Calculation of Solar Irradiances for Inclined Surfaces: Verification of Models which use Hourly and Daily Data

A Report of Task 9: Solar Radiation and Pyranometry Studies

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INTERNATIONAL ENERGY AGENCY
Solar Heating & Cooling Programme

THE INTERNATIONAL ENERGY AGENCY
SOLAR HEATING AND COOLING PROGRAMME

International Energy Agency

The International Energy Agency, headquartered in Paris, was formed in November 1974 as an autonomous body within the framework of the Organization for Economic Cooperation and Development to establish cooperation in the area of energy policy. Twenty-one countries are presently members, with the Commission of the European Communities participating under a special arrangement.

Collaboration in the research, development and demonstration of new energy technologies to help reduce dependence on oil and to increase long-term energy security has been an important part of the Agency's programme. The IEA R&D activities are headed by the Committee on Research and Development (CRD) which is supported by a small Secretariat staff. In addition, four Working Parties (in Conservation, Fossil Fuels, Renewable Energy and Fusion) are charged with monitoring the various collaborative energy Agreements, identifying new areas for cooperation and advising the CRD on policy matters.

Solar Heating and Cooling Programme

One of the first collaborative R&D agreements was the IEA Solar Heating and Cooling Programme which was initiated in 1977 to conduct joint projects in active and passive solar technologies, primarily for building applications. The eighteen members of the Programme are:

Australia	Germany	Norway
Austria	Finland	Spain
Belgium	Italy	Sweden
Canada	Japan	Switzerland
Denmark	The Netherlands	United Kingdom
European Community	New Zealand	United States
France (observer)		

A total of eighteen projects or "Tasks" have been undertaken since the beginning of the Programme. The overall programme is managed by an Executive Committee composed of one representative from each of the member countries, while the leadership and mangement of the individual Tasks is the responsibility of Operating Agents. These Tasks and their respective Operating Agents are:

*Task 1:	Investigation of the Performance of Solar Heating and Cooling Systems - Denmark
*Task 2:	Coordination of Research and Development on Solar Heating and Cooling - Japan
*Task 3:	Performance Testing of Solar Collectors - United Kingdom
*Task 4:	Development of an Insulation Handbook and Instrument Package - United States
*Task 5:	Use of Existing Meteorological Information for Solar Energy Application - Sweden
*Task 6:	Solar Heating, Cooling, and Hot Water Systems Using Evacuated Collectors - United States
*Task 7:	Central Solar Heating Plants with Seasonal Storage - Sweden
*Task 8:	Passive and Hybrid Solar Low Energy Buildings - United States
*Task 9:	Solar Radiation and Pyranometry Studies - Federal Republic of Germany
*Task 10:	Material Research and Testing - Japan
*Task 11:	Passive and Hybrid Solar Commercial Buildings - Switzerland
Task 12:	Building Energy Analysis and Design Tools for Solar Applications - United States
Task 13:	Advanced Solar Low Energy Buildings - Norway
Task 14:	Advanced Active Solar Systems - Canada
Task 15:	Advanced Central Solar Heating Plants (In Planning Stage)
Task 16:	Photovoltaics in Buildings - Germany
Task 17:	Measuring and Modeling Spectral Radiation - Germany
Task 18:	Advanced Glazing Materials - United Kingdom

*Completed Task

FINAL REPORT

IEA TASK IX

CALCULATION OF SOLAR IRRADIANCES FOR INCLINED SURFACES:

VERIFICATION OF MODELS WHICH USE HOURLY AND DAILY DATA

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EXECUTIVE SUMMARY

The overall objective of this study was to evaluate the performance of numerical models which provide estimates of inclined surface solar irradiances given direct and diffuse solar irradiances for a horizontal surface. Specifically the study:

1) evaluated the performance of 21 hourly slope irradiance models,
2) evaluated the performance of seven slope irradiance models applicable to daily and longer time integrals,
3) compared the performance of hourly and daily sloped irradiance models at the daily time scale,
4) assessed the influence of temporal averaging (for time scale longer than a day) on the errors associated with the calculation of slope irradiances.

The models were grouped into four general categories according to the time scale at which they operate and the radiative flux they attempt to model. The categories are as follows:

1) Diffuse irradiance models applicable to time integrals of an hour or less.
2) Direct irradiance models applicable to time integrals of a day or longer.
3) Sky diffuse irradiance models applicable to time integrals of a day or longer.
4) Global irradiance models applicable to time integrals of a day or longer.

The significance of the study relied on its use of a number of data sets representing a range of solar climates, extending over a number of years and exhibiting high quality. Twenty-seven data sets were used in the validation. The data sets were from Canada, Denmark, Sweden, Norway, West Germany, France, the Netherlands, USA, Italy, Switzerland, United Kingdom and Australia.

All data sets were subjected to rigorous quality control before being used in the validation.

Three statistics were used in the validation of the various models. First was the mean bias difference which assessed the long term (i.e. systematic) performance of the model. The second, the mean absolute difference, was used to depict the presence of seasonal bias. Thirdly, the root mean square difference was used to describe the short term performance.

Due to the large number of models and data sets, a means had to be found to summarize the validation results. Two methods were used. Both involved the ranking of the validation statistics.

Rank 1 provided ranks of the average validation statistics for all slopes at a given location or group of locations while,

Rank 2 represented a ranking of the sum of the rankings of the validation statistics for the individual slopes at the same location or locations.

In most instances the two methods of ranking of data produced the same or similar results.

As different applications place varying emphasis on the validation results for certain slope orientations, the statistics for the various data set categories were not only presented for all slopes combined, but also for groupings of equator facing slopes and those of other orientations.

The results of the validation were as follows:

Diffuse irradiance models applicable to time integrals for an hour or less.

The results of the validation study which used 27 data sets and commenced by evaluating 21 different models clearly lead to the recommendation that the Perez algorithm be used for hourly calculations of slope irradiance.

Direct irradiance models applicable to time integrals of a day or longer.

The validation results presented supported a recommendation for the use of the direct irradiance algorithm developed by Page.

Sky diffuse irradiance models applicable to time integrals of a day or longer.

There was very little to distinguish between the Guey 2 variants although the data presented tended to suggest the selection of Guey 2.P or Guey 2.R over the other options. The data also indicated with certainty that the isotropic algorithm could not be recommended.

Global irradiance models applicable to time integrals of a day or longer.

Of the six potential models considered in this study the Guey 2.R/Rev 2 algorithm provided the best overall performance.

In comparing the use of hourly and daily algorithms it was demonstrated that there is a significant deterioration in the accuracy of slope irradiance estimates with the use of daily as opposed to hourly data together with the associated numerical procedures.

An important question then was to determine if these significant differences decrease as a result of temporal averaging when longer term estimates are required.

The study showed that for time intervals of a week to a month the short-term errors are similar for both the hourly and daily approaches if the systematic errors are ignored.

For the daily model, monthly mean daily or even long-term monthly mean daily data produce estimates of the monthly mean irradiance that are as reliable as those obtained by totalling the estimates for individual days in the month. However, the same is not true for the hourly model. In many cases estimates based on monthly mean hourly data or long-term monthly mean hourly data result in substantially higher values of both the RMSD and MBD indicating that in some cases the mean data do not adequately represent the relevant radiation conditions and hence do not modulate the hourly model in an appropriate manner.

As well as this report which provides the validation results, both the computer programmes and many of the quality controlled data sets used in this study are available on magnetic tape. A user's guide and reference manual are also available.

TABLE OF CONTENTS

1. INTRODUCTION

The intensity of solar radiation typically shows large variations as a result of changes in the orientation of the receiving surface. It is for this reason that solar collection devices usually face the equator at angles which are dependent on the local radiation climate, on the heating or cooling application and on design considerations such as roof slope. Furthermore, in some heating and cooling applications, such as determining passive solar gains, the solar irradiance data for a wide range of slope orientations are normally required.

However, measurements of solar radiation characteristically relate to the horizontal surface. There are two main reasons for this discrepancy between the orientation of the measuring devices and the requirements of those who use solar radiation data. The first is that standardization of exposure is more readily achieved if the sensor is horizontal. Only in this orientation can one reasonably assume that all sensors in the network have the same field of view (in this case the sky hemisphere). Then it is possible to make comparisons between the values measured at separate locations and attribute any difference to the atmospheric conditions. For sensors with orientations other than horizontal, one must always be concerned about allowing for the effects of local surface conditions. Secondly, given the wide range of slope orientations, it would be economically and practically impossible to provide measured data for all aspects and slope angles. The horizontal surface, with its general spatial representativeness, provides the best basis for estimating the irradiance for other surfaces.

The estimation procedure requires a geometrically based transformation of the direct (beam) irradiance and an integration of the diffuse radiance (both sky and surface-reflected) over the field of view of the inclined surface. On an hourly basis (or less) the former calculation may be considered exact, but for longer time integrals non-linearities lead to the possibility of increasing error (Hay and Davies, 1980). Determination of the diffuse irradiance for an inclined surface necessitates that assumptions be made regarding the distribution of the solar radiance over the sky hemisphere and ground surface within the field of view of the sensor (Hay and Davies, 1980).

The study involves the validation of 21 hourly diffuse models, seven daily direct and six daily diffuse models and six daily global models. The latter include a number of "hybrid" models that combine the daily direct and diffuse algorithms. Validation statistics will be derived using 24 data sets representing lengthy records of measured irradiances in diverse climatic regimes. The data sets span the years from 1961 to 1984 and for individual stations contain from one to twelve years of data.

Every attempt has been made to ensure that both the measured irradiances and the computer coding of the various models are error free. Most of the models and data sets were included in a "mini-validation" which involved widespread distribution and thorough reviews of the computer coding and data set characteristics.

Both the computer programmes and many of the data sets used in this study are available on magnetic tape. A User's Guide and Reference Manual are included as Appendices A and B respectively, in Volume 2 of this report.

2. OBJECTIVES

The general objective of this study is to evaluate the performance of numerical models which provide estimates of inclined surface irradiances given direct and diffuse irradiances for the horizontal surface. The specific objectives are as follows:

a) To evaluate the performance of hourly slope irradiance models (these algorithms differ in their treatment of the diffuse irradiance).
b) To evaluate the performance of slope irradiance models to daily and longer time integrals (first order differentiation of these models is with respect to their treatment of the direct irradiance).
c) To compare the performance of hourly and daily slope irradiance models at the daily time scale.
d) To assess the influence of temporal averaging (for time scales longer than a day) on the errors associated with the calculation.

Objectives (a) and (b) will be addressed in Sections 7 and 8, respectively. An intercomparison of the hourly and daily models (objective (c)) involves an evaluation of their ability to estimate the total irradiance for time scales of a day or longer. The results of this analysis will be described in Section 9. Material related to objective (d) will be presented in Section 10. However, prior to presenting the results of the validations the various slope irradiance models and data sets will be documented (Sections 3 and 4, respectively). Sections 5 and 6 will describe the various data quality control and model validation procedures adopted in the study.

3. THE MODELS

Following Hay and McKay (1985) the models to be evaluated in this study may be grouped into four general categories according to the time scale at which they operate and the radiative flux they attempt to model.

3.1 Diffuse Irradiance Models Applicable to Time Integrals of an Hour or Less

At these time scales the transformation of the normal incidence direct (beam) radiation to the direct irradiance for a surface of any given orientation may be considered exact [The pertinent equations are given in Kondtratyev (1977), Hay and Davies (1980) and Hay and McKay (1985), amongst others]. Thus all the hourly inclined surface sky irradiance models focus on calculating the diffuse irradiance originating from the portion of the sky "seen" by the inclined surface. Many of the approaches have been reviewed by Hay and McKay (1985). Table 1 lists the hourly inclined surface diffuse sky irradiance models which have been validated in the present study. The following paragraphs provide a brief statement on the basis for each model. The references in Table 1 and the listing of computer code in Appendix C (Volume 2), should be consulted for further details.

Table 1: Hourly inclined surface irradiance models included in validation study. These models calcuate only the diffuse irradiance.

NAME	ABBREVIATED NAME	REFERENCE
Isotropic	Iso	Kondratyev and Manolova (1960)
		Liu and Jordan (1963)
50/50 Comb	50/50	Hay (1979)
Bugler 1	Bug1	Bugler (1977)
Bugler 2	Bug2	Hay and McKay (1985)
		Hay et al. (1986)
C & Z	C&Z	Cohen and Zerpa (1982)
DOE2	DOE2	Lawrence Berkeley Lab.(1982)
Gueymard	Gueymard	Gueymard (1983)
Hay	Hay	Hay (1979)
		Hay and Davies (1980)
Hay2	Hay2	Josefsson (Pers. Comm.,1985)
Skartveit	S&O	Skartveit and Olseth (1986)
Ineichen	Ineichen	Ineichen (1983)
Klucher	Kluch	Klucher (1979)
Kusada	Kusada	ASHRAE (1976)
Van den Brink	VB	Van den Brink
Lokmanhekim	Lok	ASHRAE (1971)
Oegema	Oegema	Oegema (1971)
Page	Page	Page (1978)
		Rogers et al. (1979)
Perez1	Perez1	Perez et al. (1983)
Perez2	Perez2	Perez (Pers. Comm., 1985)
Puri	Puri	Puri et al. (1980)
T & C	T&C	Temps and Coulson (1977)

ISOTROPIC - This algorithm represents the earliest and simplest form of the diffuse irradiance transformation to inclined surfaces. It assumes that the diffuse radiance is uniformly distributed over the sky hemisphere. Consequently, integration of these irradiances over the portion of the sky hemisphere "seen" by the slope yields a simple dependency on the inclination of the slope.

