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THE ESTIMATION OF SOLAR RADIATION IN NEW ZEALAND

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Abstract—Measurements of solar radiation which were made during the solar energy projects at DSIR, together with Meteorological Service data have been used to establish New Zealand parameters for the ASHRAE clear sky radiation model. It is shown that these new parameters give good agreement between observed and estimated values for both horizontal and vertical surfaces. There is, however, some complication for east- and south-facing surfaces. The values of sky–diffuse radiation on clear days were appreciably lower than those observed in the US and some other countries. Otherwise the diffuse/global ratios differed by not more than 15% from those of other investigators for most of the range.

1. INTRODUCTION

In the design of equipment and buildings it is often necessary to obtain an estimate of the solar radiation likely to be available at any time of the day, on any day of the year, on a surface of any orientation. A method often used to obtain such estimates is the one described by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [1]. The parameters used in the ASHRAE model are based on American experience and even these have been the subject of modification[2].

In connection with its projects on solar energy in New Zealand, the Department of Scientific and Industrial Research (DSIR) had set up a solar radiation measurement facility on the roof of its laboratory at Gracefield, near Wellington. When the solar energy work was abandoned at the end of 1985, two years of almost continuous recording had been made. It was clear that this data provided the possibility of evaluating the ASHRAE parameters for new Zealand conditions and of comparing the radiation values, particularly the diffuse/global ratios with the values obtained in other countries.

To this end a joint project was set up with the Building Research Association of New Zealand (BRANZ), Brickell Moss Ltd., and the author. The object was to process the raw data with the assistance of the Information Technology Division of DSIR and make it available for evaluation and comparison. The New Zealand Meteorological Service (NZMS) collaborated by supplying additional data.

2. APPARATUS AND MEASUREMENT

Three types of pyranometer were used in the measurements:

1. An Eppley precision spectral pyranometer (PSP).
2. 5 Li-Cor-type 2000SB pyranometers.
3. An Eppley black and white pyranometer mounted in a shading band.

This work was performed under contract to the Building Research Association of New Zealand.

The PSP pyranometer was set up to measure the radiation received on a horizontal surface. The 5 Li-Cor pyranometers were mounted, one on the horizontal and the others on vertical surfaces facing north, south, east, and west.

A PSP does not have a very good cosine response. Measurement of the response of the instrument at DSIR showed that the error increased rapidly for incident angles above 70°. This agrees with the observations of others[3,4]. The Li-Cor instruments were of the semiconducting diode type. These are insensitive to tilt and their cosine response is better than that of the PSPs. However, they have a limited spectral response. It has been shown[5–8] that in the range 0.4 to 0.7 μm, the spectral distribution of the direct plus sky radiation is approximately constant even when clear and overcast days are compared. Errors due to different sky conditions may be expected to be small and will not generally be distinguishable from the small day to day variations inherent in the phenomenon. Experience has shown that if these limitations are understood, good agreement can be obtained between measurements with the PSP or thermal type instruments and the Li-Cor or silicon cell type. An account of a direct comparison is given by Biran[9].

The shading band was constructed to the dimensions recommended by Eppley. It was decided to use the shade band corrections supplied by the Eppley Laboratory, which is the procedure used by the NZMS. The problem is discussed by Basher[10].

All the pyranometers had been calibrated by the NZMS at Kelburn, Wellington. The constants supplied by the manufacturers of the Li-Cor instruments were found to be in agreement with the NZMS calibrations. The constant supplied by Eppley was found to be approximately 5% higher than that measured by NZMS for the PSP. Other workers have noted similar discrepancies.

Each pyranometer was connected to its own integrator and the outputs were continuously recorded on a data logger. At intervals a reference PSP pyranometer was obtained from NZMS and used to check all the instruments. In this way a continuous watch was kept on their performance.

The measurements at the laboratory of DSIR were made between 1 January 1984 and 12 November 1985. According to NZMS records over the last 10 years, the mean annual radiation received on the horizontal at Kelburn was 1410 kWh/m^2 with a standard deviation of 3%. The total energy received in 1984 was 1422 kWh/m^2 and in 1985 was 1500 kWh/m^2. The mean annual values for 1954–1964 quoted by Benseman and Cook[11] using NZMS data was 1414 kWh/m^2 with a standard deviation of 2.5%. The 1954 data was referred to the International Pyrheliometric Scale (IPS), and the more recent data was referred to the World Radiation Reference Scale (WRR) of 1974. The WRR scale gives values 2.2% higher than the IPS Scale. The 1414 kWh/m^2 would be 1445 kWh/m^2 on the WRR Scale. Details of IPS and WRR are given by Forgan[12].

Kelburn-Wellington is situated at lat. 41.28 S, long. 174.77 E. Gracefield is 13 km from Kelburn at lat. 41.24 S, long. 174.92 E.

3. CLEAR SKY RADIATION

A clear sky in this context is exemplified by a continuous smooth recording of radiation intensity with steady values at any instant. An indicator of sky conditions which is often used is the "clearness index" K, defined as

$$K = G/ET \quad (1)$$

where G = daily global radiation (direct plus diffuse received on a horizontal surface); ET = daily extraterrestrial radiation. Obviously K cannot exceed unity and in practice would not be expected to exceed 0.8. It has been stated[11] that in New Zealand, K lies between 0.1 and 0.75. The present data support this.

