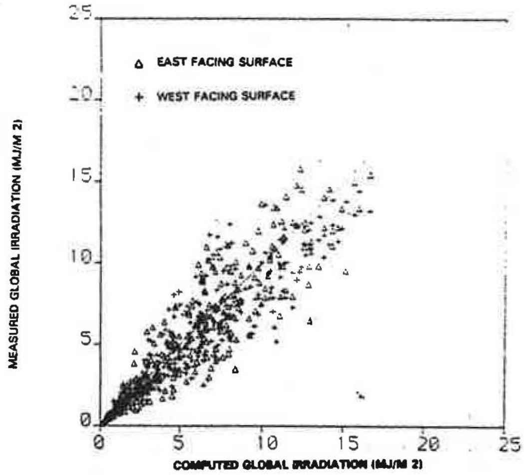


Figure 16 Performance of the daily isotropic model - Easthampstead (all surfaces)



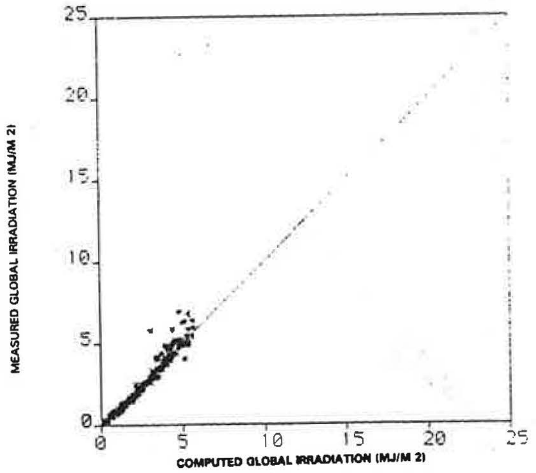
PROPOSED MODEL

Figure 17 Peformance of the daily anisotropic model - Easthampstead (south facing surfaces)



PROPOSED MODEL

Figure 18 Performance of the daily anisotropic model - Easthampstead (east and west facing surfaces)



PROPOSED MODEL

Figure 19 Performance of the daily anistropic model - Easthampstead (north facing surfaces)