50/50 COMB - Prior to the development of parameterizations which allowed variations in the portion of the diffuse irradiance which was considered circumsolar, anisotropy was given a somewhat token recognition by assuming that a fixed portion of the diffuse irradiance was isotropic with the remainder circumsolar. The ratio was arbitrarily defined and the equal portions that are used in the 50/50 Comb model tended to be preferred.

BUGLER 1 - This model is based on the assumption that anisotropy in the diffuse irradiance may be accommodated by treating 5% of the direct irradiance as the circumsolar portion of the diffuse irradiance.

BUGLER 2 - The original formulation of Bugler (1977) ignores the fact that a portion of the diffuse irradiance is treated as both isotropic and circumsolar. A modification which conserves the diffuse irradiance has been suggested by Hay and McKay (1985), with a corrected equation in Hay et al. (1986).

COHEN and ZERPA - In this algorithm an initial formulation which assumes that the diffuse radiance is isotropically distributed is empirically corrected using the ratio of the observed total solar irradiance to the corresponding extraterrestrial value.

GUEYMARD - The inclined surface diffuse irradiance conversion factor is expressed as a function of the solar zenith angle, the incidence angle of the direct solar beam (with respect to the slope normal), slope angle and cloud opacity. Separate parameterizations of the sky radiance patterns are provided for clear and cloudy skies. These are combined in a linear manner according to the observed cloud opacity or the ratio of the diffuse and total solar irradiances for the horizontal surface. In the present study we have not included Gueymard's correction for the circumsolar radiation measured by a pyrheliometer while of necessity, cloud opacity was estimated using Gueymard's empirical relationship and the ratio of the diffuse and global irradiance.

HAY - This approach uses the atmospheric transmittance for direct solar irradiance as an "anisotropy index" which defines the portion of the diffuse irradiance to be treated as isotropic with the remainder considered circumsolar.

HAY 2 - Josefsson (Pers. Comm., 1985) has suggested an empirical correction to the Hay algorithm to incorporate the effects of horizon darkening under overcast skies and horizon brightening for cloudless skies. The adjustments made to the estimated diffuse irradiance for the slope are a function of slope angle and the "clearness parameter" (the global irradiance as a portion of the extraterrestrial irradiance, both for the horizontal surface).

SKARTVEIT AND OLSETH - Recently Skartveit and Olseth (1986) modified the Hay algorithm to include sky radiance anisotropy for overcast as well as cloudless skies. They assumed that under the former conditions 30% of the horizontal diffuse irradiance may be treated as collimated radiation from the zenith with the remainder being an isotropic radiance from the sky dome. The relative importance of the zenithal radiance term decreases linearly with the "anisotropy index" defined by Hay (1979) until it is zero for an index value of 0.15. Their model also includes a correction for local horizon effects, but this was not included in the present study.

INEICHEN - This algorithm assumes that a portion of the diffuse equal to at least 6% of the direct irradiance is circumsolar and that the portion increases linearly with the optical air mass. The remainder of the diffuse is considered to be isotropically distributed.

KLUCHER - Klucher adopts the cloudless sky radiance distribution described by Temps and Coulson (1978). The modulation factor between this and the isotropic condition is the portion of the total solar irradiance which is diffuse. Klucher also suggested that the modulating factor could be the square of this ratio. Since the non-linear factor produced marginally better results when applied to data from Vancouver, Canada it has been adopted in subsequent analyses.

EMGP2 - The diffuse irradiance is divided equally between clear and overcast sky conditions, with the latter being treated as isotropic. Alternative methods that base the partitioning on the sunshine duration or cloud cover were not evaluated in the present study. Under clear skies the ratio of the diffuse irradiances for a vertical and horizontal surface is based on a relationship initially presented by Threkheld (1962) and expressed as a second order polynomial involving the angle of incidence of the direct rays on the vertical surface. Interpolation of the clear sky diffuse irradiance for an inclined plane involves a weighting based on the cosine of the slope angle.

LOKMANHEKIM - This is the "official" ASHRAE model as described in ASHRAE (1971). Gueymard (Pers. Comm., 1985) provided an analytical method for calculating Lokmanhekim's version of the ratio of the diffuse irradiance for the inclined surface to that for the horizontal surface.

KUSUDA - The "official" ASHRAE model (Lokmanekim) was revised by Kusuda.

OEGEMA - This model is similar to that of EMGP2 except that: 1) the partitioning of the diffuse between clear and overcast sky conditions involves a dependency on the cosine of the solar zenith angle. An alternative method that bases the partitioning on the clearness index by Van den Brink was not evaluated in the present study; 2) the empirical function which defines the ratio of the vertical to horizontal diffuse irradiance for clear skies uses somewhat different coefficients; and 3) the interpolation weights for the horizontal and vertical diffuse irradiances are the cosine and sine of the slope angle, respectively.

PAGE - Again the approach is to distinguish between the diffuse radiance distribution for clear and overcast skies and to subsequently combine these limiting cases according to the value of a modulating factor. The present model uses bright sunshine data (in the present study and following Hay, 1979 this is parameterized in terms of the observed total solar irradiance) to quantify the clear and overcast sky portions. For the latter conditions the sky radiance distribution of Moon and Spencer (1942) is adopted. The clear sky irradiance is subdivided into its isotropic and circumsolar portions by means of an empirical function. Finally Page includes an empirically derived azimuthal correction factor.

PEREZ 1 - An attempt is made to replicate both circumsolar and horizon brightening by superimposing both a disc and a horizontal band with increased irradiance upon the isotropic radiance field. The appropriate enhancement factors were evaluated empirically and expressed as a function of the diffuse and total irradiances and of the solar zenith angle. In the Perez 1 version of the model the 420 empirical coefficients required by the model are based on global irradiance data for one horizontal and seven inclined sensors at Albany, New York.

PEREZ 2 - This version of the algorithm uses empirical coefficients based on data from Carpentras, France.

PURI - This model uses the ratio of the observed to extraterrestrial total solar irradiance to modulate between isotropy and anisotropy. The latter condition is expressed in terms of the view factor for a given slope angle. These factors must be numerically evaluated for each slope and require an assumed distribution of the diffuse radiance over the sky hemisphere under cloudless sky conditions.

TEMPS AND COULSON - The T&C algorithm is strictly applicable to cloudless skies but in the present study it has been evaluated for all conditions. As noted earlier, Klucher (1979) adopted the Temps and Coulson cloudless sky distribution for one component of his model. The distribution empirically accommodates both horizon brightening and circumsolar enhancement.

DOE-2 - This algorithm uses the empirical relationship developed by Threkheld (1962) to specify the ratio of the diffuse irradiances for the inclined and horizontal surfaces under cloudless skies. However, if the slope angle is less than 45° the two irradiances are assumed to be equal.

Table 2: **Daily inclined surface irradiance models included in the validation study. These models calculate only the direct irradiance.**

NAME	ABBREVIATED NAME	REFERENCE
Bremer	Bremer	Bremer (1983)
Jones*	Jones	Jones (1980)
Revfeim* (Unweighted)	Rev1	Revfeim (1976, 1979, 1982a, 1982b)
Revfeim (Weighted)	Rev2	Revfeim (1976, 1979, 1982a, 1982b)
Page	Page	Page (1961)
L & J	L & J	Liu and Jordan (1960)
K & T	K & T	Klein and Theilacker (1981)
Desinica	DPD	Desnica et al. (1986)

* These models produce identical results.

3.2 Direct Irradiance Models Applicable to Time Integrals of a Day or Longer

For the models falling into this category the major challenge is to integrate the geometrical relationships between the sun and the normal to the slope in such a way that the model is valid over the longer time scales. This involves accommodating such factors as the diurnal distribution of the direct radiation, diurnal variations in the atmospheric transmittance and the double sunrises and sunsets which occur on poleward-facing slopes in the summer months. Table 2 lists the approaches evaluated in the present study. The listed references and the computer code (Appendix C, Volume 2) may be consulted for further details. The following paragraphs present brief descriptions of the various algorithms.

LIU AND JORDAN - In the strictest sense this is not a daily model since the procedure is to use the relationships originally developed by Liu and Jordan (1960) to determine the diurnal distribution of both the diffuse and total solar irradiances given only the daily integrals. The functional relationships provided by Collares-Pereira and Rabl (1979a, b, c) have been used in the present study. Given the hourly values that have been estimated from the daily data, it is possible to use the equations which are valid for any instant in time (see Section 3.1).

JONES/REVFEIM (Unweighted) - These models represent the culmination of the work initiated by Liu and Jordan (1962) and continued by Klein (1977). It is assumed that the ratio of the daily integrals of the direct radiation for the inclined and horizontal surfaces is the same at the Earth's surface as it is at the top of the atmosphere. The alternative formulae presented by Jones (1980) and Revfeim (1976) are applicable to all orientations (including surfaces which experience double sunrise/sunset) and they yield identical results.

REVFEIM (Weighted) - Revfeim recognized that variations in the atmospheric transmittance associated with diurnal variations in the solar zenith angle are incompatible with the assumption which forms the basis of the preceding Jones/Revfeim model. In this version Revfeim recommended use of a weighting function defined by cos(πh/ 2H), where h is the hour angle and H is the half day length.

BREMER - As an alternative to the weighting function proposed by Revfeim (1982), Bremer uses cos (z), where z equals the solar zenith angle.

KLEIN AND THEILACKER - This model uses the relationships between hourly and daily irradiances, as developed by Liu and Jordan (1960) and Collares-Pereira and Rabl (1979a, b, c), to compute the ratio of the daily integrals of the direct irradiances for the inclined and horizontal surfaces. The need for hourly calculations is thereby avoided and the effects of atmospheric attenuation are implicitly incorporated in the model.

PAGE - Page incorporates the effects of atmospheric attenuation by using a standard direct radiation curve representative of a tropical atmosphere. To avoid the need to make iterative calculations, Page's curve was parameterized to meet the form of a second order polynomial in the cosine of the solar zenith angle. Although the parameterized curve has an overall fit better than ±2%, the equation is only an approximation of the original data. Even small deviations in certain regions of the curve may in some situations cause significant differences between the results obtained using this curve and those based on the use of a more precise fit to Page's original data.

DESNICA ET AL. - Whereas Revfeim (1982a, 1982b) used a weighting factor of 2, i.e. cos (π/2 h/H) Desnica et al. used an empirically derived value of 1.25 i.e. cos (1.25 h/H).

3.3 Sky Diffuse Irradiance Models Applicable to Time Integrals of a Day or Longer

Four distinct approaches may be followed when daily data are used to estimate daily or longer-term values of the diffuse irradiance for an inclined surface. Table 3 shows that models representative of each category have been analyzed in the present study.

Table 3: Daily inclined surface irradiance models included in the validation study. These models calculate only the diffuse irradiance.

NAME	ABBREVIATED NAME	REFERENCE
Isotropic	Iso	Kondratyev and Manolova (1960) Liu and Jordan (1963)
Guey1	Guey1	Gueymard
Guey2.K	Guey2.K	Gueymard
Guey2.R	Guey2.R	This study
Guey2.P	Guey2.P	This study
Guey2.D	Guey2.D	This study

3.3.1 One Calculation Per Day

Models in this category either exclude dependencies on solar position or assume a representative value for the entire day. The former approach is used in the Isotropic model where, as in the hourly version, the slope factor varies only with the inclination of the surface.

3.3.2 Hourly Calculations

Models in this category essentially follow the approach used in the Liu and Jordan model for daily direct irradiance calculations - namely, estimate hourly irradiances from the daily total and then sum the values provided by the hourly model in order to obtain the daily total for the inclined surface. This is the procedure used in Guey.1. The diurnal distribution of the diffuse irradiance is derived using relationships provided by Collares- Pereira and Rabl (1979a, b, c) and hourly irradiances for the inclined surface are then calculated using the Gueymard hourly model. It is also possible to use any of the other 20 hourly diffuse irradiance models in this configuration, but a decision was made to limit the current validation to Gueymard's model since it is the only published approach and the hourly validation results showed that it performs second only to the model of Perez.