3.1 *ASHRAE model*

The ASHRAE clear sky model as given in [1] is a seasonal one which uses an algorithm as follows:

$$I_n = A \cdot \exp(-B \cdot \operatorname{cosec} b) \quad (2)$$

$$I_d = C \cdot I_n \quad (3)$$

where I_n = the direct normal component of radiation intensity (W/m^2); I_d = the sky diffuse component of radiation intensity (W/m^2); b = solar altitude (degrees above the horizontal); A = apparent solar intensity at air mass 0 (W/m^2); B = apparent extinction coefficient; C = diffuse radiation coefficient (ratio diffuse/direct normal, intensity); m = air mass (=cosec b for $b > 10°$).

On a surface of any orientation, the total radiation received will be given by:

$$I_t = I_n \cos j + C I_n F_s + G \cdot g \cdot F_g \quad (4)$$

where j = angle of incidence; F_s = the proportion of the sky which is *seen* by the surface, i.e. F_s = 1.0 for horizontal surfaces, 0.5 for vertical surfaces; g = reflectance of the foreground; F_g = the proportion of the ground which is *seen* by the surface, i.e., F_g = 0 for horizontal surfaces, 0.5 for vertical surfaces.

Values for A, B, and C are listed in [1]. These have been derived for American conditions. In New Zealand, DSIR suggested some years ago that values of A should be used such that $A = 0.85ET$ and B and C would remain the same. The values of A listed in ASHRAE vary from $0.83ET$ in summer to $0.88ET$ in winter. Thus the use of the constant factor 0.85 allows for the increased radiation in the southern hemisphere in summer and reduced values in winter due to variation in the earth's orbit.

This procedure often gave acceptable results, but as more measurements became available it began to be suspected that there were discrepancies. In 1985 modified values for the ASHRAE parameters for American conditions were proposed[2].

In view of this situation it was decided to use the measurements at Gracefield to derive values of the ASHRAE parameters for New Zealand.

3.2 *Derivation of parameters for Gracefield, New Zealand*

As many clear days as possible were selected from the 1984/85 measurements. For each day selected, the mean direct normal intensity I_n was calculated from the measured values for each hour. Values of $\log_e I_n$ were then plotted against the appropriate values of air mass m = cosec b. This relationship for 5 January 1985 is shown in Fig. 1. A straight line was then fitted by the method of least squares. For convenience, values of A have been expressed in watts/m^2. The intercept on the vertical axis, corresponding to $m = 0$ was then the appropriate value of A for that day. The slope of the line gives the value of B. Values of C were determined as the ratio I_d/I_n. Since this varied to some extent throughout the day, a mean value was taken. The standard deviation was about 10% of this mean value.

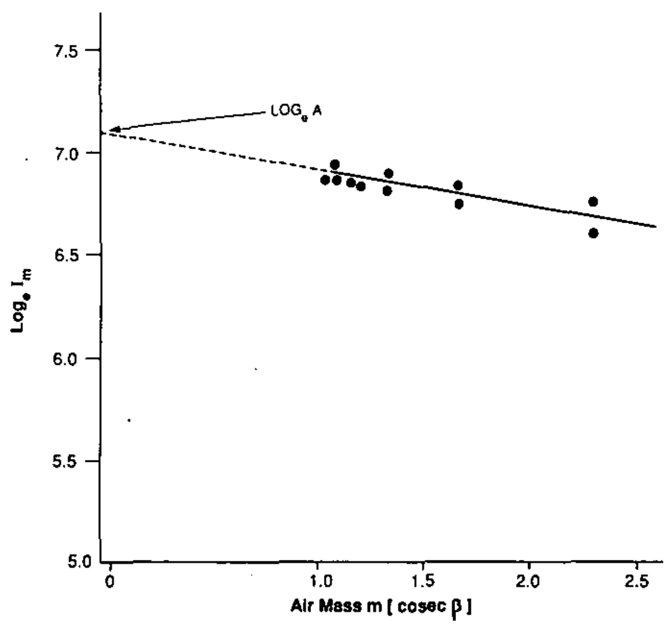

Fig. 1. Direct normal intensity as a function of air mass for each clear day.

Values of A, B, and C so obtained are shown in Fig. 2 together with the ASHRAE values, values of $0.85ET$ and the modified values of Machler and Iqbal[2].

The curves representing these parameters for Gracefield were fitted to the data by linear regression analysis with the assumption that the curves were continuous from year to year. Values of the parameters, regression coefficients, standard errors and analysis of variance are shown in Table 1.

The values for the parameters A derived from the Gracefield data are increased in summer and reduced in winter compared with the ASHRAE values but the differences are not large. The values of B are generally reduced, especially in winter. The diffuse coefficient is considerably reduced, particularly in summer which may indicate that skies are often clearer in New Zealand in summer.

These values of A, B, and C are referred to as the Gracefield values.

3.3 *Clear sky calculations with New Zealand parameters*

When daily radiation values on a horizontal surface were calculated using the new parameters, the results were in better agreement with measured values as can be seen in Fig. 3. This comparison was also made for Auckland Airport (lat. 37.00 S, long. 174.80 E) and Invercargill Airport (lat. 46.42 S, long. 168.33 E) using NZMS records. The results are shown in Fig. 4 which indicates that the Gracefield values can be used with good accuracy for other New Zealand sites.

