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Systematic Design Assessment Techniques for Solar Buildings

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Systematic design assessment techniques for solar buildings

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Solar building design involves the systematic study of complex interrelationships between the interacting temporal patterns of solar energy supply and energy demand within buildings. Variations in weather exercise a dominant role. Peak energy demands and solar supply tend to be antiphase. While the temporal matches between such dynamic inputs and outputs can be improved by the introduction of appropriate thermal storage, the building fabric itself acts as a capacitance phase regulator. It is necessary to be able to model the solar inputs and weather dependent energy losses dynamically to predict thermal performance.

A team in the Department of Building Science, University of Sheffield, has been studying how to automate the complex climatological design assessment of passive and active solar buildings with the use of interactive computer aided design techniques with associated graphics. This paper describes the various approaches developed for the detailed modelling of the relevant climatic input variables. A report is made of the techniques developed to generate systematic short wave radiation data for vertical and inclined surfaces for different types of weather. The analysis is based on types of day – sunny, average and overcast. Work on the accurate estimation of the magnitude of the associated weather variables affecting heat transfer in the external environment is also reported – these studies cover air temperature, wind speed and long wave radiation exchanges. The outputs of this climatological analysis provide inputs into detailed thermal analysis programmes developed to predict different aspects of solar building thermal performance.

1. Introduction

A successful solar building must match a highly variable supply of solar energy with a highly variable pattern of demand for that energy. The accurate prediction of thermal performance is complex for three reasons. First, the instantaneous flows of solar energy into the collection system and through the windows change so rapidly. Secondly, the demands for energy for space heating and cooling are very variable and out of phase. Thirdly, the substantial thermal capacity of buildings complicates the responses.

Alterations in cloud amount and atmospheric aerosol content produce random short term solar variations which are superimposed on the basic diurnal rhythms of solar irradiance resulting from the daily rotation of the Earth on its axis. Spells of cyclonic and anticyclonic weather impose additional short term patterns. Such variations in turn are superimposed on the annual rhythms resulting from the movement of the Earth in its elliptical orbit round the Sun with the polar axis inclined at 23° 27′ to the ecliptic plane.

The precise energy demand at any instant depends on complex interactions between the thermal properties of the basic fabric, variations in the activities within the conditioned space and changes in the external climates that impinge on the various external surfaces of the fabric, each surface of which has a different surface climate. As buildings are normally constructed of materials of substantial thermal capacity, they have an important 'thermal memory' which influences subsequent instantaneous energy demands.

While partially solar heated buildings will use less energy overall than ordinary buildings, they may still produce, in the absence of adequate thermal storage, big peak energy demands in cold weather to be met from conventional energy sources when insufficient solar energy is available. This will add to the simultaneous peak load created elsewhere by the cold weather. This will influence the economics of solar buildings, because, given adverse peak to average load ratios, the supply utilities may be forced to increase their charges to meet their overheads as suppliers of standby power. Systematic climatic analysis is thus a key factor in design. The complexity of the necessary dynamic thermal analysis makes it essential to adopt sophisticated climatological computing approaches.

2. Climatological simulation compared with meteorological simulation

There are two fundamental choices open for mathematical simulation of the influence of weather on the thermal performance of solar buildings:

(i) Meteorological simulation, which demands feeding into the analysis a sequential input of a long series of simultaneously recorded meteorological observations of the relevant weather variables in precisely the same sequence in which they were observed in real time.

(ii) Climatological simulation based on statistical descriptions of the probabalistic properties of climate derived from a consistent set of meteorologically observed data. These statistically derived functions have more compact form than the original set of observed real time data and, therefore, offer economy in computation at the expense of some loss of information.

In meteorological simulation of solar building performance, hourly observed values of the solar energy input variables are typically used together with hourly values of the other relevant meteorological factors affecting heat transfer at the external surfaces, namely air temperature, wind speed and the incoming long wave radiation. Observed data are not usually available for vertical and inclined surfaces, and suitable techniques have to be evolved to estimate the solar radiation and other meteorological impacts on all non-horizontal surfaces from the observed set of horizontal surface data. The amount of hourly input data available from any long period of observation is so large that the computing costs in simulation become very high – 10 years hourly data for five meteorological variables implies a data bank of 438 000 observations for horizontal surfaces alone. As a result, to contain computing costs, recourse is made to short cuts in dynamic modelling like the selection of a 'standard design year' for the modelling of solar building thermal performance. The selection of a standard design year sounds simple, but once one considers the detailed problems of converting data from horizontal surfaces to inclined surfaces, one cannot even be certain one is choosing a representative month for a particular inclined surface as opposed to a representative month for a horizontal surface, because different radiation conversion weightings are needed for surfaces of different aspect. There are also so many basic data to handle in random order that it is difficult to introduce additional corrections to allow for microclimatic effects like the effect of height on air temperature and wind speed or urban heat island effects. These effects vary with weather type. Furthermore the outputs from such complex meteorological analyses, costly though they are in computing time, are difficult to interpret in building design terms because performance in different types of weather is all intertwined. The outputs tend to lack a structured clarity so it is difficult architecturally to identify and rectify with certainty the precise design shortcomings.

Furthermore, standard design years are only available for a very restricted range of stations, usually only one or two per country. In practice the meteorological variations from place to place are significantly large; everyone living in the U.K. knows it is much better climatologically to winter in Cornwall than in the Shetlands. Thus full meteorological simulation, however attractive it may be in theory, has a number of serious practical drawbacks.

Climatological simulation also uses dynamic analytical modelling techniques, but instead of putting into the final simulation all the hourly data for, say, a 10 year period, the observed data are first processed to produce far more compact statistical descriptions of the hourly values of the weather variables for different types of weather. This data compaction process allows the statistical use of long periods of observed data without paying the penalty of excessive computing costs implied by hour to hour simulation analyses over periods of years. No recourse has to be made to scientifically dubious selection procedures like the selection of a standard design year, which usually involves the assembly of monthly data for selected months chosen from different years to produce a somewhat subjective assessment of what is a typical year. As the data bank to be handled in climatological simulation is so much smaller than in meteorological simulation, it becomes feasible to introduce microclimatic modifiers to make allowances for the important vertical variations in climate in different types of weather. Standard screen temperature data and standard 10 m wind data can thus be modified to match the actual scale of and position on the building being simulated; this may be important as building height typically exceeds the height of the standard meteorological screen by one to two orders of magnitude.

For these reasons, in the Department of Building Science in Sheffield we have preferred to develop mathematical models based on climatological series for the thermal assessment of solar building performance.

3. The systems framework adopted for climatological analysis of buildings

(a) *General considerations*

In our group we consider all buildings with windows as solar buildings, but some buildings are clearly more solar than others. Figure 1 is a system diagram for the overall climatological simulation system developed for building thermal analysis in Sheffield.

Our approach is based on a monthly statistical classification based on the levels of daily global irradiation observed on a horizontal surface. Essentially, we had available, from the Meteorological Office data analyses, monthly mean hourly weather data for days of high irradiation (sunny days) and for days of low irradiation (overcast days), and average days with associated monthly mean hourly values of the other relevant weather variables derived from all hourly observed data for four stations at Kew, Eskdalemuir, Lerwick and Aberporth for the 10 year period 1959–68. We have attempted to develop from this basic U.K. radiation network a prediction system for vertical and inclined surfaces to provide overall national coverage for the three classes of days. The basic system is modular and is designed to cover any location in the world, but some locally determined input parameters, like atmospheric turbidity and precipitable water vapour, are needed to obtain accurate data for specific locations. Initially we have concentrated on U.K. data, but work has now started, partially funded from the E.E.C., to extend our radiation studies to cover the whole of northwest Europe.