3.3.3 Two Calculations on Daily Partitions

Algorithms in this category assume that the diffuse slope factor may be linearly interpolated between the corresponding values for that part of the day when only diffuse radiation is received by the slope and the part or parts of the day when there is at least the potential for both direct and diffuse radiation to be incident upon the slope. Effective values of both the solar zenith angle and the angle of incidence of the direct radiation on the slope must be determined for each of these portions of the day. In addition, the model must partition the daily diffuse irradiance into the amounts occurring in each part of the day [i.e. period(s) of diffuse and (potential) direct and period(s) of diffuse only].

The effective solar angles during the period(s) of potential direct radiation may be determined using any of the daily direct irradiance algorithms described in Section 3.2. Validation results for these models suggest that four of them (Rev2, K&T, Page and DPD) warranted examination in the present context.

The partitioning of the daily diffuse into the periods with and without potential direct radiation requires knowledge of the diurnal distribution of the diffuse irradiance. In all versions the partitioning of the daily diffuse was performed using the diurnal distribution described by Collares-Pereira and Rabl (1979a, b, c).

It should be noted that the Guey2.K model is equivalent to the diffuse component of the total irradiance model proposed by Gueymard (see Section 3.4). The other versions (Guey2.R, Guey2.P and Guey2.D) simply replace the K&T description of the diurnal distribution of the direct irradiance by that postulated in the Rev2, Page and DPD daily direct irradiance models respectively. The weak dependency on the diurnal distribution suggests that there should be little distinction between the performance of these four routines. All the Guey2 variants required a modification for application to short-term data (i.e. individual daily values) since the original relationships proposed by Gueymard are not valid under extremely low values of the clearness index. When the radiation was essentially all diffuse any influence of solar position was ignored and the diffuse radiance distribution was assumed isotropic.

A fourth possible modelling approach was also considered. The procedure was to determine "representative" hourly irradiance estimates for each of the two partitions (i.e. the diffuse only and the diffuse and potential direct partitions) and then apply any of the hourly diffuse irradiance models described in Section 3.2. A review of the relevant literature suggests that such an approach has never been attempted. The challenge is to provide the models with representative hourly values consistent with the effective angles associated with the two partitions. In the present study we simply assumed that an appropriate value of the normal incidence direct radiation for the period of potential beam may be determined by assuming a constant value during the partition. Hence the value is given by the daily direct irradiance divided by the duration of the partition. For each of the two partitions the diffuse irradiance is handled in a similar manner.

Certain hourly models (e.g. Hay and Gueymard) use the hourly irradiances to compute ratios (e.g. opacity, anisotropy index) to categorize the radiation environment whereas other models (e.g. Perez) rely more heavily on the actual hourly irradiances. Hence, to the extent that the computation of the representative hourly irradiances fails to represent the effective radiation conditions, the consequences will be felt more by the latter grouping of models than by the former. Indeed, for models in the former group still more accurate estimates may result if the ratios are based on daily rather than hourly values.

Such approaches were evaluated using the Perez2, Gueymard and Hay hourly diffuse models and some of the representative data sets from Category A. The results indicated that there was no advantage to be gained from using such an approach and in many cases (e.g. with Perez) the hourly values obtained in the manner described above did not adequately represent the relevant characteristics of the radiation environment.

Appendix C in Volume 2 lists the codes for these models.

3.4 Global Irradiance Models Applicable to Time Integrals of a Day or Longer

For daily or longer time scales calculation of the global sky irradiance for an inclined surface involves either a global irradiance model developed specifically for that purpose or the use of a combination of one of the daily direct irradiance models (described here in Section 3.2) and a daily or hourly sky diffuse model (Section 3.3), where the latter is used with a partitioning algorithm allowing it to be used with daily data. Table 4 lists the global irradiance models evaluated in the present study while Appendix C (Volume 2) contains a listing of the relevant computer codes.

Table 4: Daily inclined surface irradiance models included in the validation study. These models calculate the total solar irradiance.

NAME	REFERENCE
Gueymard.1	Gueymard
Gueymard.2	Gueymard
Guey2.D/DPD	This study
Guey2.P/Page	This study
Guey2.R/Rev2	This study
McFar	McFarland et al.

Gueymard.1 is an iterative hourly model that uses the hourly diffuse model of Gueymard and the "exact" equations for the direct irradiance. The hourly direct and diffuse irradiances are estimated from their daily counterparts using the diurnal distributions presented by Liu and Jordan (1960) and Collares-Pereira and Rabl (1979a, b, c).

Gueymard.2, which is a true daily model combines separate diffuse and direct algorithms. The former, including a minor modification that is required if the model is to be used with short-term (i.e. daily) data, has already been described in the previous section while the calculations of the direct irradiance use the K&T algorithm. Hence the model could also be designated Guey2.K/K&T. Furthermore, the Guey2.D/DPD, Guey2.R/Rev2 and Guey2.P/Page are similar to Gueymard.2 except that the K&T direct radiation algorithm has been replaced by an alternative formulation.

We have evaluated only one model that proceeds directly to an estimate of the global irradiance rather than first considering the diffuse and direct components. The MCFAR algorithm employs empirical coefficients derived using least-squares regressions between the monthly mean total irradiances for the horizontal and inclined surfaces and a solar position parameter (latitude minus mid-month solar declination) and a clearness parameter (fraction of extraterrestrial solar irradiance). The inclined surface irradiances were initially calculated for discrete slope and azimuth angles using an hourly time step and the isotropic assumption. For the present study it was necessary to interpolate in order to estimate the irradiance for slope orientations not included in the original calculations. Since data for poleward facing surfaces were not included in the regression, the model cannot make estimates for such surface orientations. Appendix C (Volume 2) contains a listing of the computer code for the MCFAR algorithm.

3.5 Reflection from Adjacent Surfaces

Calculation of the global irradiance for an inclined surface includes consideration of not only the fluxes from the sky but also those associated with reflection from the adjacent surfaces which can be "seen" by the given inclined surface. In some slope irradiance measurement and modelling programmes the complexities associated with reflection from heterogeneous ground surfaces are avoided by equipping the sensors with artificial horizons that intercept radiation reflected by surfaces below the horizontal plane. In other cases the reflected component must be included. In some situations the hemispheric reflectance of the surface can be deduced from measurements; otherwise an assumed value is adopted.

Where it is necessary, computation of the reflected irradiance for the surface is simplified by assuming isotropic reflection. Directional reflectance models have been developed (e.g. Temps and Coulson, 1977; Gueymard, 1986; Ineichen, 1983), but there are few data sets which allow specific validation of such models. Hay and McKay (1985) present preliminary results based on data from Vancouver, Canada.

The lack of a rigorously validated reflected irradiance model means that in the present study, whenever total inclined surface irradiances are calculated for stations where the inclined sensors were not equipped with artificial horizons, isotropic surface reflection has been assumed. In these situations the "observed" diffuse irradiance attributed to each of these sensors was obtained by subtracting the isotropically reflected irradiance and the calculated direct irradiance from the observed global irradiance. Since sensors equipped with artificial horizons avoid the need to invoke the assumption of isotropic reflection a decision was made to place more weight on the validation statistics for stations using artificial horizons. However, the following points should be considered: 1) there are additional measurement errors associated with the use of artificial horizons; 2) typically the reflected component is a very small portion of the global irradiance; and 3) isotropic reflection is often the most realistic model that can be adopted.

In the validation of the direct irradiance models (see Section 8) the "measured" direct irradiance for a slope is determined using the normal incidence direct radiation and the "exact" equations for converting that irradiance to the inclined surface. The daily values are the sum of the hourly values calculated in that manner. Hence the validation of direct models can be achieved without invoking the assumption of isotropic reflection.

4. DATA SOURCES

The significance of the present study relies on its use of a number of data sets representing a range of solar irradiance climates, extending over a number of years and exhibiting high quality. The last attribute will be addressed in Section 5. Table 5 describes the data sets used to verify the slope irradiance models.

A number of characteristics of the individual data sets have been included in the Table 5a. They are fundamental to the successful implementation of the irradiance models and during and after the "mini-validation" every effort was made to confirm their validity.

Table 5a: Characteristics of Data Sets Used in the Validation Study (See also Table 5b)

Category A
Artificial Horizon; Measured Direct

Location	Lat.	Long.	Std. (1)	Time (2)	Valid (3)	Horizon (4)	Albedo (5)	Dir/Dif (6)	K/K0 (7)
Albany	47.67N	73.83W	75W	LST	End	Yes	N.A.	Dir	0.456
Bracknell.2	51.42N	0.75E	N.A.	LAT	Mid	Yes	N.A.	Dir	0.395
Lerwick	60.13N	1.18W	N.A.	LAT	Mid	Yes	N.A.	Dir	0.372
Lulea	65.55N	22.13E	15E	LST	End	Yes	N.A.	Dir	0.446
Norrkoping	58.62N	16.15E	15E	LST	End	Yes	N.A.	Dir	0.443
San Antonio	29.42N	98.50W	90W	LST	End	Yes	N.A.	Dir	0.533

Category B
Measured Albedo; Measured Direct

Location	Lat.	Long.	Std. (1)	Time (2)	Valid (3)	Horizon (4)	Albedo (5)	Dir/Dif (6)	K/KO (7)
Cabauw.1	51.96N	4.93E	0	LST	End	No	Meas.	Dir	0.397
Carpentras	44.06N	5.03E	N.A.	LAT	End	No*	Meas.*	Dir	0.561
Golden	39.74N	105.16W	105W	LST	End	No	Meas.	Dir	0.540
Toronto	43.80N	79.56W	N.A.	LAT	Mid	No	Meas.	Dir	0.474
Trappes	48.76N	2.00E	N.A.	LAT	End	No*	Meas.*	Dir	0.412
Vancouver	49.25N	123.25W	N.A.	LAT	Mid	No	Meas.	Dir	0.499

Category C
Estimated Albedo; Measured Direct

Location	Lat.	Long.	Std. (1)	Time (2)	Valid (3)	Horizon (4)	Albedo (5)	Dir/Dif (6)	K/KO (7)
Atlanta	33.80N	84.38W	75W	LAT	End	No	0.2	Dir	0.505
Bergen	60.40N	5.33E	N.A.	LAT	Mid	No	0.2	Dir	0.370
Los Alamos	35.80N	106.00W	105W	LST	Mid	No	0.2	Dir	0.577

Table 5a (Continued)

Category D
Artificial Horizon; Measured Diffuse

Location	Lat.	Long.	Std. (1)	Time (2)	Valid (3)	Horizon (4)	Albedo (5)	Dir/Dif (6)	K/KO (7)
Bracknell.1	51.42N	0.75E	0	LST	End	Yes	N.A.	Dif	0.408
Griffith	34.27S	146.33E	N.A.	LAT	End	Yes	N.A.	Dif	0.615
Hamburg	53.65N	10.12E	N.A.	LAT	End	Yes	N.A.	Dif	0.402
Highett	37.82S	144.97E	N.A.	LAT	End	Yes	N.A.	Dif	0.515
Townsville	19.27S	146.82E	N.A.	LAT	End	Yes	N.A.	Dif	0.576
Vaerlose	55.78N	12.38E	15E	LST	End	Yes	N.A.	Dif	0.411

* Slope data for Carpentras and Trappes, as supplied by Dr. R. Perez, had previously been corrected for ground reflection.

Category E
Measured or Estimated Albedo; Measured Diffuse

Location	Lat.	Long.	Std. (1)	Time (2)	Valid (3)	Horizon (4)	Albedo (5)	Dir/Dif (6)	K/KO (7)
Cabauw.2	51.96N	4.93E	0	LST	End	No	Meas.	Dif	0.397
Geneva	46.20N	6.15E	N.A.	LAT	End	No	0.2	Dif	0.467
Ispra	45.80N	8.62E	N.A.	LAT	End	No	0.2	Dif	0.461
Locarno	46.17N	8.72E	N.A.	LST	End	No	0.2	Dif	0.520
Odeillo	42.50N	2.03E	15E	LST	End	No	0.2	Dif	0.595
Valentia	51.92N	10.43W	0	LST	End	No	0.2	Dif	0.393

NOTES:

(1) Std. — Meridian used in conversion from LST to LAT

(2) Time — LAT - Local Apparent Time; LST - Local Standard Time

(3) Valid — Time valid for: End - End of observation hour; Mid - Middle of observation hour

(4) Horizon — Inclined sensor(s) fitted with artificial horizon

(5) Albedo — Method used to determine reflected irradiance
Meas. - Measured
Number - Assumed constant value

(6) Dir/Dif
Dir - Measured direct solar irradiances available
Dif - Measured diffuse solar irradiances available

(7) K/KO — Mean Clearness Index

In addition to the range of slope orientations represented in a given data set, the suitability of a data set for the present study is also influenced by the need to consider ground reflection and, if so, the methods used to define ground albedo and by the method used to determine the direct and diffuse components of the global solar irradiance. As a result, in Table 5a the data sets have been grouped into six categories as defined in the table. In the analysis of the validation data the last two categories have been combined due to the presence of only one station in the fifth category.