Figure 5 shows a comparison between the calculated and measured sky diffuse radiation values. Because of its nature, measured sky diffuse values are more scattered than global values but the trend is clear. Since the values of the parameter C used to calculate the broken line in Fig. 5 were those given by ASHRAE 1981 and the revised values are higher[2], it would appear that the sky diffuse radiation in New Zealand in summer is considerably lower than in the United

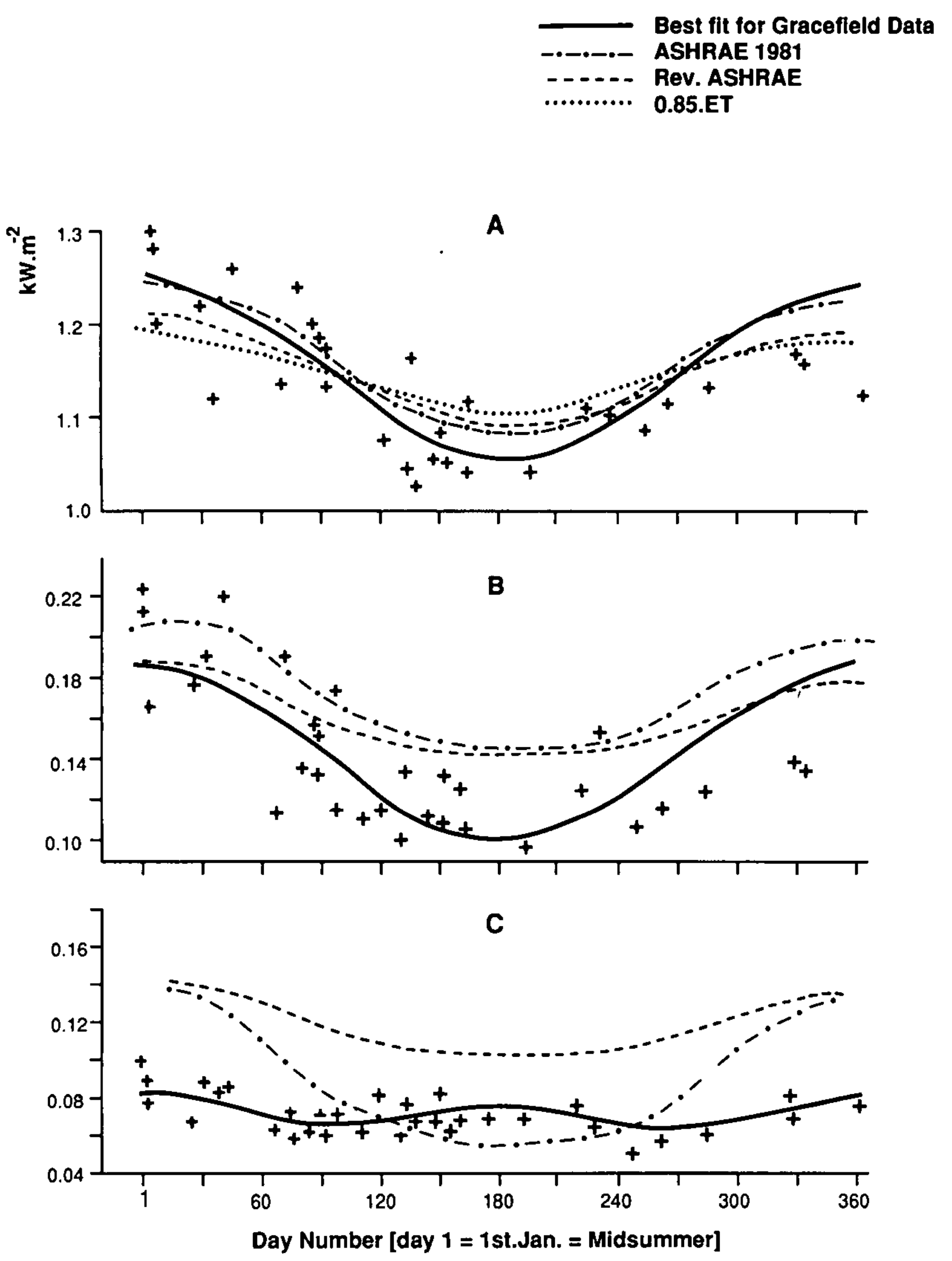

Fig. 2. Variation of parameters A, B, C throughout the year.

Table 1. NZ parameters *A*, *B*, and *C* for 21st of each month and analysis of variance for the regression

Coefficients	A			B			C		
Equations for coefficients	$1.148 + 0.0962 \cos wd$			$0.143 + 0.0441 \cos wd$			$0.0715 + 0.00448 \cos wd + 0.00661 \cos 2wd$		
Analysis of variance	*DF*	*SS*	*MS*	*DF*	*SS*	*MS*	*DF*	*SS*	*MS*
Regression	1	0.1708	0.1708	1	0.0358	0.0358	2	0.00125	0.000624
Residual	35	0.1110	0.00317	35	0.0349	0.000996	34	0.00135	0.0000396
Total	36	0.2819	0.00783	36	0.0707	0.00196	36	0.00259	0.0000720
% Variance accounted for	59.5			49.3			45.1		

Months	*A*	*B*	*C*
Jan	1.283	0.1845	0.0806
Feb	1.208	0.1708	0.0728
Mar	1.167	0.1518	0.0662
Apr	1.116	0.1286	0.0648
May	1.076	0.1100	0.0690
Jun	1.054	0.0998	0.0732
Jul	1.057	0.1015	0.0724
Aug	1.086	0.1146	0.0675
Sep	1.131	0.1356	0.0645
Oct	1.180	0.1580	0.0678
Nov	1.222	0.1770	0.0761
Dec	1.243	0.1866	0.0820

DF = degrees of freedom; *SS* = sum of squares; *MS* = mean sum of squares; d = day number (i.e., Jan 1 = 1); $w = 0.986$ (0.984 for a leap year).

States. Unfortunately, diffuse data is not at present available in New Zealand except for Wellington.