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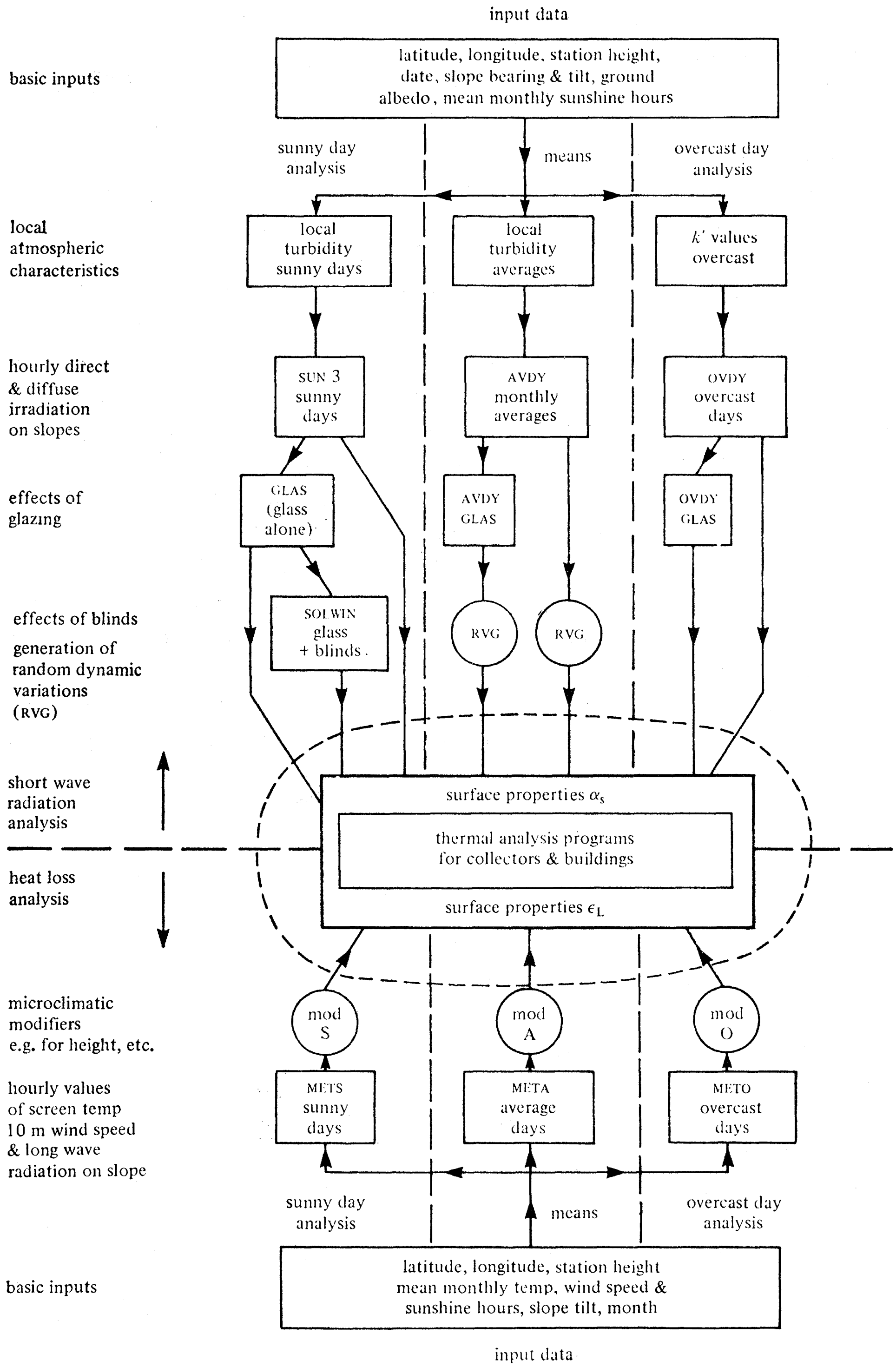

FIGURE 1. System diagram showing flow of climatological information through University of Sheffield Department of Building Science computing system into thermal programs.

(*b*) *Solar radiation modules*

The top part of figure 1 sets out the modules we have developed for climatologically assessing short wave gains on inclined surfaces for three types of day, clear, average and overcast. The option exists to insert glazing materials with different transmission properties in the beam for all three cases. These glazing programs take full account of all angle of incidence and reflexion effects on glazing transmission and absorption. We can also calculate the effects of inserting internal shading blinds on sunny days. At a later stage we hope to be able to use random number statistical data generation techniques to produce hourly dynamic series of radiation data for slopes from our average day program AVDY to study the effect of rapidly varying conditions.

Many earlier prediction methods used in solar studies have been based on the adoption of standard radiation curves, for example, the data of Moon (1940). However, in a more sophisticated modelling approach, proper account has to be taken of the effects of variations in atmospheric turbidity on available solar radiation. These effects are particularly important when the Sun is low, which is the case in winter in the U.K.

In order to achieve accurate modelling, a suitable meteorologically validated radiation transmission model of the atmosphere had first to be selected. This model had to allow accurately for local variations in both atmospheric water content and atmospheric clarity in the prediction of the clear sky direct irradiances. The turbidity model proposed by Unsworth & Monteith (1972) was adopted. This transmission model is based on a turbidity coefficient, τ_a, which relates the measured direct normal solar irradiance, G_{bn}, with a stated amount of precipitable water vapour in the atmosphere to the clean air direct normal irradiance G^*_{bn} with the same amount of precipitable water vapour by the expression

$$G_{bn} = cG^*_{bn} \exp(-\tau_a m), \tag{1}$$

where m is the optical air mass and G^*_{bn} is the irradiance normal to the beam for a standard clean atmosphere containing the stated precipitable water vapour content and standardized specific amounts of the normal atmospheric absorbing and scattering gases, ozone, carbon dioxide, etc. and c is a correction factor to allow for variations in Sun–Earth distance to adjust the value of G^*_{bn} to allow for actual solar distance for the date in question. G^*_{bn} depends on atmospheric water vapour content and the path length. All our direct beam mathematical models closely follow the basic theory described by Unsworth (1975). Typical values of τ_a for different types of air mass for different areas of the U.K. are given in table 1.

The turbidity coefficient may vary quite considerably from day to day. In order to obtain statistically based values of turbidity coefficients for different types of day at different sites in the U.K. a systematic study was made for the period 1959–68 of the data from four long-established Meteorological Office stations recording hourly values of the horizontal global and diffuse radiation and duration of bright sunshine. These stations are at Aberporth, Eskdalemuir, Lerwick and Kew. For each site and for each month of the year, all the days in that same month over the 10 year period had already been ranked by the Meteorological Office in descending order of daily total global solar radiation. Then the data had been split into the following monthly categories for the 10 years:

(1) the day with the highest daily total in that month in the 10 year period,

(2) the 6 days with the highest daily totals,

(3) the 12 days with the highest daily totals,
(4) the 28, 30 or 31 days (depending on the month) with the highest daily totals,
(5) the 57, 60 or 62 days (depending on the month) with the highest daily totals.

Table 1. Characteristic values of the Monteith & Unsworth turbidity coefficients τ_a for the U.K. showing the influence of air mass type and location in relation to pollution sources

	air mass type	τ_a
northerly island site, minimum pollution from land sources	polar	0.05
	average	0.20
	continental	0.35
rural or coastal site exposed to natural aerosol pollution and small amounts of smoke	polar	0.10
	average	0.25
	continental	0.40
urban site within or close to a large town (say population exceeding 100000)	polar	0.25
	average	0.40
	continental	0.55

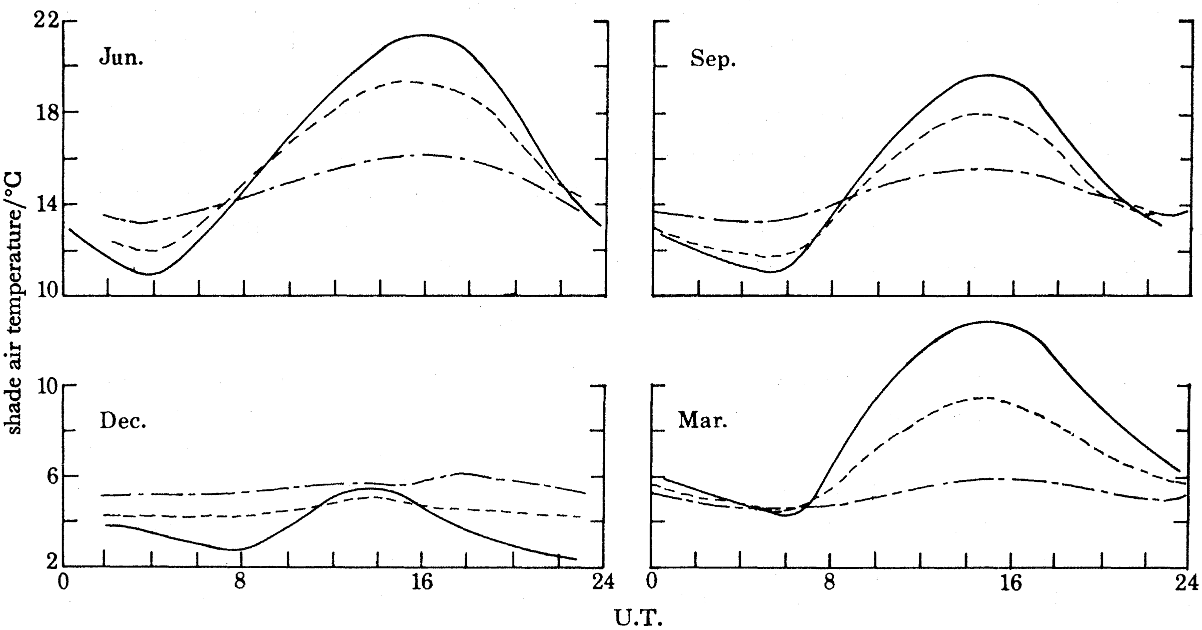

Figure 2. Diurnal variations in shade air temperature at Kew for three classes of daily global irradiation; smooth curve, days of high radiation, dotted curve, average days; and smooth curve with circles, days of low irradiation; for the months of March, June, September and December.