The data quality control (to be described in the following section) is able to detect gross errors in the interpretation of the individual data sets (e.g. wrong conversion factors; incorrect slope azimuth; use of local standard rather than local apparent times), but the effects of some errors are more subtle and were detected only after careful review of the information contained in Table 5a.

In addition to the original hourly data, subsidiary data sets were created from these files using the procedures described in the User's Guide and Reference Manual (Appendices A and B, Volume 2). The supplementary data files consisted of daily totals, monthly mean hourly and daily totals and long-term (i.e. total period) monthly mean hourly and daily totals. Most of these files are also available on magnetic tape.

5. DATA QUALITY CONTROL

All data sets were subjected to rigorous quality control since a preliminary investigation showed that all data sets contained erroneous information despite the rejection of all data flagged as erroneous or questionable. Even a few incorrect observations have an adverse effect on the validation statistics for a given month. Quality control consisted of recognizing and deleting erroneous data that were not flagged as such. There was no additional processing of the original data files to apply corrections for such effects as temperature dependency in the pyranometers or additional attenuation of the diffuse radiation due to a shadow band. Rather, quality control occurred at the three levels described in the following sections.

5.1 Limit Checks

All negative data and values which exceeded the solar constant were set to missing.

5.2 Consistency Checks Using "Redundant" Data

Where there were "redundant" data (e.g. simultaneous observations of direct, diffuse and total solar irradiances for the horizontal surface) these values were evaluated for mutual consistency. If the absolute value of the anomaly exceeded (200 + 10%) kJ $m^{-2}h^{-1}$ of the measured irradiance the data for that hour were flagged as questionable and subjected to manual examination for evidence of error and possible rejection.

5.3 Consistency Checks for Slope Data

The irradiance data for a given inclined surface were examined for consistency with the data for the horizontal surface (direct, diffuse, reflected and total) and with the data for adjacent inclined surfaces (at stations where multiple slope irradiance measurements were conducted). Quantitative guidance was provided by comparing the observed slope irradiances with values estimated using the Hay slope irradiance model. If the absolute value of the anomaly exceeded (200 + 10%) kJ $m^{-2}h^{-1}$ of the measured irradiance the data for that hour were again flagged as questionable and subjected to manual examination and possible rejection.

5.4 Rejection of Data

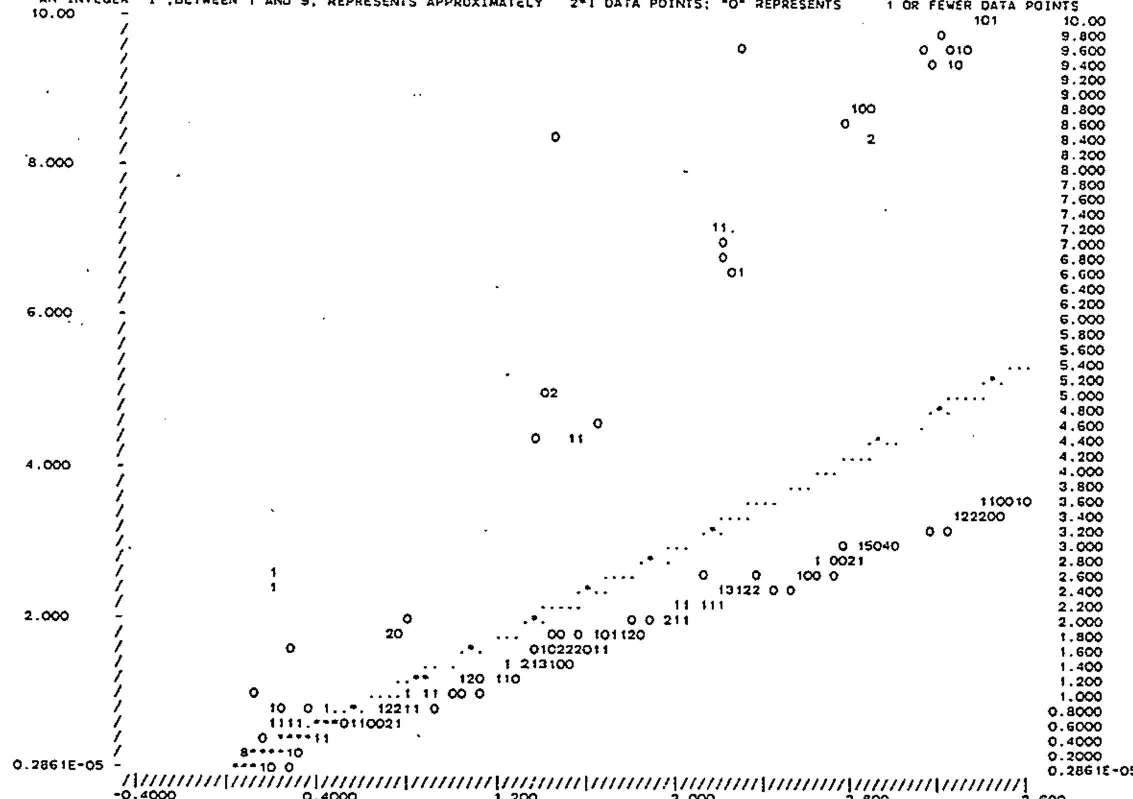
Observed data were rejected only if there was unambiguous reasons for doing so. Typically data which were flagged as potentially erroneous showed large residuals in scatter diagrams (see Fig. 1) and were also associated with large inconsistencies in the direct/diffuse/total comparisons and/or in comparisons with the irradiances for adjacent slopes. At stations where the components of the global radiation were obtained through measurements of the diffuse rather than the direct radiation, large differences between the observed and calculated slope irradiances (irrespective of the model used to generate the latter) often occurred near sunrise and sunset for the inclined surface. If the direct and diffuse components could be estimated from measured direct irradiances these differences were usually considerably less. For locations where both direct and diffuse irradiances were measured the former were used (along with the global) in preference to the latter. Inconsistent data near sunrise and sunset were rejected if only diffuse and total irradiances were available.

5.5 Results of Quality Control

Table 5b provides a full accounting of the slope orientations, measurement periods and number of observations for each data set after quality control. These data provided the observed values used in the model validations.

DEP.VAR.	INDEP.VAR.	A(CONST.)	B(COEFF.)	FRATIO(B)	FPROB(B)	STD.ERR.A	STD.ERR.B	STD.ERR.Y	RSQ
CSLP1M	OSLP1M	-0.6061E-01	1.522	522.6	0.0	0.1189	0.6656E-01	1.563	0.5486

PLOT OF Y VS X AND PLOT OF THE REGRESSION LINE.
THE "." AND "*" ARE USED TO PLOT THE REGRESSION LINE; THE "*" IS USED WHEN A PLOT POINT COVERS DATA POINTS
AN INTEGER "I",BETWEEN 1 AND 9, REPRESENTS APPROXIMATELY 2*I DATA POINTS; "O" REPRESENTS 1 OR FEWER DATA POINTS



DISTANCE BETWEEN SLASHES ON THE X-AXIS IS 0.4000E-01

Figure 1. An example of graphical output obtained during quality control.

TABLE 5b

Slope Orientations, Data Duration and Number of Hourly Observations (Before and After Quality Control for the Data Sets Described in Table 5a.

ALBANY

SLOPE AZIMUTH	SLOPE ANGLE	DATE START	DATE END	NUMBER OF OBSERVATIONS
0	33	2/80	1/82	8880
0	43	"	"	8884
0	53	"	"	8802
180	90	"	"	8774
-90	90	"	"	8733
0	90	"	"	8762
90	90	"	"	8742

ATLANTA

SLOPE AZIMUTH	SLOPE ANGLE	DATE START	DATE END	NUMBER OF OBSERVATIONS
0	34	4/79	6/81	9054

BERGEN

SLOPE AZIMUTH	SLOPE ANGLE	DATE START	DATE END	NUMBER OF OBSERVATIONS
0	45	6/78	6/83	19583
0	90	"	"	18448
90	90	"	"	18871
-90	90	"	2/81	8801
180	90	"	6/83	18313

BRACKNELL.1

SLOPE AZIMUTH	SLOPE ANGLE	DATE START	DATE END	NUMBER OF OBSERVATIONS
180	90	1/67	12/76	38279
-90	90	"	"	37990
0	90	"	"	37902
90	90	"	"	37969

TABLE 5b (Cont.)

BRACKNELL.2

SLOPE AZIMUTH	ANGLE	DATE START	END	NUMBER OF OBSERVATIONS
180	90	1/79	12/83	24521
-90	90	"	"	24527
0	90	"	"	24438
90	90	"	"	24461
0	51.4	11/80	"	15182

CABAUW.1*

SLOPE AZIMUTH	ANGLE	DATE START	END	NUMBER OF OBSERVATIONS
180	90	1/81	12/81	4564
-90	90	"	"	4490
0	90	"	"	4549
90	90	"	"	4541
-90	45	"	"	4605
-45	45	"	"	4599
0	45	"	"	4613
45	45	"	"	4615
90	45	"	"	4596
0	67.5	"	"	4587

CABAUW.2*

SLOPE AZIMUTH	ANGLE	DATE START	END	NUMBER OF OBSERVATIONS
180	90	1/80	12/80	4490
-90	90	"	"	4415
0	90	"	"	4470
90	90	"	"	4457
-90	45	"	"	4500
-45	45	"	"	4505
0	45	"	"	4517
45	45	"	"	4518
90	45	"	"	4492
0	67.5	"	"	4508

* Additional (i.e. 11th) slope not included due to validation programme to 10 slopes.
The Cabauw.1 data set may include some data from 1979 or 1980.
The Cabauw.2 data set may include some data from 1979 or 1981.

Table 5b (Cont.)

CARPENTRAS

SLOPE AZIMUTH	ANGLE	DATE START	END	NUMBER OF OBSERVATIONS
0	45	1/79	12/80	7112
180	90	"	"	7015
-90	90	"	"	7013
0	90	"	"	7088
90	90	"	"	7024

GOLDEN

SLOPE AZIMUTH	ANGLE	DATE START	END	NUMBER OF OBSERVATIONS
0	40	1/82	12/82	3974
0	90	"	"	3921

GENEVA

SLOPE AZIMUTH	ANGLE	DATE START	END	NUMBER OF OBSERVATIONS
0	90	7/79	6/82	12479
90	90	"	"	12306
180	90	"	"	12410
-90	90	"	"	12344
0	45	"	"	12483

GRIFFITH

SLOPE AZIMUTH	ANGLE	DATE START	END	NUMBER OF OBSERVATIONS
180	34	3/79	12/81	8115

HAMBURG

SLOPE AZIMUTH	ANGLE	DATE START	END	NUMBER OF OBSERVATIONS
0	30	1/80	12/83	16031
0	53.6	"	"	16091
0	90	"	"	15244

HIGHETT

SLOPE AZIMUTH	ANGLE	DATE START	END	NUMBER OF OBSERVATIONS
180	38	1/79	12/81	9190

Table 5b (Cont.)

ISPRA

SLOPE AZIMUTH	SLOPE ANGLE	DATE START	DATE END	NUMBER OF OBSERVATIONS
0	45	1/80	12/82	11939
0	60	1/79	12/82	16197
0	90	1/81	12/82	8127

LERWICK

SLOPE AZIMUTH	SLOPE ANGLE	DATE START	DATE END	NUMBER OF OBSERVATIONS
180	90	1/81	12/83	12670
-90	90	"	"	12677
0	90	"	"	12603
90	90	"	"	12644
0	60.1	"	"	12901

LULEA

SLOPE AZIMUTH	SLOPE ANGLE	DATE START	DATE END	NUMBER OF OBSERVATIONS
0	90	7/83	12/84	6355
0	60	"	"	6458
0	30	"	"	6548

LOCARNO

SLOPE AZIMUTH	SLOPE ANGLE	DATE START	DATE END	NUMBER OF OBSERVATIONS
180	90	4/61	11/71	38524
0	90	"	"	38385
-90	90	"	"	38709
90	90	"	"	38546

LOS ALAMOS

SLOPE AZIMUTH	SLOPE ANGLE	DATE START	DATE END	NUMBER OF OBSERVATIONS
-14	45	1/82	12/83	7628
0	90	"	"	7659

NORRKOPING

SLOPE AZIMUTH	SLOPE ANGLE	DATE START	DATE END	NUMBER OF OBSERVATIONS
0	60	7/78	6/79	3650

Table 5b (Cont.)