To calculate the radiation that would be received on a vertical surface, knowledge of the foreground reflectance is required. See eq(4). The vertically mounted pyranometers were intended to measure the total ra-

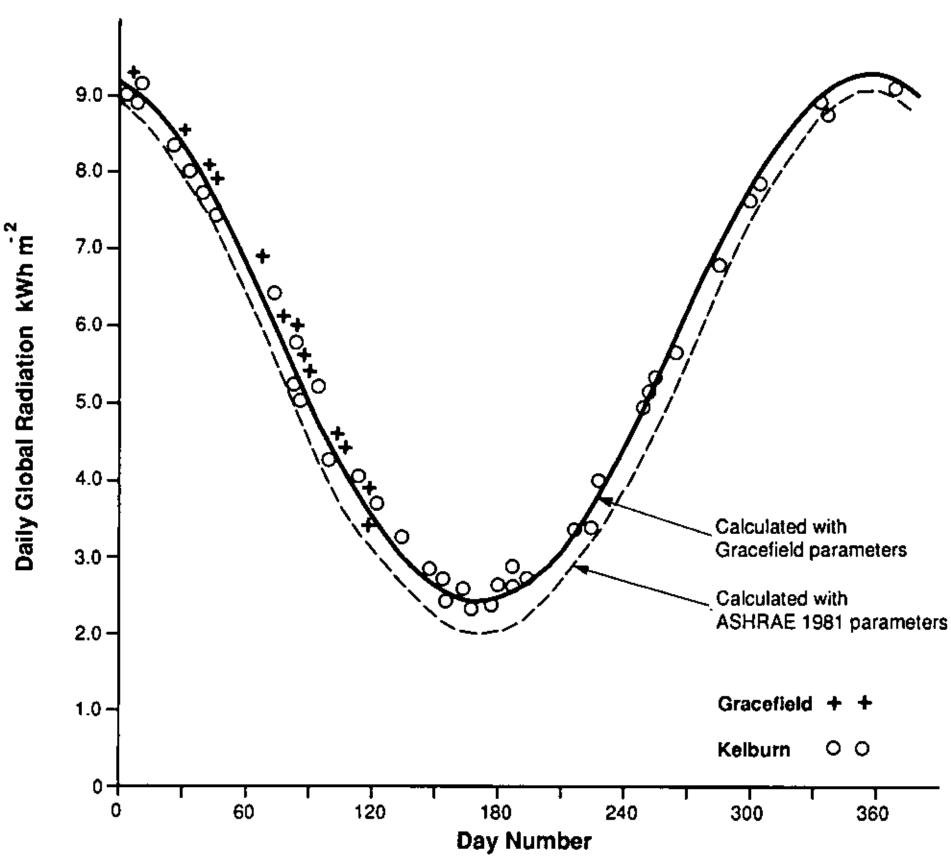

Fig. 3. Estimated and measured daily global radiation on the horizontal for Wellington.