Similar categories were available for the days of low global irradiation. For each category the Meteorological Office has prepared a table for hourly intervals of time of global and diffuse radiation, sunshine duration, associated screen air temperature and 10 m wind speed based on the means of the corresponding values of all the days in that particular category for that station. The Meteorological Office summaries also give the monthly mean values.

All these data have been systematically analysed to derive appropriate mean values of the turbidity coefficient τ_a for each class of radiation day using typical monthly levels of precipitable water vapour over the U.K. The detailed values of τ_a obtained for different classes of radiation day have been published by Souster *et al.* (1979) together with some mapped data for the U.K.

(c) *Programs for generating the heat loss weather variables*

The bottom half of figure 1 sets out the range of programs developed for predicting simultaneous hourly values of wind speed at 10 m, dry bulb screen air temperature and the incoming long wave radiation on the required slope which are needed to estimate heat losses. These variables are not statistically independent of the short wave radiation inputs. The data generated by the programs indicated in the bottom half of figure 1 had to be based on data sorted to be correctly associated in phase and magnitude with the solar radiation data for different classes of radiation day above. Figure 2 shows the monthly mean diurnal temperature cycles for three classes of radiation day for four months for Kew.

Corresponding data for Aberporth, Eskdalemuir and Lerwick were available.

We have found it possible to collapse the associated U.K. climatological data for the four sites into reasonably simple predictive formulae for each type of day by using Fourier analysis and thus avoiding the use of extensive data banks based on specific stations (Page *et al.* 1979). Our programs generate appropriate climatological data for each specific place from monthly temperature, mean monthly wind speed and mean monthly sunshine hours by using basic equations held in the computer. At a later stage we hope to incorporate microclimatic modifiers to allow for observed effects like the effects of height on wind speed and temperature, and urban heat islands.

The long wave radiation models developed for slopes have been based on the detailed work of Unsworth & Monteith (1975) and Unsworth (1975).

4. Computer aided design and architecture: design philosophy for computing

Our system has simultaneously been developed with the user very much in mind. For a start we believe it is important that a building designer should retain choice and that any good design system should be of a branching nature, so the designer can explore the potential against the constraints, which are often very formidable. For example, the site constraints may make it impossible to make a solar house face precisely south. We also believe that architectural designers are unlikely ever to become efficient programmers. We do not like a situation where the programmer always has to intervene between the architect and the exploration of his problem. We have, therefore, developed our system to be interactive by using simple conversational programs open to direct use by architects regardless of their basic computing skills. The complexities lie within the programs and not in their use. Emphasis has also been placed on the use of well formulated outputs which always include the input data. The teletype print-out or visual display unit output thus provides an immediately intelligible communication document requiring no further processing to form an effective communication tool in its own right. This bypasses the need for follow-up typing pools with all the consequent delays and risks of numerical typing errors. The automation of the prediction of performance must be worked right through to meet the overall communication requirement. Accurate communication is one of the most fundamental problems of design of buildings in practice as large teams of designers and design regulators (Town Hall by-law officials, etc.) are always involved.

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5. The prediction of horizontal surface irradiances on cloudless days: program SUN1

Our program SUN1 enables the user to estimate the direct (G_{bh}), diffuse sky (G_{dh}) and global irradiances (G_h) on a horizontal surface from the turbidity for any date and place in the world for a given precipitable water vapour content. The direct beam irradiance G_{bn} is estimated by using equation 1. Then, for a horizontal surface,

$$G_{bh} = G_{bn} \cos i = G_{bn} \sin \alpha, \qquad (2)$$

where i is the angle of incidence and α is the solar altitude. The diffuse irradiance is also dependent on turbidity and solar altitude, increasing with increasing turbidity in contrast to G_{bh}. We had, therefore, to develop a suitable diffuse sky irradiance model linked to the Monteith & Unsworth turbidity system. The diffuse radiation model incorporated in our program

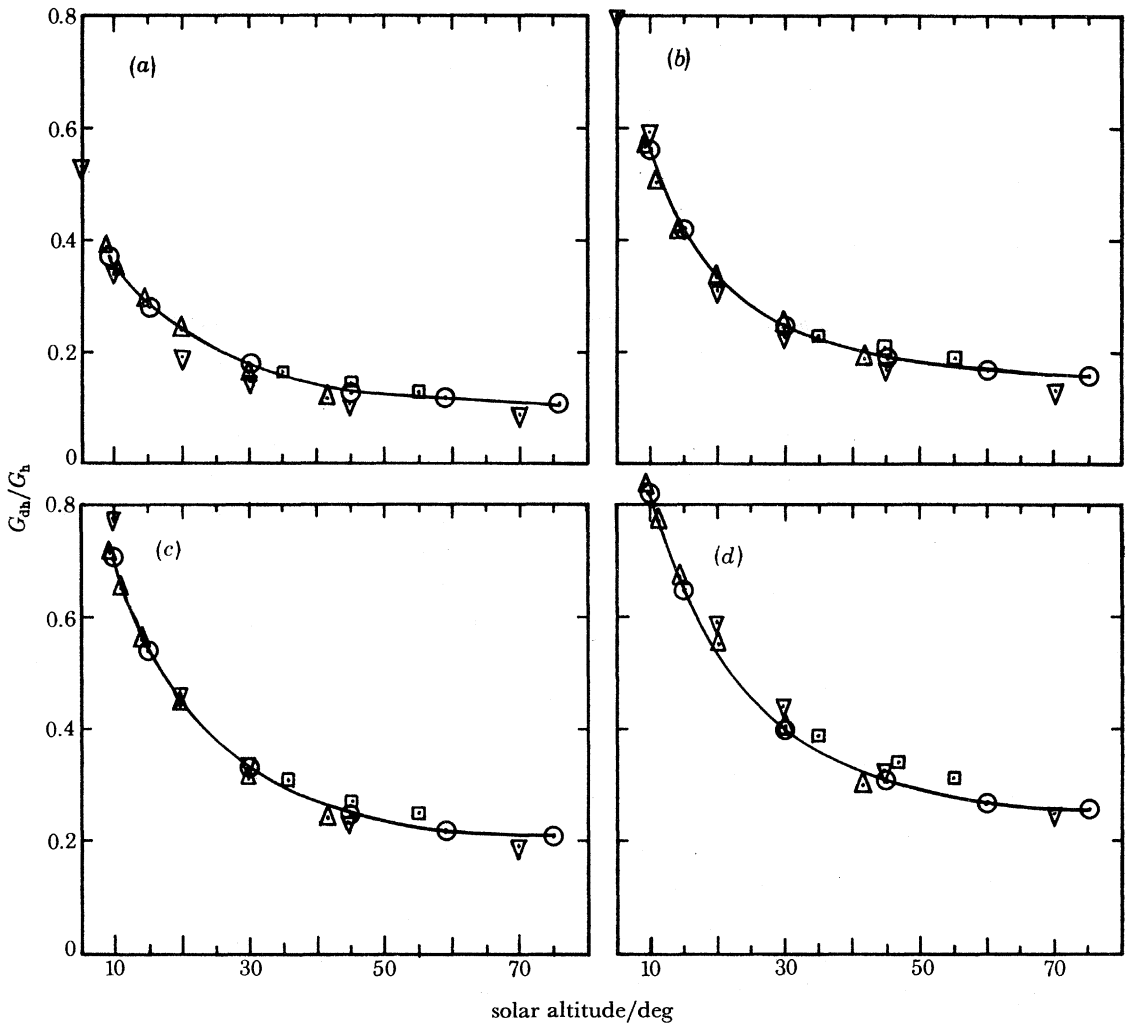

FIGURE 3. Dependence of the cloudless day ratio of the diffuse irradiance on a horizontal surface G_{dh} to the global irradiance G_h on solar altitude for τ_a = 0.1 (*a*), 0.2 (*b*), 0.3 (*c*) and 0.4 (*d*) as predicted by SUN1 and as observed by various authors: ▿, Valko; ⊡, McCartney & Unsworth; ▵, Parmelee, Blackwell; ⊙, SUN1.