ODEILLO

SLOPE AZIMUTH	SLOPE ANGLE	DATE START	DATE END	NUMBER OF OBSERVATIONS
0	90	4/71	6/75	16117

SAN ANTONIO

SLOPE AZIMUTH	SLOPE ANGLE	DATE START	DATE END	NUMBER OF OBSERVATIONS
0	20	1/80	3/82	8372
0	30	"	"	8124
0	40	"	"	7912
180	90	"	"	7889
-90	90	"	"	8243
0	90	"	"	8366
90	90	"	"	8433

TORONTO

SLOPE AZIMUTH	SLOPE ANGLE	DATE START	DATE END	NUMBER OF OBSERVATIONS
0	30	11/76	12/83	25682
0	60	"	"	25250
0	90	"	"	25635
-90	90	7/79	"	19212
90	90	"	"	19187
180	90	"	"	19399
-45	90	4/80	"	16355
45	90	"	"	16392

TOWNSVILLE

SLOPE AZIMUTH	SLOPE ANGLE	DATE START	DATE END	NUMBER OF OBSERVATIONS
180	19	3/79	12/81	8994

TRAPPES

SLOPE AZIMUTH	SLOPE ANGLE	DATE START	DATE END	NUMBER OF OBSERVATIONS
0	45	4/79	12/80	5612
180	90	"	"	5472
-90	90	"	"	5249
0	90	"	"	5544
90	90	"	"	5249

Table 5b (Cont.)

VAERLOSE

AZIMUTH	SLOPE ANGLE	DATE START	DATE END	NUMBER OF OBSERVATIONS
180	90	12/77	11/78	3745
0	90	"	"	3770
-90	90	"	"	3771
90	90	"	"	3753

VALENTIA

AZIMUTH	SLOPE ANGLE	DATE START	DATE END	NUMBER OF OBSERVATIONS
0	90	3/76	2/78	8643

VANCOUVER

AZIMUTH	SLOPE ANGLE	DATE START	DATE END	NUMBER OF OBSERVATIONS
0	30	1/77	12/83	31893
0	60	"	"	31677
0	90	"	"	31666
-90	90	2/80	"	18477
90	90	9/79	"	19599
180	90	12/77	"	26462
180	60	9/79	"	18564

6. MODEL VALIDATION PROCEDURES

Three statistics will be used in the validation of the various models. The first is the mean bias difference (MBD) which assesses the long-term (i.e. systematic) performance of a model. The second, the mean absolute difference (MAD), will be used to depict the presence of seasonal biases while the root mean square (RMSD) is used to describe the short-term ("instantaneous") performance. Assistance with the interpretation of these error statistics may be obtained by reference to Won (1981), Willmott (1981, 1982) and Willmott et al. (1985).

In many studies the validation statistics are referred to as "errors" rather than "differences", the term we have used in the present study. The terms are not used to distinguish between different validation statistics for the formulae are the same in both cases. Rather "difference" is used to reflect the fact that the measured data used in the calculations and against which the model estimates are compared are themselves subject to error. These errors are typically between 5 and 10% for individual hourly values, but they typically reduce to around 2% for long-term averages (Hay and Wardle, 1982). Since the validation statistics are based on the differences between measured and calculated values, both of which contain errors, it is incorrect to attribute all the discrepancy to inadequacies in the model. The designation "difference" is used to emphasize the fact both the input and validation data are subject to measurement errors.

Most of the validation statistics are quoted in energy units. The large geographical, angular and seasonal variations in solar irradiance make it difficult to interpret relative values which typically becomes very large for high latitude locations, poleward-facing slopes and in the winter months. For these situations the actual irradiances are relatively small resulting in large relative differences, even if the absolute value of the modelling "error" is comparatively small. If required, relative differences can be derived from the tabulations of the validation statistics since the mean observed irradiances have been listed in Table 6.

TABLE 6

Mean observed irradiances (hourly data in MJ m^{-2} h^{-1}; daily data in MJ m^{-2} h^{-1}).

ALBANY

SLOPE/ AZIM	HOURLY GLOBAL	DAILY DIRECT	DAILY DIFFUSE	DAILY GLOBAL
33S	1.115	8.367	5.649	14.203
43S	1.102	8.317	5.372	14.012
53S	1.053	8.051	4.773	13.308
90N	0.199	0.217	1.121	2.542
90E	0.505	3.281	1.959	6.489
90S	0.667	5.175	2.121	8.516
90W	0.499	3.230	1.887	6.365

BRACKNELL.1

SLOPE/ AZIM	HOURLY GLOBAL	DAILY DIRECT	DAILY DIFFUSE	DAILY GLOBAL
90N	0.220	0.122		
90E	0.454	1.819		
90S	0.592	2.923		
90W	0.438	1.625		

BRACKNELL.2

SLOPE/ AZIM	HOURLY GLOBAL	DAILY DIRECT	DAILY DIFFUSE	DAILY GLOBAL
90N	0.180	0.128	1.345	2.420
90E	0.359	1.833	2.051	4.832
90S	0.488	3.146	2.454	6.553
90W	0.343	1.674	1.972	4.594
51.4S	0.733	4.328	5.259	9.943

VANCOUVER

SLOPE/ AZIM	HOURLY GLOBAL	DAILY DIRECT	DAILY DIFFUSE	DAILY GLOBAL
30S	1.120	8.235	5.949	14.394
60S	1.050	7.736	5.032	13.433
90S	0.786	5.267	3.492	10.070
90E	0.496	2.709	2.555	6.585
90W	0.584	3.376	2.953	7.588
90N	0.279	0.200	1.991	3.490
60N	0.342	0.651	2.967	4.247

VAERLOSE

SLOPE/ AZIM	HOURLY GLOBAL	DAILY DIRECT	DAILY DIFFUSE	DAILY GLOBAL
90N	0.183	0.202		
90S	0.613	3.931		
90E	0.455	2.565		
90W	0.445	2.573		

Table 6 (Cont.)

SAN ANTONIO

SLOPE/ AZIM	HOURLY GLOBAL	DAILY DIRECT	DAILY DIFFUSE	DAILY GLOBAL
20S	1.394	11.817	6.315	18.225
30S	1.389	12.156	6.201	18.598
40S	1.363	11.837	5.782	18.010
90N	0.260	0.188	1.266	2.973
90E	0.588	3.990	2.114	7.704
90S	0.769	6.015	2.480	10.185
90W	0.677	4.737	2.261	8.634

NORRKOPING

SLOPE/ AZIM	HOURLY GLOBAL	DAILY DIRECT	DAILY DIFFUSE	DAILY GLOBAL
60S	0.792	5.936	5.871	10.509

LERWICK

SLOPE/ AZIM	HOURLY GLOBAL	DAILY DIRECT	DAILY DIFFUSE	DAILY GLOBAL
90N	0.148	0.106	1.029	1.815
90E	0.282	1.080	1.749	3.526
90S	0.414	2.148	2.430	5.304
90W	0.285	1.139	1.702	3.551
60.1S	0.566	2.861	4.098	7.361

GOLDEN

SLOPE/ AZIM	HOURLY GLOBAL	DAILY DIRECT	DAILY DIFFUSE	DAILY GLOBAL
40S	1.274	12.957	5.332	18.671
90S	0.876	7.689	3.400	12.693

CABAUW.1

SLOPE/ AZIM	HOURLY GLOBAL	DAILY DIRECT	DAILY DIFFUSE	DAILY GLOBAL
90N	0.281	0.096	2.391	3.528
90E	0.468	1.700	3.046	5.787
90S	0.606	2.938	3.608	7.587
90W	0.461	1.493	3.227	5.761
45E	0.634	2.741	4.993	8.038
45SE	0.776	3.856	5.668	9.829
45S	0.816	4.235	5.824	10.364
45SW	0.768	3.675	5.767	9.747
45W	0.626	2.500	5.116	7.921
67.5S	0.746	3.869	4.906	9.417

CABAUW.2

SLOPE/ AZIM	HOURLY GLOBAL	DAILY DIRECT	DAILY DIFFUSE	DAILY GLOBAL
90N	0.288	0.118	2.295	3.470
90E	0.473	1.679	2.925	5.636
90S	0.626	3.133	3.447	7.612
90W	0.495	1.815	3.109	5.999
45E	0.653	2.818	4.870	7.957
45SE	0.805	3.988	5.574	9.821
45S	0.860	4.603	5.641	10.514
45SW	0.821	4.142	5.588	10.017
45W	0.676	2.970	4.991	8.268
67.5S	0.778	4.164	4.738	9.522

ATLANTA

SLOPE/ AZIM	HOURLY GLOBAL	DAILY DIRECT	DAILY DIFFUSE	DAILY GLOBAL
34S	1.318	11.005	6.019	

TORONTO

SLOPE/ AZIM	HOURLY GLOBAL	DAILY DIRECT	DAILY DIFFUSE	DAILY GLOBAL
30S	1.095	7.814	5.735	13.880
90N	0.358	0.206	2.646	4.602
90E	0.631	3.197	3.077	8.108
90S	0.815	4.994	3.604	10.470
60S	1.123	7.335	5.888	14.238
90W	0.637	2.952	3.370	8.113
90SE	0.786	4.504	3.716	10.134
90SW	0.768	0.459	3.656	9.883

VALENTIA

SLOPE/ AZIM	HOURLY GLOBAL	DAILY DIRECT	DAILY DIFFUSE	DAILY GLOBAL
90S	0.601	2.879		

BERGEN

SLOPE/ AZIM	HOURLY GLOBAL	DAILY DIRECT	DAILY DIFFUSE	DAILY GLOBAL
45S	0.774	5.103		
90S	0.577	3.655		
90W	0.407	2.079		
90E	0.393	1.900		
90N	0.191	0.159		

GENEVA

SLOPE/ AZIM	HOURLY GLOBAL	DAILY DIRECT	DAILY DIFFUSE	DAILY GLOBAL
90S	0.728	4.913		
90W	0.569	3.049		
90N	0.290	0.186		
90E	0.548	2.685		
45S	0.191	0.159		

GRIFFITH

SLOPE/ AZIM	HOURLY GLOBAL	DAILY DIRECT	DAILY DIFFUSE	DAILY GLOBAL
34N	1.569	16.251		

HAMBURG

SLOPE/ AZIM	HOURLY GLOBAL	DAILY DIRECT	DAILY DIFFUSE	DAILY GLOBAL
30S	0.873	5.040		
53.6S	0.835	5.039		
90S	0.569	3.483		

HIGHETT

SLOPE/ AZIM	HOURLY GLOBAL	DAILY DIRECT	DAILY DIFFUSE	DAILY GLOBAL
38N	1.322	10.573		

TOWNSVILLE

SLOPE/ AZIM	HOURLY GLOBAL	DAILY DIRECT	DAILY DIFFUSE	DAILY GLOBAL
19N	1.615	14.318		

LULEA

SLOPE/ AZIM	HOURLY GLOBAL	DAILY DIRECT	DAILY DIFFUSE	DAILY GLOBAL
90S	0.531	3.683	1.998	6.314
60S	0.683	4.528	3.151	8.009
30S	0.691	4.211	3.666	7.990

ISPRA

SLOPE/ AZIM	HOURLY GLOBAL	DAILY DIRECT	DAILY DIFFUSE	DAILY GLOBAL
45S	1.244	8.572		
60S	1.150	8.104		
90S	0.859	5.546		

LOCARNO

SLOPE/ AZIM	HOURLY GLOBAL	DAILY DIRECT	DAILY DIFFUSE	DAILY GLOBAL
90E	0.680	5.394		
90S	1.055	6.720		
90W	0.659	3.597		
90N	0.262	0.191		

LOS ALAMOS

SLOPE/ AZIM	HOURLY GLOBAL	DAILY DIRECT	DAILY DIFFUSE	DAILY GLOBAL
45ESE	1.551	11.920		
90S	1.048	6.928		

ODEILLO

SLOPE/ AZIM	HOURLY GLOBAL	DAILY DIRECT	DAILY DIFFUSE	DAILY GLOBAL
90S	1.215	7.887		

TRAPPES

SLOPE/ AZIM	HOURLY GLOBAL	DAILY DIRECT	DAILY DIFFUSE	DAILY GLOBAL
45S	0.916	5.430	6.621	12.384
90N	0.219	0.200	1.327	2.724
90E	0.481	2.889	2.783	6.900
90S	0.567	3.378	3.074	7.597
90W	0.431	2.513	2.341	6.099

CARPENTRAS

SLOPE/ AZIM	HOURLY GLOBAL	DAILY DIRECT	DAILY DIFFUSE	DAILY GLOBAL
45S	1.396	12.090	6.099	18.661
90N	0.205	0.333	0.744	2.593
90E	0.619	4.802	1.983	8.405
90S	0.862	7.218	2.626	11.449
90W	0.645	4.835	2.050	8.506

The computer programmes which perform the data manipulation and generate the validation statistics have been assembled into a package called Slope Irradiance Model Analysis Package (SIMAP) and the User's Guide and Reference Manual may be found in Volume 2, Appendices A and B, respectively. The computer code and most of the original (but quality controlled) data sets (and their longer-term derivatives) are available on magnetic tape.

Due to the large number of models and data sets some means had to be found to summarize the validation results. Two methods have been used. Both involve the ranking of the validation statistics. "Rank.1" gives the ranks of the average validation statistics for all slopes at a given location or group of locations while "Rank.2" represents a ranking of the sum of the rankings of the validation statistics for the individual slopes at the same location or locations. In most cases the two methods of ranking the data produce the same or similar results, but in some situations (such as where models have similar performance on some slopes but not on others) the two rankings will diverge. Where this happens additional caution must be exercised when interpreting the results.