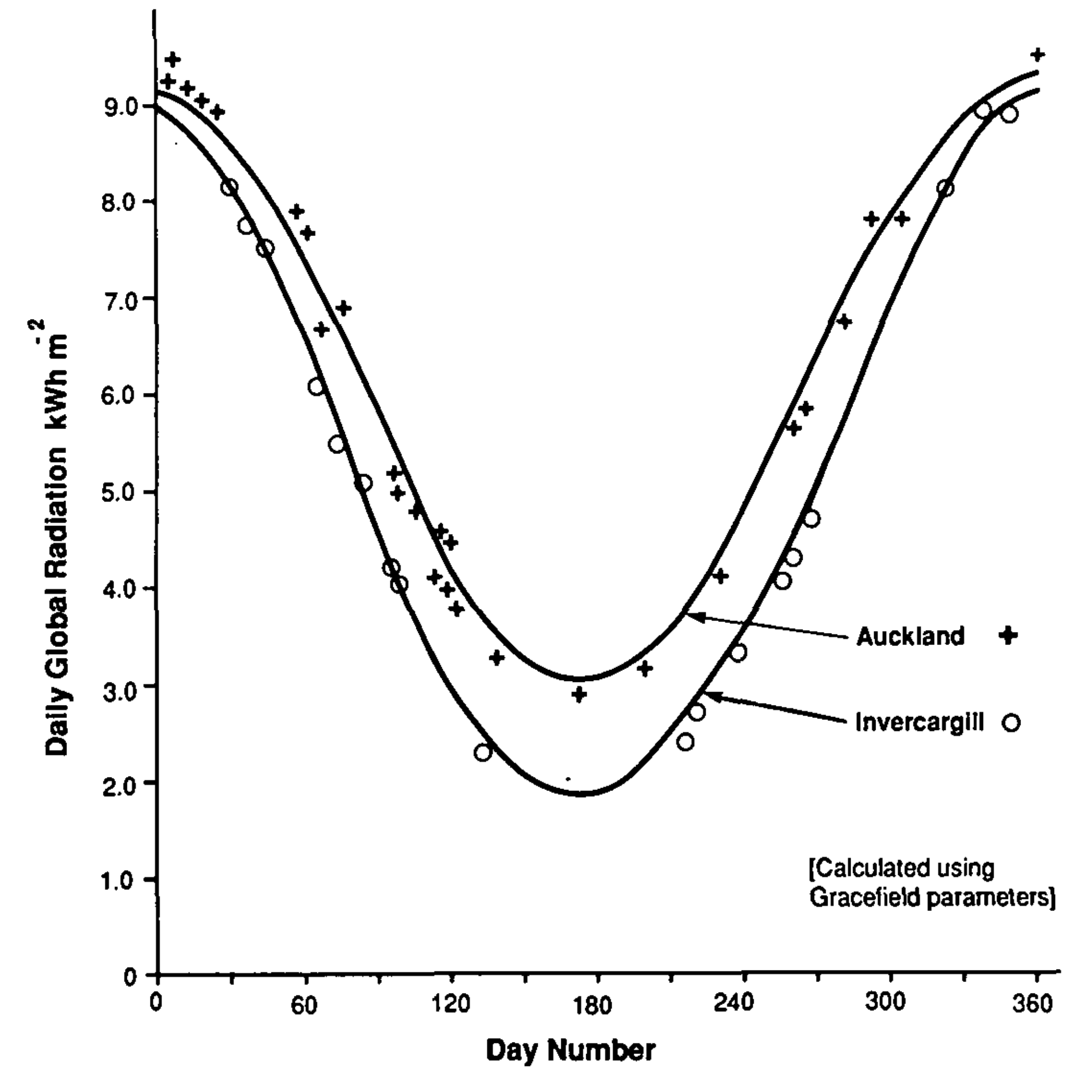

Fig. 4. Estimated and measured daily global radiation on the horizontal for Auckland and Invercargill.

diation received on vertical surfaces and since the global values are known, only that from the foreground remains to be determined.

The roof on which the pyranometers were mounted was of galvanised steel painted with a mid-green matt paint. Published works[13,14] quote a reflectance of 0.5 for light green paint on steel. Estimates of the radiation on a north-facing surface on a clear day using the Gracefield parameters showed that a ground reflectance of 0.45 gave a good agreement with measurement. This was also true for a west-facing surface.

When a reflectance of 0.45 was used to estimate the radiation on an east-facing surface however, the calculated values were 10% too high.

Asymmetry referred to solar noon between east and west-facing surfaces has been noted by Brothers and Benseman[15], who commented that in Wellington, Christchurch and Invercargill a west-facing surface received more radiation during their study while in Auckland an east-facing surface received more. Examination of the hourly data for Wellington suggests that this may be a morning/afternoon phenomenon

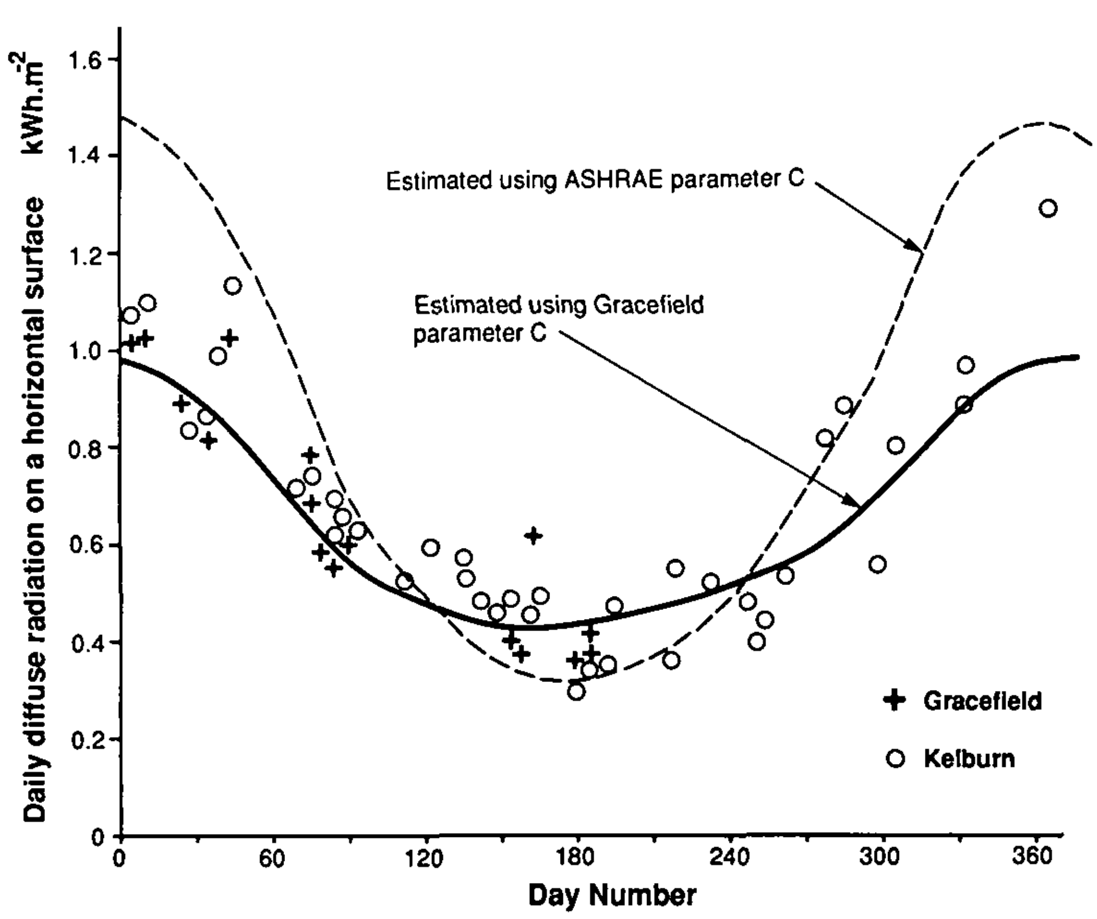

Fig. 5. Estimated and measured sky diffuse radiation for Wellington and Gracefield.