SUN1 was initially developed from Parmelee's (1954) data for Ohio, obtained on days which, although cloudless, differed considerably in atmospheric clarity. His horizontal surface observations show that, for fixed solar altitude, a linear relation exists between the diffuse horizontal surface irradiance G_{dh} and the direct horizontal surface irradiance G_{bh} of the form

$$G_{dh} = a_0 + a_1 G_{bh}, \tag{3}$$

where a_0 and a_1 are constants which depend on the solar altitude. When the predictions of a computer program based on equation 3, which included the conversion of the Parmelee clarity values to corresponding values of τ_a, were compared systematically with measured European data obtained by Blackwell (1954), Dogniaux (1954), McCartney (1978), Valko (1975) and M. H. Unsworth & H. A. McCartney (1975, personal communication), certain minor inconsistencies in the original Parmelee data were revealed. This led to a detailed reconsideration of all the observational data. As a result of this review, an improved diffuse radiation model was developed for program SUN1. The turbidity range was also extended by using some extrapolation from the original Parmelee data together with theoretical studies of the Rayleigh sky to cover a wider range of turbidities ranging from a perfect Rayleigh sky with $\tau_a = 0$ to a very turbid atmosphere with $\tau_a = 0.6$. Full details of this analysis have been given by Rodgers *et al.* (1978). Figure 3 illustrates the variation of the ratio of the clear day horizontal diffuse irradiance G_{dh} to the global irradiance G_h with solar altitude for different turbidities as predicted by our revised diffuse sky model. Observed values of this ratio obtained by various workers are given for comparison. The agreement is extremely good. The new equations were incorporated into our cloudless day horizontal surface mathematical model for clear days SUN1.

The two irradiance components are then added together to obtain the global irradiance. Program SUN1 outputs irradiances hour by hour. Numerical integration also provides daily totals of the direct beam horizontal surface irradiation, diffuse horizontal surface irradiation and global irradiation for the chosen date, latitude, turbidity and precipitable water vapour content.

6. The prediction of the irradiance on slopes on cloudless days: program SUN3

We then developed from this new horizontal surface model another mathematical model SUN3 for the prediction of the radiation falling on surfaces of any slope and orientation under clear sky conditions. The direct beam radiation on slopes is simply handled trignometrically by using the values of G_{dn} predicted from the turbidity model. Our diffuse sky irradiance model is based on a non-isotropic sky. An isotropic sky will give a diffuse irradiance $G_{d\beta}$ on a slope β equal to $\frac{1}{2}(1+\cos\beta)G_{dh}$ where β is the slope angle. If $\beta = 90°$, then $G_{d\beta} = 0.5G_{dh}$. The radiance of the clear sky, however, is not uniform. Our new model was originally developed from Parmelee's (1954) observed vertical surface diffuse irradiance data in Cleveland, U.S.A., in conjunction with his horizontal surface data. However, the original data again had to be re-analysed so that the model could both reproduce results that agreed with Parmelee's original measurements on vertical surfaces, but also predict reasonably accurately sky irradiances on sloping surfaces observed by other workers elsewhere in the world, for example by Kondratyev & Fedorova (1976) in the U.S.S.R. and Valko (1975) in Switzerland. The model incorporated in our program SUN3 covers the same range of turbidities as our horizontal surface model and agrees with that model for horizontal surfaces. The anisotropy of the diffuse sky radiation was taken into account by separating the total diffuse sky irradiance into two components, a circum-solar diffuse component augmenting the direct beam and associated in direction with it and an isotropic diffuse component. Justification for splitting up the diffuse radiation in this way was first given by Loudon (1967). Loudon's approach, however, assumed the two diffuse components were independent of turbidity whereas our studies have shown the magnitude of the two components are definitely strongly dependent on turbidity.

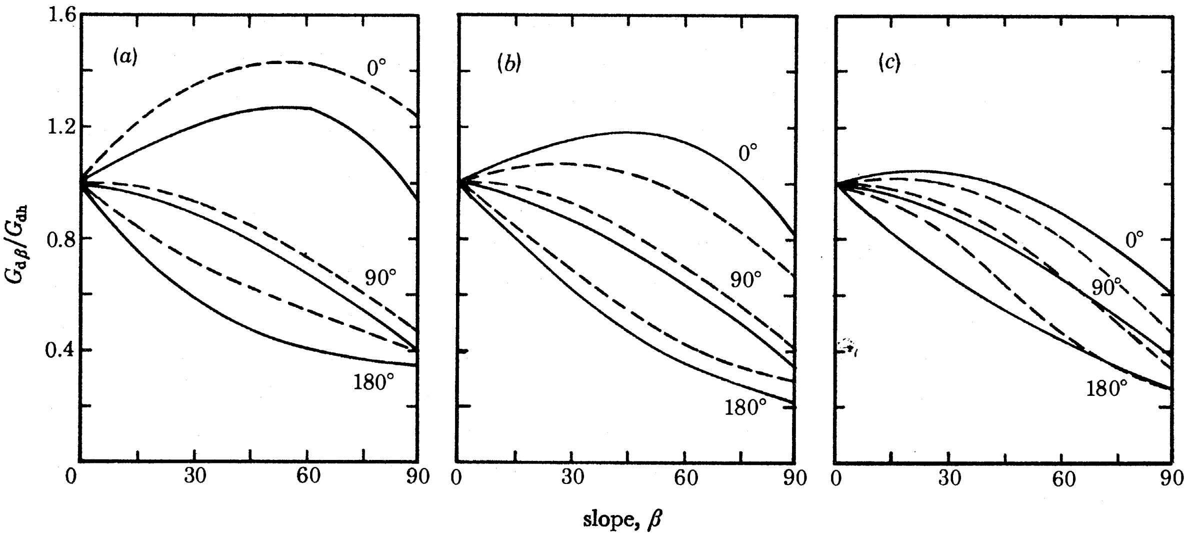

FIGURE 4. A comparison of the observed ratios of $G_{d\beta}/G_{dh}$ reported by Kondratyev & Fedorova (1976) with those predicted by program SUN3 for solar altitudes of 15° (*a*), 48° (*b*) and 68° (*c*) and wall-solar azimuths of 0°, 90° and 180°. ——, Values observed; – – –, values predicted by SUN3.

The ground reflected component is simply calculated from the global irradiance and albedo, an input variable, for the slope in question assuming uniform ground radiance.

We have compared our predicted sky diffuse irradiance on slopes with the measured values of various workers and found satisfactory agreement. Figure 4 shows a comparison of the predicted ratio of the diffuse sky irradiance on a surface of slope β, $G_{d\beta}$, to the simultaneous horizontal surface diffuse irradiance G_{dh} for different wall-solar azimuth angles and solar altitudes as predicted by the model in SUN3 compared with the reported observed U.S.S.R. data of Kondratyev & Federova (1976). Full details of the model developed and incorporated in SUN3 and the various checkouts with observed data have been assembled by Souster *et al.* (1978). The program also enables daily values of clear day irradiation on slopes to be found by numerical integration. Graphical outputs can also be provided by the programs.

7. CLOUDLESS DAY RESULTS FROM SUN3 FOR LATITUDE 55° N

The significance of modelling turbidity and non-isotropic sky radiance in solar studies can perhaps be made clearer by presenting graphically some results derived from our clear day program SUN3. A latitude of 55° N has been chosen as representative of a high latitude solar house location. Figure 5*a* shows the monthly variations of the clear day direct beam daily total irradiation on a horizontal surface H_{bh} and figure 5*b* shows the corresponding variations in clear day diffuse daily irradiation on horizontal surfaces H_{dh} for different values of τ_a. A logarithmic plot has been used as the summer–winter range is so wide. The large effect of high turbidity on the direct irradiation in winter is evident. Neglect of turbidity differences obviously leads to large errors. The increase of diffuse daily irradiation with increased turbidity is shown in figure 5*b*. Standard diffuse irradiance curves are not satisfactory for accurate prediction.

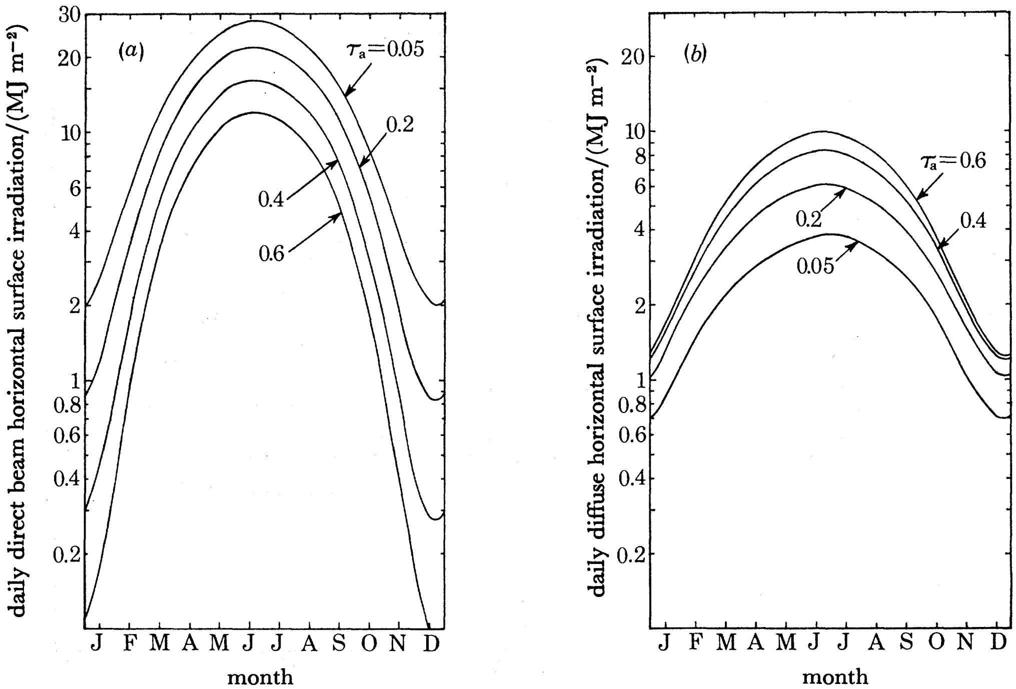

FIGURE 5 (*a*). Daily direct beam horizontal surface irradiation H_{bh} for different values of τ_a; cloudless days, latitude 55° N. Note sharp decrease with increasing turbidity in winter. (*b*) Daily diffuse irradiation from the sky on a horizontal surface H_{dh} for different values of τ_a; cloudless days, latitude 55° N. Note increase of H_{dh} with turbidity.