Since different applications will place varying emphasis on the validation results for certain slope orientations, the statistics for the various data set categories are not only presented for all slopes combined, but also for groupings of equator-facing slopes (equatorward of east and west) and those of other orientation.

7. VALIDATION OF THE HOURLY DIFFUSE IRRADIANCE MODELS

7.1 Introduction

For the hourly time scale the various models are evaluated with respect to the global solar irradiance for each inclined surface. Thus the diffuse irradiance from the sky is calculated using the named model, while the other components (the direct irradiance and, where applicable, the reflected irradiance) are calculated in identical fashion for all models: the direct component is based on the "exact" equations valid at a given instant in time and in this case the mid point of the hour is used; where the sensor for a given slope has not been equipped with an artificial horizon the component resulting from reflection by adjacent surfaces is determined using the isotropic assumption (see Section 3.5). The validation statistics quoted in energy units provide the errors associated with the calculation of both the diffuse component alone and the total solar irradiance, but when these errors are expressed as relative values they are being assessed in relation to the observed total solar irradiance for the given slope. Where the data for a given slope have been obtained using an artificial horizon the latter errors will typically be higher since they are expressed relative to a smaller quantity. This is despite the fact that the absolute error may well be smaller due to the exclusion of errors associated with modelling the reflected component.

7.2 Procedures

Given that this validation exercise involves 21 models and 27 data sets a method which would reduce both the computational and analytical burdens had to be devised. A decision was made to perform a comprehensive validation of all 21 models using a manageable number of data sets and to consider only those data sets where the direct radiation had been measured and either the slope irradiance sensors had been equipped with artificial horizons or the surface albedo had been measured. As noted in Table 5a twelve data sets meet these requirements.

The MAD and RMSD statistics were generated and subsequently ranked according to the procedures described in Section 6. Thus rankings of model performance are available not only for all slopes at individual locations but in addition the statistics are grouped and ranked by data set category. A distinction is also made between equator-facing and other slope orientations. However, the effects of variations in climatic conditions and data quality between the twelve stations are treated implicity rather than explicitly.

Since the preceding analysis has limited power to distinguish between models it was used to isolate the top four models which were then validated using data from both the 12 original and the 15 remaining sites. Both analyses provided sufficient evidence to support the choice of a single model which was subsequently subjected to a more comprehensive validation.

7.3 Results

7.3.1 Model Selection

On the basis of the preliminary validation of all the hourly diffuse models using the 12 category A and B data sets, a decision was made to eliminate all but four models (Gueymard, Hay and the two variations of Perez) from further evaluation. The remaining models had only the occasional high ranking for an individual slope and were therefore consistently out-performed by the four models retained for further assessment.

Validation statistics for the total period of observation for all 27 locations and the four top-ranked models are listed in Table 7a. These data were used to rank the four models in terms of their systematic and short-term performances and these results are also to be found in Table 7a.

For completeness Table 7b shows the ranking of all the models for all slopes at ten selected locations.

Table 7(a). Validation statistics and rankings of four selected hourly diffuse irradiance models. Results based on hourly global irradiances (Units: kJ m^{-2} h^{-1}).

ALBANY

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
33S	37	56	38	58	26	40	26	41
43S	45	69	48	72	29	47	30	47
53S	41	69	49	73	35	53	36	54
90N	33	50	55	77	27	38	23	33
90E	49	77	65	92	33	49	33	49
90S	39	63	50	72	44	67	44	67
90W	52	84	66	95	40	59	39	58
All	42	68	53	78	33	51	33	51
Rank.1	3	3	4	4	2	2	1	1
Rank.2	3	3	4	4	1=	1=	1=	1=

BRACKNELL.2

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
90N	27	45	47	69	32	45	28	40
90E	43	74	60	95	47	74	47	74
90S	34	61	42	65	50	77	52	79
90W	39	67	55	93	54	87	54	88
51.4S	43	71	41	65	40	65	42	68
All	37	64	49	79	45	71	45	72
Rank.1	1	1	4	4	2=	2	2=	3
Ramk.2	1	1=	4	4	2	1=	3	3

LERWICK

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
90N	29	56	49	81	35	56	31	53
90E	44	90	55	100	41	74	40	73
90S	57	117	55	106	39	96	38	76
90W	41	88	51	93	41	74	41	75
60.1S	65	127	58	114	38	79	37	77
All	47	99	54	99	39	77	37	71
Rank.1	3	3	4	4	2	2	1	1
Rank.2	3	3	4	4	2	2	1	1

LULEA

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
90S	44	78	48	80	32	50	30	48
60S	43	78	43	75	31	50	30	48
30S	27	49	26	47	21	34	20	34
All	38	70	39	69	28	45	27	44
Rank.1	3	4	4	3	2	2	1	1
Rank.2	3=	4	3=	3	2	2	1	1

NORRKOPING

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
60S	47	79	51	82	35	57	34	55
Rank.1	3	3	4	4	2	2	1	1
Rank.2	3	3	4	4	2	2	1	1

SAN ANTONIO

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
20S	27	42	27	40	22	32	22	33
30S	35	53	37	54	25	37	26	39
40S	45	68	49	70	34	48	36	52
90N	51	72	88	120	49	69	53	74
90E	78	113	100	138	62	90	65	94
90S	75	106	99	136	64	87	68	93
90W	75	113	103	146	65	97	67	100
All	55	85	72	109	46	70	48	74
Rank.1	3	3	4	4	1	1	2	2
Rank.2	3	3	4	4	1	1	2	2

CATEGORY A

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
All	45	79	56	90	39	65	39	64
Rank.1	3	3	4	4	1	2	2	1
Rank.2	3	3	4	4	1	1	2	2
Equatorward	44	78	48	79	35	60	36	59
Rank.1	3	3	4	4	1	2	2	1
Rank.2	3	3	4	4	1	1	2	2
Poleward	47	80	66	102	44	70	43	71
Rank.1	3	3	4	4	2	1	1	2
Rank.2	3	3	4	4	2	1	1	2

CABAUW.1

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
90N	28	46	46	69	26	38	24	35
90E	46	83	62	93	38	59	37	57
90S	48	84	53	84	36	56	35	55
90W	54	101	64	105	37	63	36	62
45E	51	88	54	87	35	58	33	54
45SE	60	104	60	101	37	67	36	64
45S	56	95	53	90	35	59	35	58
45SW	62	102	60	98	35	58	34	56
45W	53	94	55	91	33	55	31	52
67.5S	58	101	57	95	39	63	39	62
All	52	91	56	92	35	58	34	56
Rank.1	3	3	4	4	2	2	1	1
Rank.2	3	4	4	3	2	2	1	1

CARPENTRAS

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
45S	66	94	69	95	34	49	31	45
90N	37	56	63	82	39	50	32	41
90E	48	69	74	96	39	53	37	50
90S	54	81	77	102	37	55	34	52
90W	52	73	74	96	37	53	35	50
All	51	76	71	94	37	52	34	48
Rank.1	3	3	4	4	2	2	1	1
Rank.2	3	3	4	4	2	2	1	1

GOLDEN

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
40S	48	73	47	73	55	86	56	86
90S	43	71	49	75	50	72	48	72
All	46	72	48	74	53	79	52	79
Rank.1	1	1	2	2	4	3=	3	3=
Rank.2	1	1	2	2=	4	2=	3	2=

TORONTO

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
30S	37	57	39	58	53	77	55	80
60S	89	136	88	133	61	91	62	92
90S	45	76	54	79	51	73	51	75
90N	37	57	66	91	34	48	33	48
90E	51	80	63	90	47	69	45	68
90W	50	84	67	98	39	64	38	63
90SE	54	87	67	94	44	63	45	64
90SW	47	75	59	84	48	70	49	70
All	51	85	63	93	47	70	47	71
Rank.1	3	3	4	4	1	1	2	2
Rank.2	3	3	4	4	1	1	2	2

TRAPPES

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
45S	65	96	57	87	35	56	33	53
90N	40	67	60	88	40	57	34	50
90E	60	98	72	106	39	59	38	57
90S	53	89	61	92	40	59	39	58
90W	49	78	62	87	42	61	40	58
All	53	86	62	92	39	58	37	55
Rank.1	3	3	4	4	2	2	1	1
Rank.2	3	3	4	4	2	2	1	1

VANCOUVER

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
30S	39	67	35	60	30	52	30	51
60S	39	67	48	78	49	79	49	78
90S	48	84	48	78	50	78	48	76
90E	54	83	55	84	69	91	65	85
90W	41	69	51	76	40	58	36	53
90N	45	77	65	97	54	77	47	68
60N	63	103	65	102	56	76	49	67
All	47	79	52	83	50	74	46	69
Rank.1	2	3	4	4	3	2	1	1
Rank.2	2	3	4	4	3	2	1	1

CATEGORY B

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
All	51	84	59	90	42	65	41	63
Rank.1	3	3	4	4	2	2	1	1
Rank.2	3	3	4	4	2	2	1	1
Equatorward	53	88	57	89	43	67	43	67
Rank.1	3	3	4	4	2	2	1	1
Rank.2	3	3	4	4	2	2	1	1
Poleward	48	80	62	91	41	62	38	58
Rank.1	3	3	4	4	2	2	1	1
Rank.2	3	3	4	4	2	2	1	1

ATLANTA

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
34S	33	48	31	45	33	48	36	51
Rank.1	2=	2=	1	1	2=	2=	4	4
Rank.2	2=	2=	1	1	2=	2=	4	4

BERGEN

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
45S	41	61	44	64	61	86	64	89
90S	58	99	69	105	91	136	94	138
90W	62	89	70	95	79	104	76	101
90E	67	87	82	104	89	111	87	109
90N	46	69	60	85	59	78	54	71
All	55	82	65	92	76	105	75	104
Rank.1	1	1	2	2	4	4	3	3
Rank.2	1	1	2	2	4	4	3	3

LOS ALAMOS

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
45ESE	145	289	139	279	141	272	141	274
90S	136	285	123	265	127	247	126	249
All	141	287	131	272	134	260	134	262
Rank.1	4	4	1	3	3	1	2	2
Rank.2	4	4	1	3	3	1	2	2

CATEGORY C

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
All	74	158	77	155	85	155	85	156
Rank.1	1	4	2	1	4	2	3	3
Rank.1	1=	1	1=	2	3=	3	3=	4
Equatorward	67	156	67	148	78	149	80	151
Rank.1	2	4	1	1	3	2	4	3
Rank.2	2	1=	1	1=	3	3	4	4
Poleward	80	161	88	162	92	161	90	160
Rank.1	1	3	2	4	4	2	3	1
Rank.2	1	1	2	3	4	4	3	2

BRACKNELL.1

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
90N	38	62	60	86	44	61	38	55
90E	59	110	73	121	60	103	58	102
90S	51	88	58	90	66	100	68	101
90W	59	108	74	118	59	101	58	99
All	52	94	66	105	57	93	56	91
Rank.1	1	3	4	4	3	2	2	1
Rank.2	1	3	4	4	3	2	2	1

GRIFFITH

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
34N	110	148	110	147	128	165	125	162
Rank.1	1=	2	1=	1	4	4	3	3
Rank.2	1=	2	1=	1	4	4	3	3

HAMBURG

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
30S	36	58	37	59	30	47	31	48
53.6S	51	83	56	88	43	66	44	66
90S	52	100	68	116	63	102	63	101
All	46	82	54	91	45	75	46	75
Rank.1	3	3	4	4	1	2	2	1
Rank.2	3	3	4	4	1	1=	2	1=

HIGHETT

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
38N	81	120	82	123	79	116	81	118
Rank.1	2=	3	4	4	1	1	2=	2
Rank.2	2=	3	4	4	1	1	2=	2

TOWNSVILLE

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
19N	41	66	43	68	39	65	40	65
Rank.1	3	3	4	4	1	1=	2	1=
Rank.2	3	3	4	4	1	1=	2	1=

VAERLOSE

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
90N	30	44	50	66	40	52	34	44
90S	45	63	53	76	48	73	48	72
90E	46	75	57	91	49	86	48	84
90W	40	65	59	82	53	75	50	72
All	40	63	55	79	48	73	45	70
Rank.1	1	1	4	4	3	3	2	2
Rank.2	1	1	4	4	3	3	2	2

CATEGORY D

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
All	53	89	63	98	57	92	56	90
Rank.1	1	1	4	4	3	3	2	2
Rank.2	1	2	4	4	3	3	2	1
Equatorward	58	95	63	100	62	98	63	98
Rank.1	1	1	4	4	2	3	3	2
Rank.2	1=	1=	4	4	1=	1=	3	1=
Poleward	45	81	62	96	51	82	48	79
Rank.1	1	2	4	4	3	3	2	1
Rank.2	1	2	4	4	3	3	2	1