Table 2. Estimated daily radiation on various surfaces with deviation of measured values

Location	Wellington					Auckland	Invercargil
Direction	H	N	W	E	S	H	H
Range min.	2.32	4.23	2.00	1.81	0.82	2.90	1.68
$kWh/m^2/day$ max.	9.14	6.20	6.03	5.47	3.54	9.20	9.10
RMS deviation of measured values about estimated values	0.18	0.20	0.34	0.22	0.16	0.35	0.15
Reflectance g required to make estimated values agree with meas. values	—	0.45	0.45	0.33	0.55	—	—
Error in estimated values if $g = 0.45$	—	0	0	+10%	−12%	—	—

as the hours after solar noon usually have 5%–10% more radiation than the hours before noon even allowing for some horizon asymmetry in the Gracefield site. However, this was not invariable.

The calculated values for the south-facing surface were 12% lower than the measured values. This is difficult to explain. The fact that sky illumination is known to be nonuniform would be expected to produce lower observed values. It is possible that there is some bias in the site but an increase of 20% in reflectivity seems unlikely.

Estimated values for surfaces facing in various directions and their comparison with measured values are summarized in Table 2. The range gives the extreme values of daily energy received throughout the year. The RMS deviation is a measure of the scatter of the measured values about the calculated values (standard deviation is not appropriate because the measured values do not necessarily have a "mean" which coincides with the calculated values).

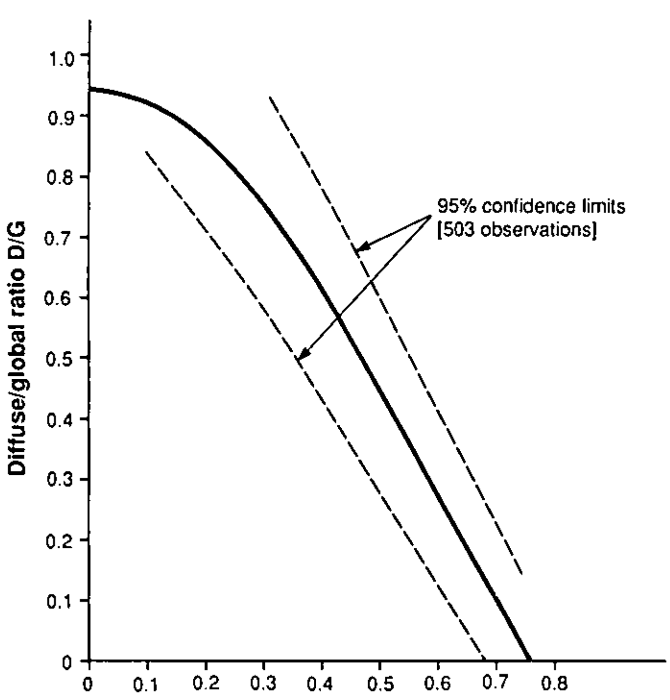

Fig. 6. Daily diffuse/global ratios as a function of clearness index for Wellington and Gracefield.

4. DIFFUSE/GLOBAL RATIOS FOR ALL CONDITIONS

4.1 *Ratios for New Zealand*

On days when skies are not clear it is often necessary to be able to estimate the probable value of the diffuse component. This problem was first dealt with comprehensively by Liu and Jordan[16].

The diffuse/global ratios as a function of clearness index K for the Gracefield data, are shown in Fig. 6, and the diffuse/extraterrestrial ratios in Fig. 7. These figures embrace all the data from the two years of measurement. They are in the form of frequency tables for simplicity. Curves fitted to the data are shown together with the broken lines which indicate the areas within which 95% of observations may be expected to lie. Details of the procedure used to obtain these curves and the equations representing the curves are given in the Appendix.

Various suggestions have been made by other investigators about the extremities of these characteristics. It is reasonable to assume that in Fig. 7 the curve goes through the origin. In Fig. 6 the values of I_d/G cannot exceed unity. The curve of Fig. 6 was therefore constrained in the regression procedure to pass through $I_d/G = 1$ for $K = 0$. Since Fig. 7 clearly shows that the slope near zero is slightly less than 45°, there seems to be no justification for thinking that the curve of Fig. 6 is horizontal below $K = 0.1$ as some writers have assumed. Since no data exist for $K > 0.75$, there is no practical purpose in defining the characteristic beyond this value.

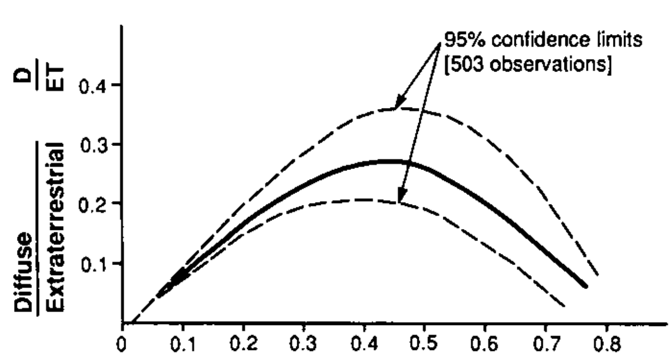

Fig. 7. Daily diffuse/extraterrestrial ratios as a function of clearness index.

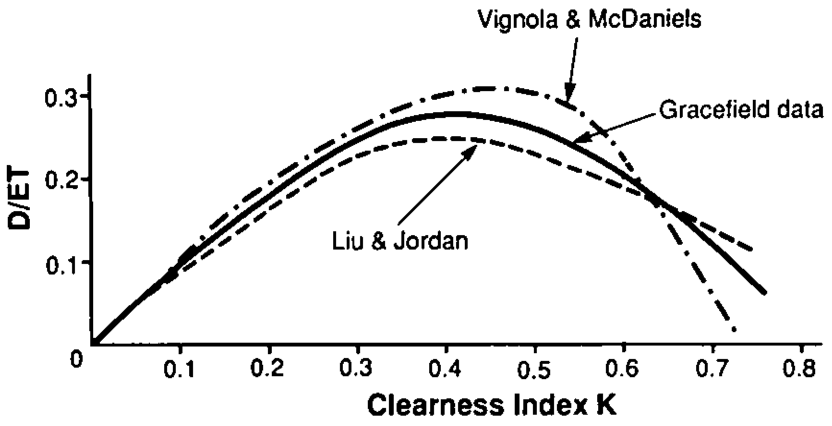

Fig. 8. Diffuse/extraterrestrial ratios compared with published data.