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The direct daily irradiation on clear days on slopes H_{bs} can be obtained by multiplying the horizontal direct irradiation H_{bh} from figure 5*a* by the appropriate slope multiplier derived from daily predicted totals of slope irradiation derived using our program SUN3. Systematic tables of these daily multipliers for different values of the turbidity have been prepared for a number of orientations and slopes for latitudes 30–60° N at 5° intervals of latitude. These will be published shortly. Figure 6 shows the slope multipliers for daily direct beam irradiation for cloudless days on certain selected surfaces at latitude 55° N for a value of $\tau_a = 0.2$ plotted against solar declination.

The big fall in this ratio from winter to summer for south vertical surfaces is evident. The crossing of the vertical south multiplier curve by the southeast–southwest and the east–west vertical curves shows that on clear days in summer, more direct energy is received on these surfaces than on vertical south surfaces. The corresponding data for the clear sky diffuse radiation with $\tau_a = 0.2$ are given in figure 7.

Our model shows that in the middle of the winter the daily south-facing diffuse slope–

diffuse horizontal surface irradiation ratio $\bar{H}_{ds}/\bar{H}_{dh}$ exceeds, by a factor of nearly three, the values predicted from the isotropic approximation. As the year progresses, and the Sun's declination increases towards its maximum on 21 June, the values fall back towards the isotropic approximation. The ratio $\bar{H}_{ds}/\bar{H}_{dh}$ on north-facing slopes is always less than the isotropic approximation value. The vertical east–west values lie, as might be expected, in between.

The effect of turbidity on the ratio for the direct beam is shown in figure 8.

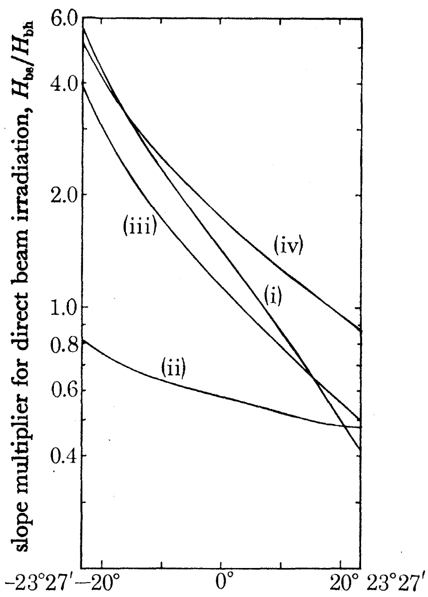

FIGURE 6

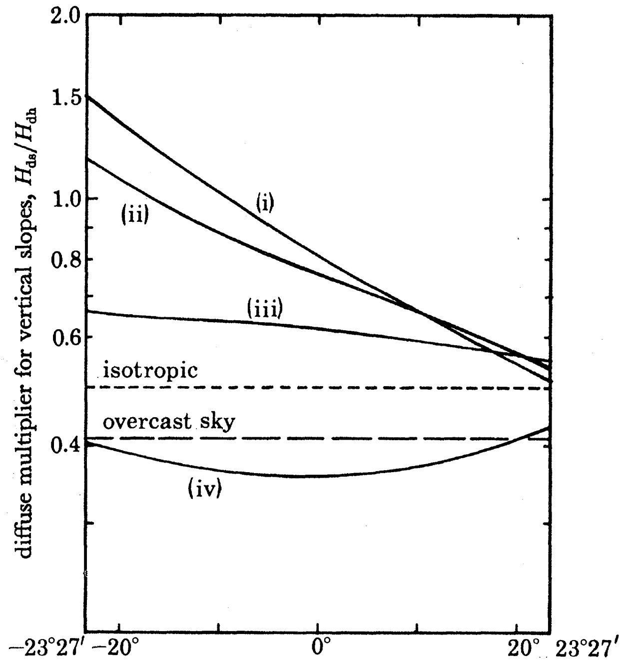

FIGURE 7

FIGURE 6. Variation of the values of the slope multiplier for daily direct beam irradiation on (i) vertical south, (ii) east–west, (iii) southeast–southwest surfaces and (iv) a south-facing surface with tilt = latitude, with solar declination τ_a = 0.2; cloudless days, latitude 55° N.

FIGURE 7. Variation of the diffuse multiplier for vertical slopes H_{ds}/H_{dh} with solar declination for (i) vertical south, (ii) southeast–southwest, (iii) east–west and (iv) north-facing surfaces; latitude 55° N, cloudless days, τ_a = 0.2. Note comparison with isotropic value of 0.5 (– – –) and overcast sky value of 0.412 (— — —).

The turbidity has very little effect on the direct radiation slope multiplier for south-facing slopes because the peak irradiance on the south slope coincides in time with the peak on the horizontal surface, so that turbidity tends to affect both components equally. The proportional influence of turbidity on the corresponding multiplier for an east and vertical surface is, however, considerable, and for vertical northeast/northwest surfaces even larger. On these orientations on cloudless days, the low Sun makes the greater contribution to the daily slope irradiation and, as the air mass is then large, the effects of turbidity are much greater. The effects of turbidity on the diffuse ratio H_{ds}/H_{dh} are rather less marked and so are not discussed in detail here.

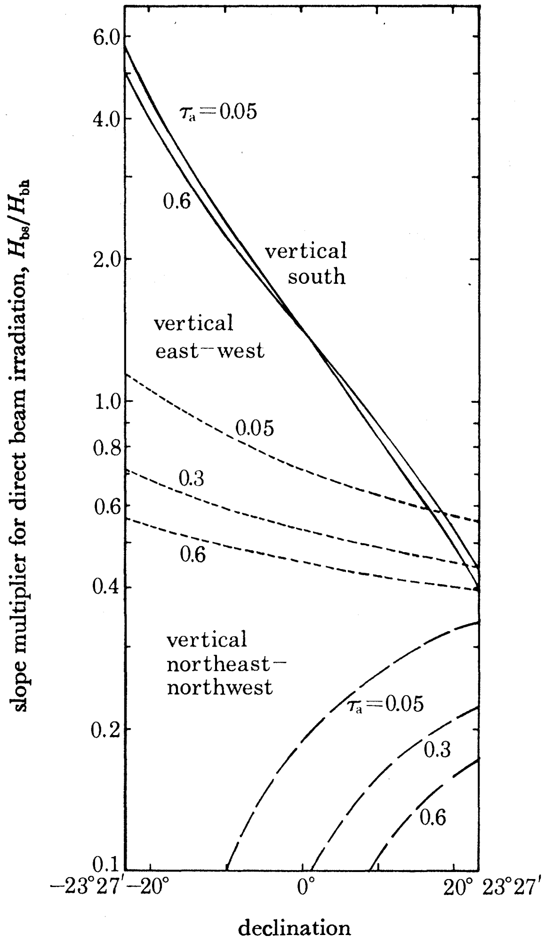

FIGURE 8. The effect of variations in turbidity on the slope multiplier H_{bs}/H_{bh} for direct irradiation for different vertical surfaces at different times of year; latitude 55° N, cloudless days.

8. Solar heat gains through glazing on clear days

The clear sky solar radiation programs have been used as the basis of programs to determine solar heat gains through glazing materials whose transmittance varies with angle of incidence.

The program GLAS determines the short wave radiation gains through one or two sheets of glass in a surface of any slope and orientation. The ability of the glass to transmit short wave radiation is specified in terms of the KL value (which is the product of the absorption coefficient K and the glass thickness L) and its refractive index. The transmittance is a function of angle of incidence. The SUN3 model enabled the transmittance calculations for the non-isotropic short wave diffuse radiation to be compactly handled by splitting the incident diffuse irradiance into the circumsolar diffuse component assumed to come from a bright patch of sky in the vicinity of the Sun and the isotropic background diffuse component. The circumsolar component then augments the direct beam. When vertical glazing is specified, the program also works out the heat gains due to the proportion of the energy absorbed in the glass, which is released inwards by convection and by long wave radiation, based on the standard procedures reported in the Institution of Heating and Ventilating Engineers Guide (1970). Field research is being carried out in the Department with the aim of refining these procedures to take account of the effect of the local climate on the detailed convective and long wave radiative heat exchanges from building surfaces.