CABAUW.2

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
90N	27	47	45	67	27	40	24	36
90E	47	82	64	95	42	64	42	63
90S	45	79	64	95	45	72	45	72
90W	49	85	61	95	40	64	40	63
45E	50	85	52	84	37	57	36	56
45SE	59	99	61	97	39	63	40	62
45S	52	88	52	86	37	60	38	60
45SW	57	92	57	91	38	59	37	58
45W	51	86	53	84	38	58	37	57
67.5S	54	92	58	93	44	71	45	72
All	49	85	57	89	39	61	38	61
Rank.1	3	3	4	4	2	2	1	1
Rank.2	3	3=	4	3=	2	2	1	1

GENEVA

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
90S	52	79	57	81	87	119	86	120
90W	70	101	69	100	96	129	92	125
90N	46	68	55	79	51	68	45	60
90E	68	101	70	99	93	132	89	129
45S	44	67	46	68	64	93	66	95
All	56	85	59	86	78	111	76	109
Rank.1	1	1	2	2	4	4	3	3
Rank.2	1	1	2	2	4	4	3	3

ISPRA

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
45S	104	166	109	171	124	185	125	185
60S	131	208	137	213	150	227	150	226
90S	67	112	69	112	98	146	97	145
All	101	167	105	170	124	189	124	188
Rank.1	1	1	2	2	3=	4	3=	3
Rank.2	1	1	2	2	3=	4	3=	3

LOCARNO

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
90E	92	136	103	150	112	161	109	158
90S	87	128	99	140	108	150	107	150
90W	104	153	112	163	130	187	127	184
90N	112	147	103	143	118	141	110	132
All	99	141	104	149	117	161	113	157
Rank.1	1	1	2	2	4	4	3	3
Rank.2	1	1	2	2	4	4	3	3

ODEILLO

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
90S	91	138	107	148	91	133	91	135
Rank.1	1=	3	4	4	1=	1	1=	2
Rank.2	1=	3	4	4	1=	1	1=	2

VALENTIA

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
90S	54	99	65	116	95	148	97	149
Rank.1	1	1	2	2	3	3	4	4
Rank.2	1	1	2	2	3	3	4	4

CATEGORY E

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
All	67	112	74	117	75	121	74	119
Rank.1	1	1	2	2	4	4	3	3
Rank.2	1	2	4	4	3	3	2	1
Equatorward	69	118	75	123	78	128	79	128
Rank.1	1	1	2	2	3	3	4	4
Rank.2	1	1	4	4	2	2	3	3
Poleward	65	104	72	110	71	111	68	108
Rank.1	1	1	4	3	3	4	2	2
Rank.2	2	2	4	4	3	3	1	1

ALL LOCATIONS

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
All	55	97	63	103	54	92	53	91
Rank.1	3	3	4	4	2	2	1	1
Rank.2	3	3	4	4	2	2	1	1
Equatorward	56	99	60	101	54	94	54	93
Rank.1	3	3	4	4	1	2	2	1
Rank.2	3	3	4	4	1	1	2	2
Poleward	53	94	67	106	53	89	51	87
Rank.1	3	3	4	4	2	2	1	1
Rank.2	2	3	4	4	3	2	1	1

Table 7b. Ranking of all hourly diffuse irradiance models for all slopes at ten selected locations.

MODEL	VANCOUVER		GOLDEN		ATLANTA		NORRKOPING		BRACKNELL		LERWICK		SAN ANTON		ALBANY		TORONTO		CABAUW		OVERALL	
	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD
ISOTROPIC	16	16	12	14	13	14	14	15	15	15	16	17	15	15	16	16	15	16	15	16	16	16
KLUCHER	12	10	8	8	7	7	3	3	12	9	12	9	5	5	7	7	11	9	8	7	8	8
HAY	5	5	1	2	1	2	6	6	5	5	5	4	8	6	4	4	5	4	6	4	4	4
HAY2	6	7	3	4	1	1	4	4	10	14	8	10	4	4	5	6	6	8	4	6	6	6
S & O	3	2	4	3	1	2	8	8	2	4	4	8	12	9	6	5	4	5	5	5	5	5
LOKMAN	14	14	12	11	14	13	10	7	14	9	10	7	7	8	11	10	14	10	12	10	12	9
EMGP2	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21
GUEYMARD	2	4	1	1	4	4	5	5	1	1	3	3	3	3	3	3	1	3	3	3	2	3
PURI	6	6	5	4	9	8	9	9	6	6	7	6	10	11	7	8	7	6	7	8	7	7
PEREZ1	4	3	7	4	4	4	2	2	3	2	2	2	1	1	1	1	2	1	2	2	3	1
PEREZ2	1	1	5	4	6	6	1	1	4	3	1	1	2	2	1	1	3	2	1	1	1	1
50/50 COMB	17	17	18	18	12	12	19	18	19	19	19	19	19	18	19	19	19	19	19	18	18	18
BUGLER1	13	13	11	12	9	9	11	11	11	12	13	13	6	7	9	9	9	12	11	12	10	11
BUGLER2	11	12	10	10	11	10	12	13	13	13	14	15	11	14	13	12	12	13	14	13	13	13
T&C	19	19	15	17	16	17	15	12	18	18	18	16	16	17	17	17	18	17	17	17	17	17
PAGE	8	8	15	15	17	16	17	17	7	8	8	10	17	16	12	12	13	14	13	14	14	14
C&Z	18	18	19	19	20	20	20	20	17	16	17	18	18	19	18	18	17	18	18	19	19	19
INEICHEN	9	9	9	9	7	10	13	15	9	9	11	12	13	13	14	12	10	11	10	11	11	12
OEGEHA	15	15	14	12	18	18	7	10	8	7	5	4	10	12	9	11	8	7	8	9	9	10
KUSUDA	20	20	19	20	19	19	18	19	20	20	20	20	20	20	20	20	20	20	20	20	20	20
DOE 2	10	11	17	16	15	15	16	14	16	16	15	13	9	10	15	15	16	15	16	15	15	15

It is immediately apparent that the Hay model does not perform as well as either the Gueymard or Perez models. Typically the Perez models have the lowest systematic and short-term errors. However, this conclusion is partly based on data from Albany and Carpentras, from which empirical coefficients for Perez1 and Perez2, respectively, were derived. Interestingly, at Albany, Perez2 exhibits a slight advantage over Perez1 despite the latter being based on Albany data. While the converse does not hold [the Carpentras based version (Perez2) has a marginally better performance at that location] Perez1 significantly out-performs both Gueymard and Hay. Thus it is clear that conclusions based on the summary analyses in Table 7 are not biased by the inclusion of dependent data sets.

At the category A and B locations the Perez model is clearly superior with no significant change in error given that, for category B stations, ground reflection is also included in the analysis. At category C stations there is a substantial deterioration in the apparent performance of all models with the Perez algorithms suffering more than the other two. This trend is repeated going from category D to E. In both cases the major change is the use of a constant albedo. Model performance is apparently less sensitive to the use of diffuse rather than direct irradiance data although the distinction between models is less obvious when diffuse data are used.

For category A, station rankings of the models do not change between the two groupings of slope orientation. However, absolute values of the differences between observed and calculated irradiances are higher for slopes facing away from the equator. Given the generally lower irradiances for such slopes relative values of the differences show an even greater increase. For the other categories the ranking of the models is similarly insensitive to slope orientation. However, the increases in the absolute differences are less apparent although in general, the relative differences will still be greater for the poleward-facing slopes.

The data in Table 7 support the following conclusions:

a) When all relevant variables are directly measured the Perez algorithms provide the most accurate estimates of the diffuse irradiance on an inclined surface.

b) Errors in modelling the sky irradiance increase for slopes facing away from south, but there is no change in the relative rankings of the models.

c) The relative rankings of the models and the size of the apparent modelling errors are strongly influenced by the completeness of the data used in the slope irradiance calculations. An assumed constant surface albedo leads to significant increases in the differences between observed and calculated irradiances. Less significant effects result from the use of diffuse as opposed to direct solar radiation, and from the need to include the effects of surface reflection through the use of measured surface albedo rather than exclude it due to the use of an artificial horizon.

7.3.2 Model Performance

Figure 2 presents a comparison between the hourly observed and estimated (using Perez2) solar irradiances for the four vertical surfaces facing north, south, east and west at three category A stations (Albany, Lerwick and San Antonio). The average and root mean square values of their differences are also shown as a function of: i) the observed solar irradiance for the slope, ii) the cosine of the solar zenith angle and iii) the clearness index (K/Kzo).

The most notable feature is the tendency to underestimate the solar irradiance for all 4 slopes at San Antonio, with this bias increasing with solar irradiance, the cosine of the zenith angle, and with the clearness index. This pattern is not a consistent feature at the other 2 locations. The persistence of this bias at San Antonio is confirmed in Figure 3. Monthly and total period values of the three validation statistics for the vertical south-facing slope shows that Perez2 consistently underestimated the solar irradiance throughout the year. Similar results were obtained for the other slopes at San Antonio.

Again the other two locations do not exhibit the same underestimates. Figure 4, for Albany, shows a typical pattern with a seasonal variation in the systematic error resulting in the statistics for the total period being unrepresentative of the corresponding value for a given month.

A more comprehensive analysis that encompasses the preceding results is presented in Figure 5. It is apparent that significant underestimates are limited to San Antonio and thus may be related to the tendency for the model bias to become more negative with increasing values of the clearness index. This relationship is particularly well developed for the north-facing surface. For all four surface orientations the relative value of the mean absolute difference decreases with increasing clearness index. This same relationship is also generally reflected in the root mean square differences.

7.3.3 Conclusions

The results of the validation study which used 27 data sets and commenced by evaluating 21 different models clearly lead to the recommendation that the Perez algorithm be used for hourly calculations of slope irradiance. Despite the use of empirical coefficients it has widespread applicability and maintains its superiority through a wide range of surface orientations and climatic conditions.

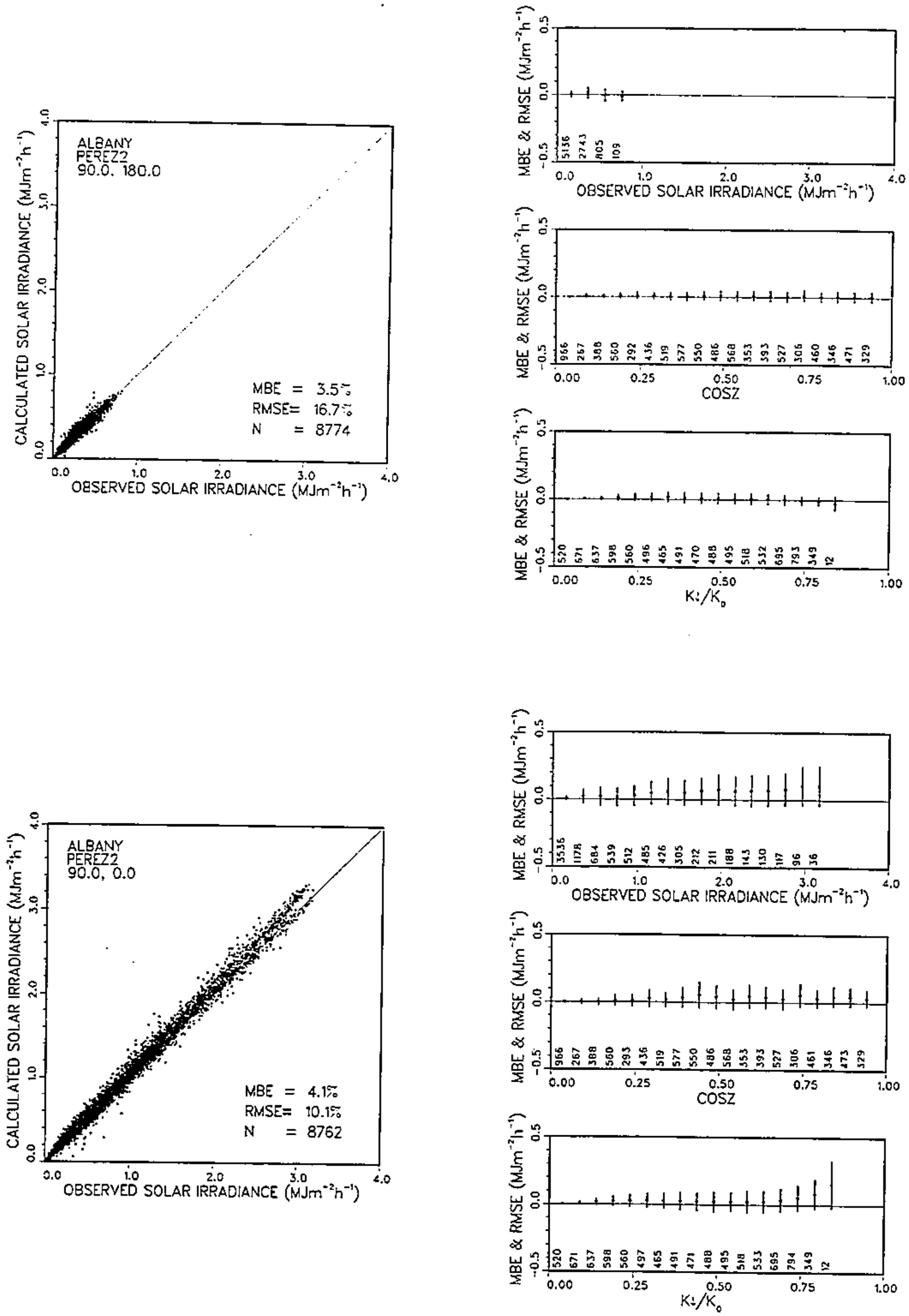


Figure 2a. Scatter diagrams of hourly estimated (using Perez 2) and observed solar irradiances for north (top) and south (bottom) facing vertical surfaces at Albany. Also shown are the average and root mean square values of the differences between the estimated and observed irradiances. These latter values are presented as a function of the solar irradiance for the slope, the cosine of the solar zenith angle and of the clearness index ($K{\downarrow}/K_0$).