4.2 *Comparison with other published data*

Having obtained the relationships for diffuse radiation from observations in New Zealand it is of interest to compare them with the results reported from other countries. There is a very large bibliography of published data on these relationships, too large to make a review of it here. Some examples are shown in Figs. 8 and 9 to give an idea of the position of the Gracefield data.

The classical work of Liu and Jordan[16] referred to data obtained over 10 years in Massachusetts. The Gracefield values are about 10% higher than those of Liu and Jordan except at high values of K where their treatment was complicated by the averaging procedure used for computing the extraterrestrial radiation.

Of particular interest is the more recent work of Vignola and McDaniels[17] using data from seven sites in the Pacific Northwest, U.S.A. Although their paper presented the results as beam/global correlations, they have supplied results in diffuse/global form in a private communication. These ratios are some 10% higher than the Gracefield results for $K < 0.5$ but are appreciably lower for $K > 0.6$. For $K = 0.7$ the difference is considerable.

Other US data, for example Erbs *et al.* [18] and Collares-Perreira and Rabl[19] agree with Vignola and McDaniels for small values of K but remain above the Gracefield values for large K.

The work of Choudbury[20] is interesting because the data were obtained in New Delhi which has a somewhat different climate. The results, however, are surprisingly similar to those of Erbs *et al.* and of Collares-Perreira and Rabl.

Work in Israel by Gordan and Hochman[21] should be interesting but they do not give regression curves and it is difficult to make a direct comparison of results. They seem to be similar to the results of Vignola and McDaniels except at high values of K where their ratios appear to be higher.

In Australia the work of Bugler[22] must be noted. While it is not easy to compare his results because of the presentation, most of which is taken up with hourly values, they are roughly in agreement with the results of Choudbury.

Although one might reasonably expect to find differences between different localities, particularly those with differing climates, the results suggest that variations due to local conditions may be smaller than might be expected. The comment of Liu and Jordan that differences of 10% had been found in two different pyranometers measuring diffuse radiation emphasises the problems which are still encountered in this work.

5. CONCLUSIONS

Parameters have been evaluated for New Zealand conditions for use in the ASHRAE model for clear sky

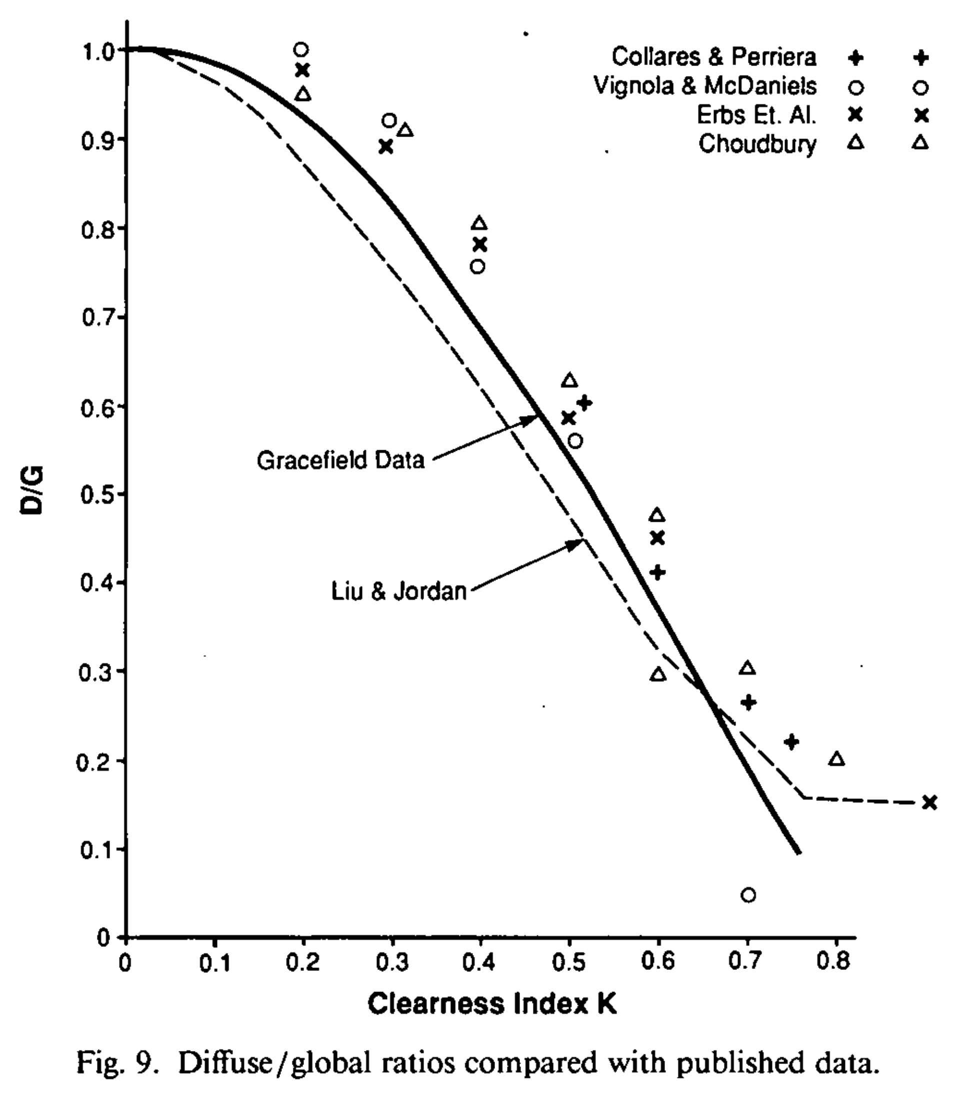

Fig. 9. Diffuse/global ratios compared with published data.

radiation. These parameters differ from those given by ASHRAE and the proposed modified values. In particular the clear sky diffuse coefficient is appreciably different, being substantially lower in summer.