Our program SOLWIN provides information on the solar heat gain through vertical windows on clear days. The program operates in a similar way to GLAS but in this case the properties of the window system are specified in terms of long wave and short wave shading coefficients quoted by the British glass manufacturer, Pilkington Brothers Ltd (1974) for their range of glasses and for various combinations of glasses and blinds. The program allows glazing to be inserted in one wall or into several walls with different orientations and the program provides information, at hourly intervals between sunrise and sunset, on the position of the Sun and on the solar gain due to the short wave transmitted radiation, the incident solar gain due to the energy absorbed in the glass which is released into the building and finally the total solar gain. These instantaneous solar gains are integrated over the day to produce the corresponding daily totals.

9. Models for days of low irradiation and overcast days

Observed data from the Meteorological Office for days of low irradiation and for overcast days has also been systematically processed for the four main U.K. radiation stations. It was found that the observed horizontal surface irradiance ${}_0G_{dh}$ on such days could be related to the solar altitude α by the relatively simple formula

$$ {}_0G_{dh} = 2 + k' \sin \alpha, \quad (4)$$

Table 2. Irradiance prediction for days of low irradiation and overcast days

(Derived values of k' for U.K. stations for use in equation (4), $G_h = 2 + k' \sin a$, for all overcast days, for 10 % minimum radiation design days and 5 % minimum radiation design days on days of low irradiation.)

station	month: Jan.	Apr.	July	Oct.	annual means
Kew (suburb of London)					
all overcast†	230 (17)	170 (5)	260 (4)	230 (11)	281 (103)
10 % min	95	160	263	155	
5 % min	64	116	213	118	
Aberporth (coastal Wales)					
all overcast	250 (16)	330 (5)	250 (6)	270 (8)	260 (99)
10 % min	152	256	298	186	
5 % min	120	191	230	139	
Eskdalemuir (lowland Scotland)					
all overcast	180 (22)	230 (6)	240 (8)	220 (12)	218 (139)
10 % min	97	160	197	113	
5 % min	64	109	157	82	
Lerwick (Shetlands)					
all overcast	200 (24)	280 (9)	270 (9)	240 (12)	235 (154)
10 % min	101	194	225	108	
5 % min	55	141	169	69	

† The mean number of overcast days is given in parentheses.

where k' is a constant for a particular month which varied according to class of radiation day and location. Table 2 gives typical values of k' found for the U.K.

Our overcast sky computer model OCDY allows the user to input values of k' and the ground albedo appropriate to the locality for any chosen date, and also to choose the surface tilt. As there is no direct irradiation, the surface orientation is not a significant variable. The program outputs hourly values of the irradiance on the slope from the sky and ground and provides daily totals by using numerical integration. The irradiance on vertical and inclined surfaces is calculated with the use of the Moon & Spencer (1942) sky radiance model,

$$N'(\theta) = \{(1+b'\cos\theta)/(1+b')\}\, N'(0), \tag{5}$$

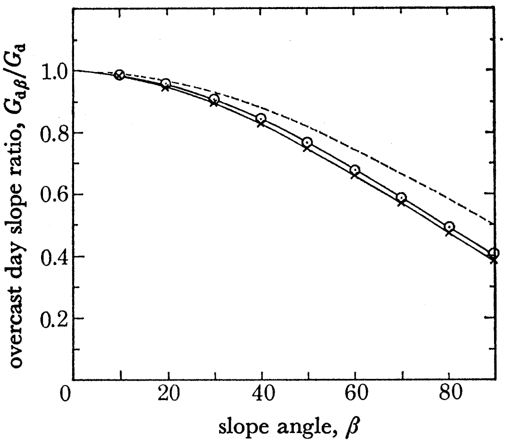

FIGURE 9. A comparison of the ratios of $G_{d\beta}/G_{dh}$ for $b' = 1.4$ and $b' = 2.0$ for overcast skies. The ratios for the isotropic sky distribution are also included. – – –, Isotropic; —⊙—⊙—, Steven's formula; —×—×—, Moon & Spencer.

where $N'(\theta)$ is the overcast sky radiance at angle θ from the zenith, $N'(0)$ is the zenith radiance and b' is a constant, equal to 2 for the standard C.I.E. Moon & Spencer luminance distribution. The value of $b' = 1.4$ found by Steven (1977) from detailed sky radiance measurements at Sutton Bonington, U.K., has been adopted in our model to predict the overcast sky radiance distribution. The overcast day irradiance on slope s with inclination β, ${}_0G_{ds}$ can then be obtained analytically from the standard overcast sky radiance formula by using the expression

$$ {}_0G_{ds}/{}_0G_{dh} = \tfrac{1}{2}(1+\cos\beta) + \frac{2b'}{\pi(3+2b')}\,(\sin\beta - \beta\cos\beta - \tfrac{1}{2}\pi(1-\cos\beta)). \tag{6}$$

Figure 9 shows the difference between the isotropic approximation and the Moon & Spencer approximation for different slopes with the use of values of $b' = 2$ and $b' = 1.4$.

The difference between the conversion factor based on the value of $b' = 1.4$ found by Steven at Nottingham and the more widely used factor obtained of $b' = 2.0$ adopted in the standard C.I.E. model based on luminance studies is small. The predicted conversion factor to convert a horizontal sky diffuse irradiance surface to a vertical surface sky irradiances on overcast days is 0.412, compared with the uniform sky radiance value of 0.50.

10. Program AVDY for the prediction of the monthly mean values of slope irradiance

(a) *General considerations*

The detailed design of solar systems obviously demands the ability to predict average values of the solar radiation received on slopes as clear days are relatively rare. Page (1962) developed a method for obtaining approximate daily values of the mean monthly irradiation on slopes from monthly mean sunshine values, but, with inadequate computing resources to handle the problems, was forced to assume the isotropic sky approximation, and adopt a standard radiation curve. However, hourly values of the monthly mean irradiance on slopes are more useful than daily values of the irradiation. The successful development of the SUN3 and OCDY programs gave us hope that we could also deal with the complex prediction problems for average days with reasonable accuracy. In order that our programs could be widely used, we decided to use the mean monthly sunshine hours as the key solar data generator. It proved possible to develop a non-isotropic variable turbidity modelling technique which has checked out well with the few actual observations on slopes available for the U.K. Program AVDY essentially splits the modelling into three parts, modelling of the mean direct beam irradiance, modelling of the mean diffuse irradiance from the sky, and modelling of the mean ground reflected irradiance. Our main aim has been to produce an accurate model for the U.K., but the model also looks appropriate for northwest Europe as well.

(b) *Modelling average direct irradiance on horizontal surfaces*

The modelling of the direct beam in AVDY has been based on a study of hourly values of the average horizontal direct beam irradiance $\bar{G}_{bh}$ at Kew. This parameter is not measured directly but may be derived by subtraction of the diffuse irradiance $\bar{G}_{dh}$ from the global irradiance $\bar{G}_{h}$. Because each hourly value of $\bar{G}_{bh}$ is obtained by averaging over the whole hour, when, in fact, bright sunshine is on average recorded for only a fraction f, say, of that hour, the actual value of the instantaneous direct beam horizontal surface irradiance during the fraction f of that hour during which the sun is actually shining may be estimated to be $\bar{G}_{bh}/f$. This adjusted hourly irradiance figure allows a monthly mean hourly turbidity τ_a to be estimated for each hour of each month from the data using the Unsworth & Monteith formula which may be rearranged as follows to take account of the hourly sunshine fraction f

$$\tau_a = -\frac{1}{m} \ln \left\{ \frac{\bar{G}_{bh}}{f} \frac{1}{(cG^*_{bn} \sin \alpha)} \right\}, \tag{7}$$

where m is the optical air mass, α is the solar altitude, G^*_{bn} is the theoretical clean air direct normal irradiance for the given precipitable water content and c is the correction for mean solar distance as explained earlier. Detailed summaries of hourly mean values of τ_a found in this way for four U.K. stations (Kew, Lerwick, Aberporth and Eskdalemuir) have been published by Page *et al.* (1979).

There are, however, difficulties in applying this model in this form to other sites. A model based on this particular approach requires the availability of hourly sunshine data. However, apart from major observatories such hourly sunshine data is simply not available. Invariably, only data on the mean monthly daily total of hours of recorded bright sunshine $\bar{n}$ are available.