On clear days, lower values of sky diffuse radiation were observed than appear to be found in the USA.

The Gracefield parameters shown in Table 1 and Fig. 2, when used in the ASHRAE algorithm will give clear sky radiation values which are in good agreement with measured values in New Zealand. There is naturally some variation in the measured values as clear sky conditions are not absolutely constant from day to day. The estimated values were observed to be generally within ±1.5% of the mean of measured values. However, the measured values for east- and south-facing surfaces were found to be 10% higher and 12% lower than the estimated values, respectively. It seems likely that the Gracefield values are applicable to most of New Zealand and they are better than the parameters formerly available.

The proportions of diffuse radiation for all conditions was about 10% lower than those reported by Vignola and McDaniels but higher than Liu and Jordan. At high values of clearness index, i.e., very clear skies, the diffuse ratio was considerably lower than those reported elsewhere.

Acknowledgments—The author is indebted to the Department of Scientific and Industrial Research and New Zealand Meteorological Service for the data on which the work was based. In particular the author is indebted to Dr. T. G. Haskell of DSIR for the preparation of the data, Mr. F. N. Blackwell of Brickell Moss Ltd. for assistance in processing the data, Mr. A. C. Penney for his assistance with NZMS data, and Building Research Association of NZ for assistance in the preparation of the paper.

NOMENCLATURE

- A, B, C Parameters in the ASHRAE clear sky model
- D Daily diffuse radiation received on a horizontal surface, kWh/m^2
- ET Daily extraterrestrial radiation (radiation that would be received on a horizontal surface outside the earth's atmopshere), kWh/m^2
- F_g Angle factor between the surface and the ground ($F_g = \frac{1}{2}[1 - \cos \Sigma]$, where Σ = surface tilt angle measured from horizontal, $\Sigma = 90°$ for a vertical surface, so $F_g = 0.5$)
- F_s angle factor between the surface and the sky ($F_s = \frac{1}{2}[1 + \cos \Sigma]$, $\Sigma = 0$ for a horizontal surface so $F_s = 1$)
- G Daily global radiation (direct plus diffuse received on a horizontal surface), kWh/m^2
- g Ground reflectance (dimensionless)
- I_d Sky diffuse component of radiation intensity, W/m^2
- I_n Direct normal component of radiation intensity, W/m^2
- I_t Total radiation intensity received on a surface of any orientation, kWh/m^2
- K Clearness index ($=G/ET$)
- m Air mass (relative mass of air through which the radiation) must pass. (air mass 1 corresponds to zenith angle 0)
- b Solar altitude (degrees from the horizontal)
- δ_1, δ_2 Limit intervals
- j Angle of incidence (degrees)

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APPENDIX

Fitting curves to the data of Figs. 6 and 7 by a straightforward least squares procedure proved unsatisfactory and was inconsistent between the two presentations. Examination of the data showed that the distribution was not normal but skew. When the data were grouped into intervals of K of 0.05 and Pearsons measure of skewness calculated for each interval it was found that the data changed from a maximum of 1.5 positive skew at the extremities to 1.2 negative skew at the centre.

To overcome this difficulty without resorting to the complexity of a robust regression, the following procedure was adopted.

The data were grouped into 20 equal intervals of K and the median value was found for each interval. A curve was then fitted to the median values and the origin by a linear least squares regression. Because the number of values in each interval was different, a weighted regression was used.

In order to provide an estimate of the limits within which the ratios m might be expected to lie, these were determined for each interval by taking the dispersion about the median given by:

$$\text{standard deviation for each } K \text{ interval} = \pm \frac{t \cdot Q}{0.60}$$

where Q = the semi-interquartile range; t = the "student t" statistic.

The factor in the denominator would be 0.67 for a normal distribution but 0.60 is more appropriate to the moderate degree of skew involved. The limits shown in Figs. 6 and 7 indicate the area within which 95% of observations may be expected to lie. A different percentage may be obtained by taking the appropriate value of t.

The resulting equations are

Diffuse/Global. $D/G = 1 + 0.146K - 2.95K^2 + 1.56K^3$

Upper limit of 95% probability $D/G\ (1 + W_1) = 1.46 - 1.44K - 0.252K^2$

Lower limit of 95% probability $D/G\ (1 - W_2) = 1.04 - 1.31K - 0.108K^2$

Diffuse/Extraterrestrial. $D/ET = 1.01K + 0.0708K^2 - 2.77K^3 + 1.43K^4$

Upper limit of 95% probability

$D/ET(1 + W_1) = 0.000857 + 1.19K - 0.211K^2 - 1.47K^3$

Lower limit of 95% probability

$D/ET\ (1 - W_2) = 0.000286 + 0.951K - 0.965K^2 - 0.347K^3$

(Note: The probability indicates that, based on the observations over two years at Gracefield, 95% of observations may be expected to lie within the limits.) All values refer to radiation received on the horizontal.

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