We therefore decided it was more practicable for solar energy modelling purposes to use daily sunshine values in our model AVDY. We assume, in the direct beam part of program AVDY, that the monthly mean observed daily sunshine $\bar{n}$ must occur during the period of day during which the predicted direct solar beam irradiance, G_{bn}, is great enough to burn the sunshine card, i.e. when $G_{bn} > 200$ W m^{-2}, assuming a standard reference turbidity of 0.2. A monthly average daily fraction of sunshine f', covering the whole day can then be calculated by dividing the mean observed sunshine, $\bar{n}$, by the maximum possible number of hours of card burning bright sunshine, $\bar{n}'_0$, in that month, which can be easily determined from our programs. The monthly

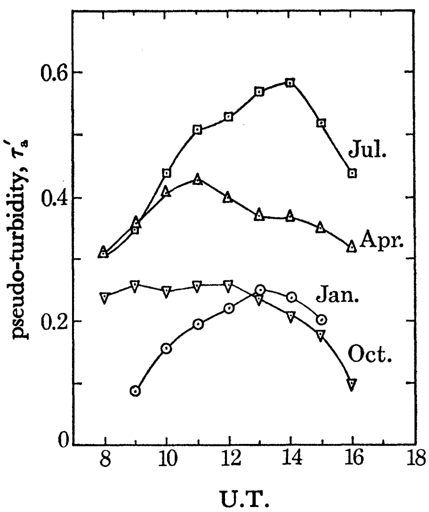

FIGURE 10. Variation of pseudo-turbidity with time of day; Kew, England (1965–75).

mean daily value, f', thus obtained can then be used in equation (7) as a constant throughout the day in place of the hourly varying values of f. The hourly values of the turbidity thus obtained are not true turbidities because they cannot incorporate any hour by hour differences of the mean monthly hourly sunshine fraction f from the daily mean sunshine fraction f'. Thus, asymmetries in daily sunshine appear in this analysis in combination with the actual hourly variations in basic turbidity. We have labelled these derived hourly turbidities as 'pseudo-turbidities' τ'_a.

Using the observed sunshine fractions f' at Kew, the variations in the mean 'pseudo turbidity' were determined hour by hour for each month of the year. The hourly values of the 'pseudo turbidities' for four selected months obtained in this way for Kew, U.K. are illustrated in figure 10.

The general increase in pseudo-turbidity from winter to summer can be noted together with different patterns of diurnal variation at different seasons. The winter–summer variations are very much linked with air mass characteristics, a point which has already emerged in table 1.

The observed monthly pseudo-turbidity curves for Kew were then fitted by an appropriate cosine function, the arguments of which varied with month and were stored internally as data in our program AVDY. With such a model it becomes a simple matter to compute mean hourly values of $\bar{G}_{bh}$ and $\bar{G}_{bs}$ from monthly mean sunshine data for Kew. The mean monthly hourly values of $\bar{G}_{bh}$ obtained from these pseudo-turbidities could then be numerically integrated over the day for each month to give the monthly mean daily direct irradiation received.

The derived daily totals of mean monthly daily direct beam horizontal irradiation $\bar{H}_{bh}$ obtained from our model for Kew for the period 1959–68 agreed to within 1% with the $\bar{H}_{bh}$ values directly obtained from the daily totals of $\bar{H}_h$ and $\bar{H}_{dh}$ at Kew. However, more recent observed monthly mean daily irradiation data covering the period 1965–75 (excluding 1973 for which no observations are available) indicated that the mean pseudo-turbidity at Kew had increased slightly during the summer. The pseudo-turbidity curves were adjusted to maintain the maximum error between the new observed and predicted values of $\bar{H}_{bh}$ at Kew to below 1% for the 1965–75 means. This model incorporates the basic asymmetries of average solar radiation between morning and afternoon at Kew which differ from month to month. Making the assumption that the patterns are the same at other stations in northwest Europe, it is then possible to use the direct beam model in AVDY to derive pseudo-turbidities for other stations.

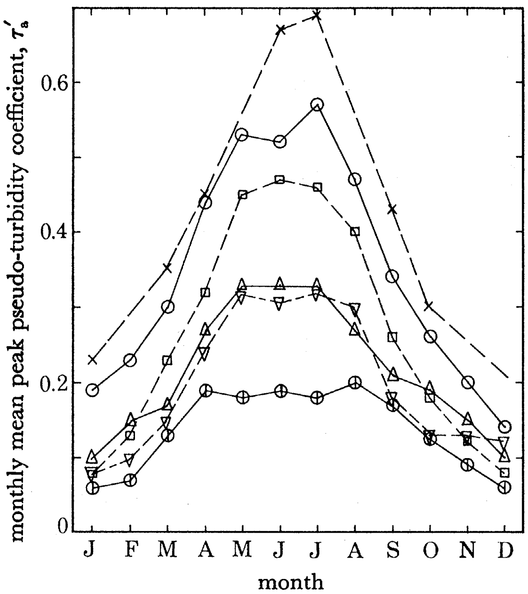

FIGURE 11. Monthly variations in mean daily maximum pseudo-turbidity for Kew, Eskdalemuir, Lerwick and Aberporth 1959–68 for average days with additional data for Hamburg and Odeillo. Key: ⊙, Kew; ⊡, Eskdalemuir; ▵, Aberporth; ▿, Lerwick; ×, Hamburg, ⊕, Odeillo.

Figure 11 shows preliminary data on typical month to month variations in the mean monthly maximum pseudo-turbidities found for several N. European sites. The highest pseudo-turbidities are associated with urban situations, Kew and Hamburg. One high level French mountain station, Odeillo, is included. The low turbidities associated with this particular site are evident. At Odeillo some turbidity increase from winter to summer is present, but is more subdued than at Kew. The remote western seaside sites have substantially lower pseudo-turbidities than urban sites. The clearest conditions at sea level are found at Valentia in the far west of Ireland, which is a considerable distance from the main continental sources of pollution and where the prevailing air masses come off the clean Atalantic Ocean. Published data in a different turbidity system for the U.S.A. by Bilton *et al.* (1967, 1974) bring out very much the same annual pattern of variation month by month.

Once the hourly pseudo-turbidities differences from Kew are known, it is a simple matter to use AVDY, which makes provision for insertion of such pseudo-turbidity differences, to predict the hourly direct beam irradiance values on slopes, and hence the daily totals of direct irradiation for any location in the U.K. We have now prepared U.K. maps showing variations in pseudo-turbidity from Kew values (Page *et al.* 1979).

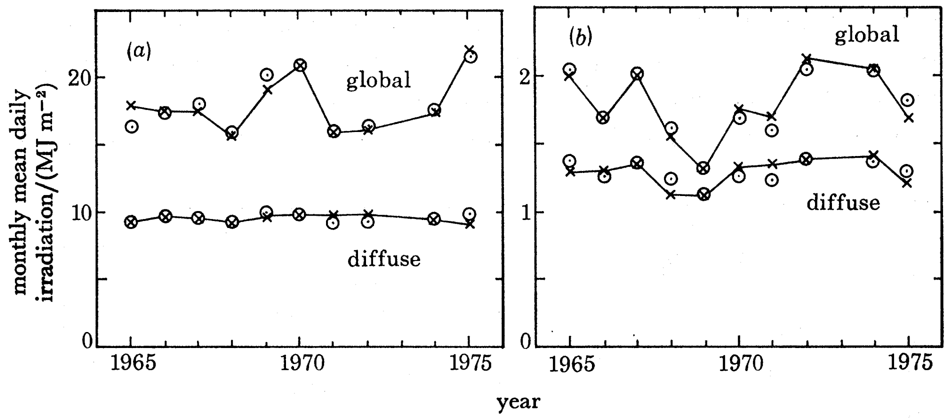

FIGURE 12. Predicted and observed annual values of the monthly mean daily global irradiation $\overline{H}_h$ and the monthly mean daily diffuse horizontal surface irradiation $\overline{H}_{dh}$ at Kew, 1965–75 for (*a*) June and (*b*) December. Note small annual variation in diffuse irradiation. ×, Observed; ⊙, predicted from sunshine hours.

(*c*) *The estimation of mean monthly hourly diffuse sky irradiances on horizontal surfaces*

The observed Kew data were also used to construct a monthly mean diffuse model for use within the program AVDY, using mean monthly hourly diffuse irradiance data for horizontal surfaces for the period 1959–68. The average sky diffuse horizontal irradiance for a given solar altitude is normally greater than either the clear sky or the overcast sky diffuse horizontal surface irradiance. It was found that, when the mean monthly hourly horizontal diffuse irradiances for a number of stations in northwest Europe were plotted hour by hour against solar altitude over the whole year, the observed data for each station could be closely fitted by the following straight line formula:

$$\overline{G}_{dh} = a' + b'\alpha, \tag{8}$$

where α is the solar altitude in degrees and a', b' are climatologically determined constants. It was found that, for Kew, $\overline{G}_{dh} = 2.18 + 4.531\alpha$. When this equation was used to predict by numerical integration the monthly mean daily diffuse horizontal irradiation for Kew for the period 1959–68, the predicted sky irradiation values agreed with the observed values to within 5 %. However, using the corresponding observed values for the later period 1965–75 (excluding 1973, for which observations were not available) the predicted values were too low, particularly in winter when the error was approximately 11 %. A comparison of the observed values of the monthly mean daily diffuse irradiations over the two periods showed that, on average, the mean monthly diffuse irradiation for the later period was some 6 % higher than for the period 1959–68. Interestingly, therefore, the successful smoke abatement programmes in the London region seem to have influenced the diffuse irradiance levels upwards rather than the direct irradiance levels. To give an up to date model, the coefficients of equation (8) were adjusted upwards before incorporation in AVDY so as to make predicted monthly values of the mean daily total diffuse irradiation for Kew match the observed values for the period 1965–75. Equation (8) thus became

$$\overline{G}_{dh} = 2 + 4.80\alpha, \tag{9}$$

which is the basic diffuse radiation model currently stored in our program AVDY, but it is adjusted subsequently to allow for actual observed sunshine in a particular month.

Having produced a long term hourly diffuse radiation model that agreed reasonably well with the most recent observed long term average diffuse horizontal surface irradiation data, on the preliminary assumption that there were no actual variations from year to year (which is only approximately true), the next step was to modify the original long term average model to make the predicted monthly mean diffuse daily total horizontal surface irradiation sensitive to actual observed sunshine hours year by year, which, as study of actual observations revealed,

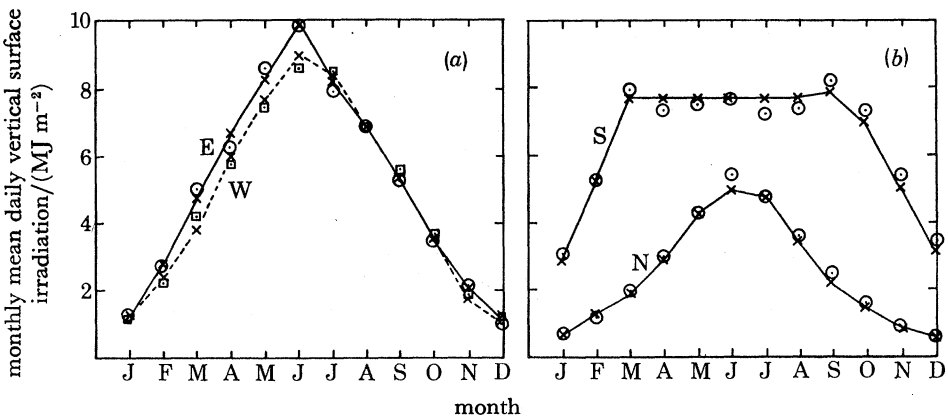

FIGURE 13. Comparison of measured and observed monthly mean daily irradiation on vertical north, south, east and west slopes at Bracknell; period 1966–73. (*a*) ⊙, predicted east; ⊡, predicted west; (*b*) ⊙, predicted.

was in fact the case. Such variations, however, are modest. The correction method was based on the use of Angstrom type regression equations. Page (1962) had shown the mean monthly global $\bar{H}_h$ and diffuse horizontal surface irradiation $\bar{H}_{dh}$ could be predicted from monthly mean sunshine hours by using the following two formulae:

$$\bar{H}_h/\bar{H}_{0h} = a+b\,\bar{n}/\bar{N}_0 \tag{10}$$

and

$$\bar{H}_{dh}/\bar{H}_h = c+d\,\bar{H}_h/\bar{H}_{0h}, \tag{11}$$

where H_{0h} is the monthly mean value of the horizontal surface extraterrestrial irradiation, $\bar{n}$ is the monthly hours of bright sunshine, $\bar{N}_0$ is the possible number of sunshine hours (daylength) and a, b, c and d are locally determined regression constants. The two equations may be combined to give a quadratic function in $\bar{n}/\bar{N}_0$. The observed Kew data were fitted to a quadratic function and the following relation found:

$$\bar{H}_{dh}/\bar{H}_{0h} = 0.153+0.289\,\bar{n}/\bar{N}_0-0.244\,(\bar{n}/\bar{N}_0)^2. \tag{12}$$

This was incorporated as a modifier to allow for year to year variations in mean monthly sunshine hours.

Equation (12) could be then used to calculate the mean monthly daily diffuse irradiation on a horizontal surface as a function of monthly sunshine hours year by year. Figure 12 shows the observed and predicted values of the monthly mean global and diffuse horizontal surface irradiations at Kew for two months, June and December, for the period 1965–75 showing the high prediction accuracy achievable with this method.

We have carried out similar studies of diffuse radiation for a number of other European centres, and have found similar relationships but the slope constant b' in equation (8) varies slightly from station to station. Currently, different techniques for correction for shading rings are being used that are producing difficulties in comparison. Our model AVDY, however, allows for the incorporation of a diffuse multiplier to allow for any local variations.

(*d*) *Average diffuse sky and ground reflected irradiance on slopes*

The precise methods used in AVDY for the prediction of the diffuse irradiance on slopes are complex. They have been described in detail by Page (1978). The techniques essentially are based on a combination of the two separate diffuse sky estimation techniques implicit in SUN3 and OVDY. The daily sunshine fraction f' is used to split the predicted horizontal surface diffuse irradiance into two proportional parts. One part is modelled as a clear blue sky, and the other part is modelled as an overcast sky. The two separated slope components are then added together to get the predicted mean monthly hourly values of the sky diffuse irradiance on the slope. Comparison with observations showed that some modest pragmatic modifications, of the order of 10%, were necessary when the Sun was perpendicular to the surface. Agreement between observation and prediction was otherwise excellent. This modification was incorporated into the program. The contribution from the ground is, at present, modelled isotropically, but later on, improvement will be incorporated to allow for increase in the ground albedo for direct radiation with increase of angle of solar incidence.

(*e*) *Checking of program* AVDY *outputs against mean monthly hourly observations*

The program AVDY derived from Kew has been checked against measured mean monthly daily irradiation and also mean monthly hourly irradiances on both horizontal and vertical surfaces independently measured at Bracknell, where observations have been made since 1966 on vertical surfaces facing north, south, east or west. The period 1966–73 was used for the comparison. Figures 13*a*, *b* show the predicted and observed mean monthly daily irradiation on surfaces facing north, south, east or west. Our studies are now being extended to cover all available observations from the E.E.C. area, and the initial studies are promising.

11. The prediction of long wave exchanges

Our computer program LWR1 calculates the net long wave radiation exchange between the incoming atmospheric long wave radiation and an inclined surface of any tilt. It is based on the experimental work of Unsworth & Monteith (1975*b*) and the theoretical work of Unsworth (1975*b*). They found the incoming atmospheric long wave radiation from clear skies on a horizontal surface was well correlated with the fourth power of the screen-height air temperature.

For inclined surfaces, Unsworth (1975*b*) divided the incoming flux into two parts, one part being a flux from an isotropic source of radiation and the other a flux that describes the degree of anisotropy. The isotropic distribution is readily found from the flux incident on an unobstructed horizontal surface. For the anisotropic flux Unsworth used the work of Kondratyev (1969), who developed an integral to describe the apparent emittance of the sky as seen by an inclined surface. Unsworth numerically evaluated this integral and produced a curve of its magnitude against the inclination of the surface. This curve has been fitted to a sine function to enable it to be used in our program LWR1. The effect of cloud cover on the incoming atmospheric long wave radiation was, following Unsworth & Monteith, treated as a linear modification to the clear sky condition.

The user can insert any cloud cover amount he chooses, and can also choose the ground surface temperature independently of the air temperature and can alter the ground emittance.

12. Programs for the estimation of hourly wind speed and temperature for different classes of radiation day

The data for temperature and wind for the 10% maximum days, the 10% minimum days and the average days for Kew, Eskdalemuir, Lerwick and Aberporth, have been systematically analysed by using Fourier series to fit the observed diurnal data. The Fourier coefficients for the fundamental, first harmonic and second harmonic were shown to be related to the mean monthly wind speed, mean monthly sunshine hours and mean monthly temperature, thus it proved possible to collapse all the data for the four stations into sets of relatively simple equations to generate hourly data for different classes of radiation day from monthly mean data. These studies form the basis for our new programs, METS, META and METO. These subscripts have been chosen to indicate sunny S, average A and overcast O. The detailed procedure for collapsing the U.K. data has been reported by Page *et al.* (1979). These programs incorporate as a subroutine the program LWR1 for long wave radiation already described. This completes the basic program structure needed for climatological simulation of solar thermal systems performance. The final improvement will be the incorporation of the microclimatic modifier modules, MODS, MODA and MODO.

13. Conclusions

The systematic studies completed in the Department of Building Science in Sheffield will enable a wide range of solar building and other solar energy climatological problems to be tackled in a more accurate and sophisticated way than at present. While we have primarily had buildings in mind in developing the system, it could prove of value in other scientific fields like horticulture, applied agriculture, and also in general engineering design. The system has been demonstrated to be climatologically accurate when compared with actual U.K. meteorological observations, and we now hope to apply the system extensively to detailed solar energy studies across the whole country and are involved in active discussion on its use in one or two specific U.K. solar projects.

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