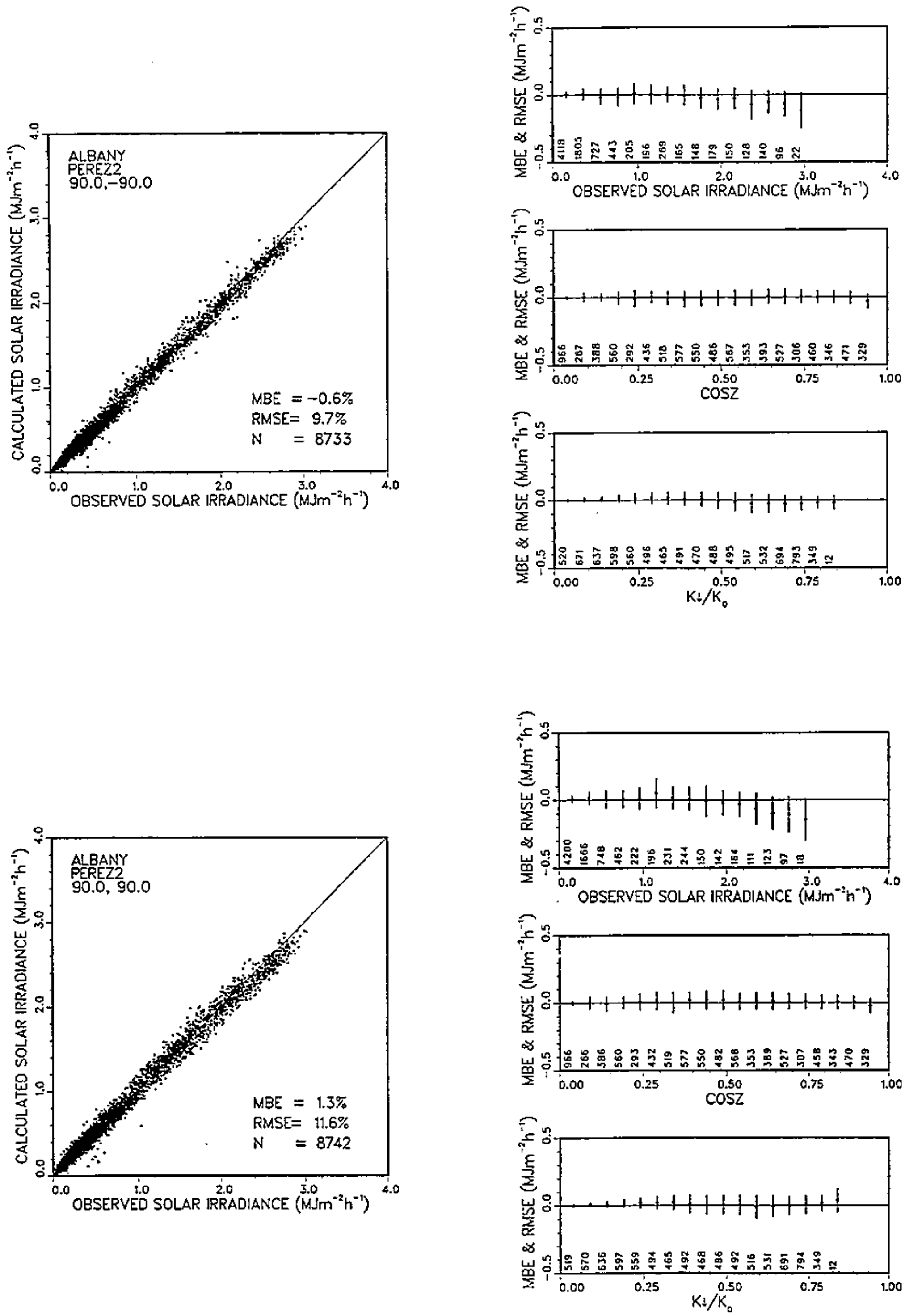


Figure 2b. As for Fig. 2a but for east (top) and west (bottom) facing vertical surfaces.

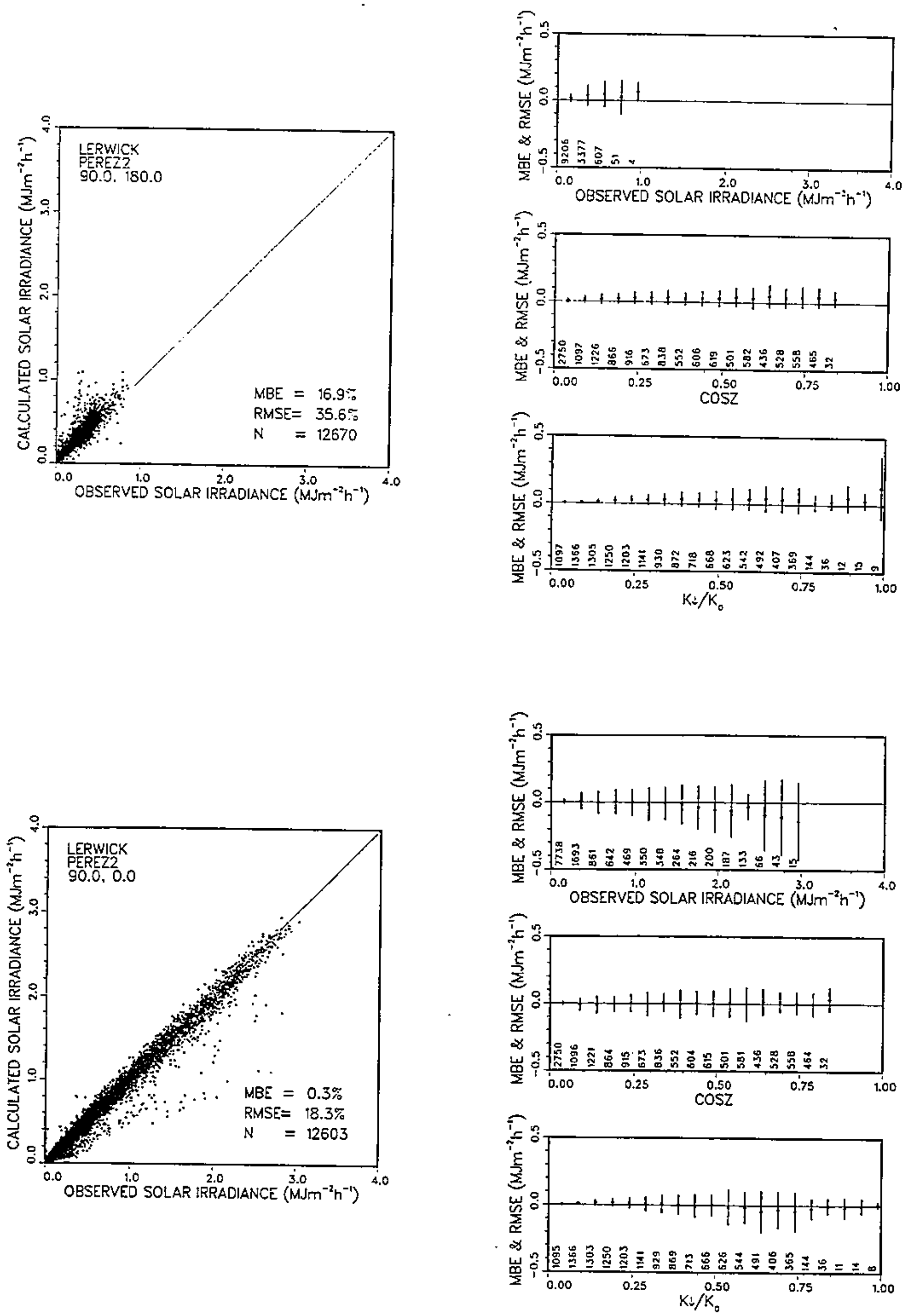


Figure 2c. As for Fig. 2a but for Lerwick.

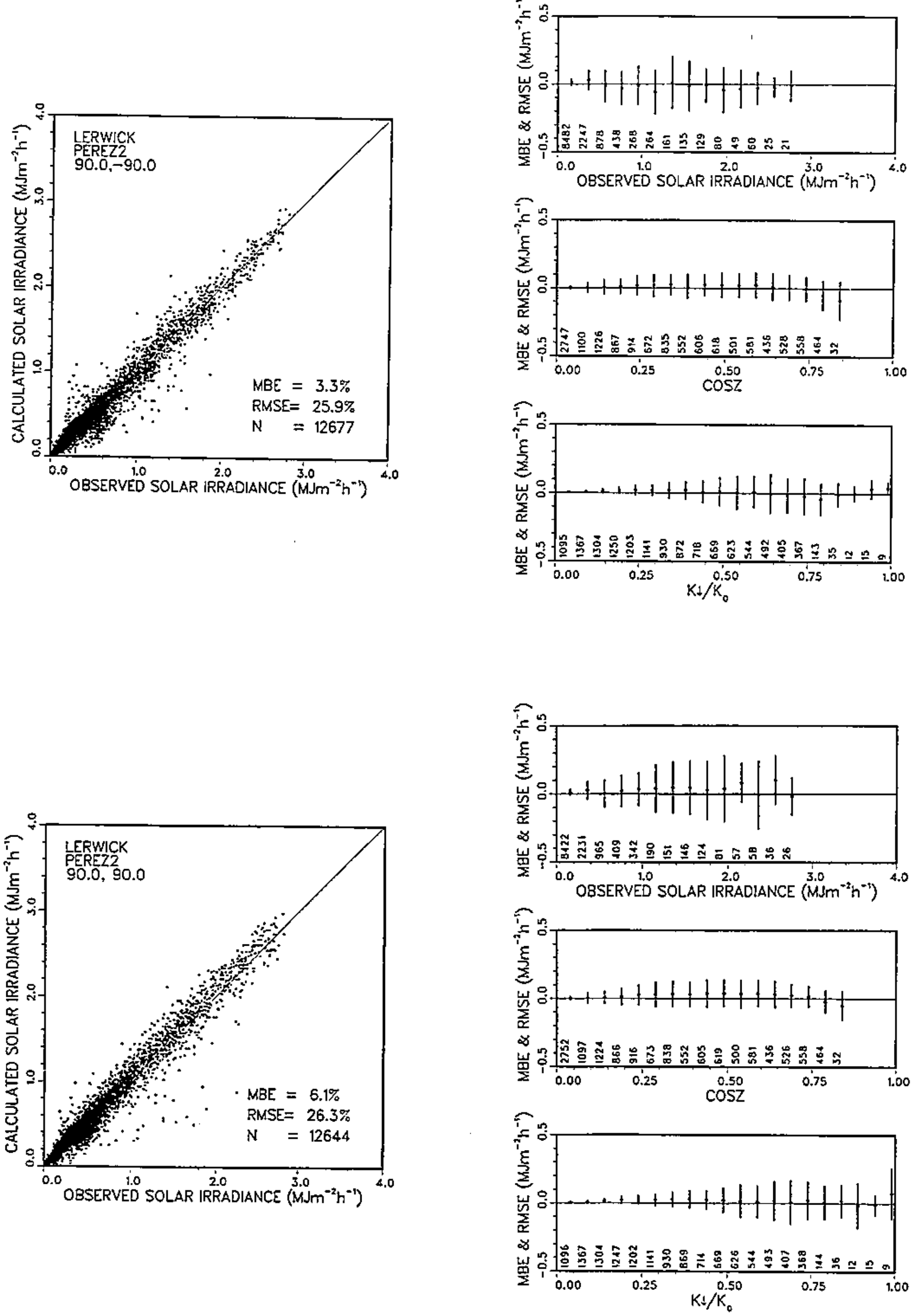


Figure 2d. As for Fig. 2b but for Lerwick.

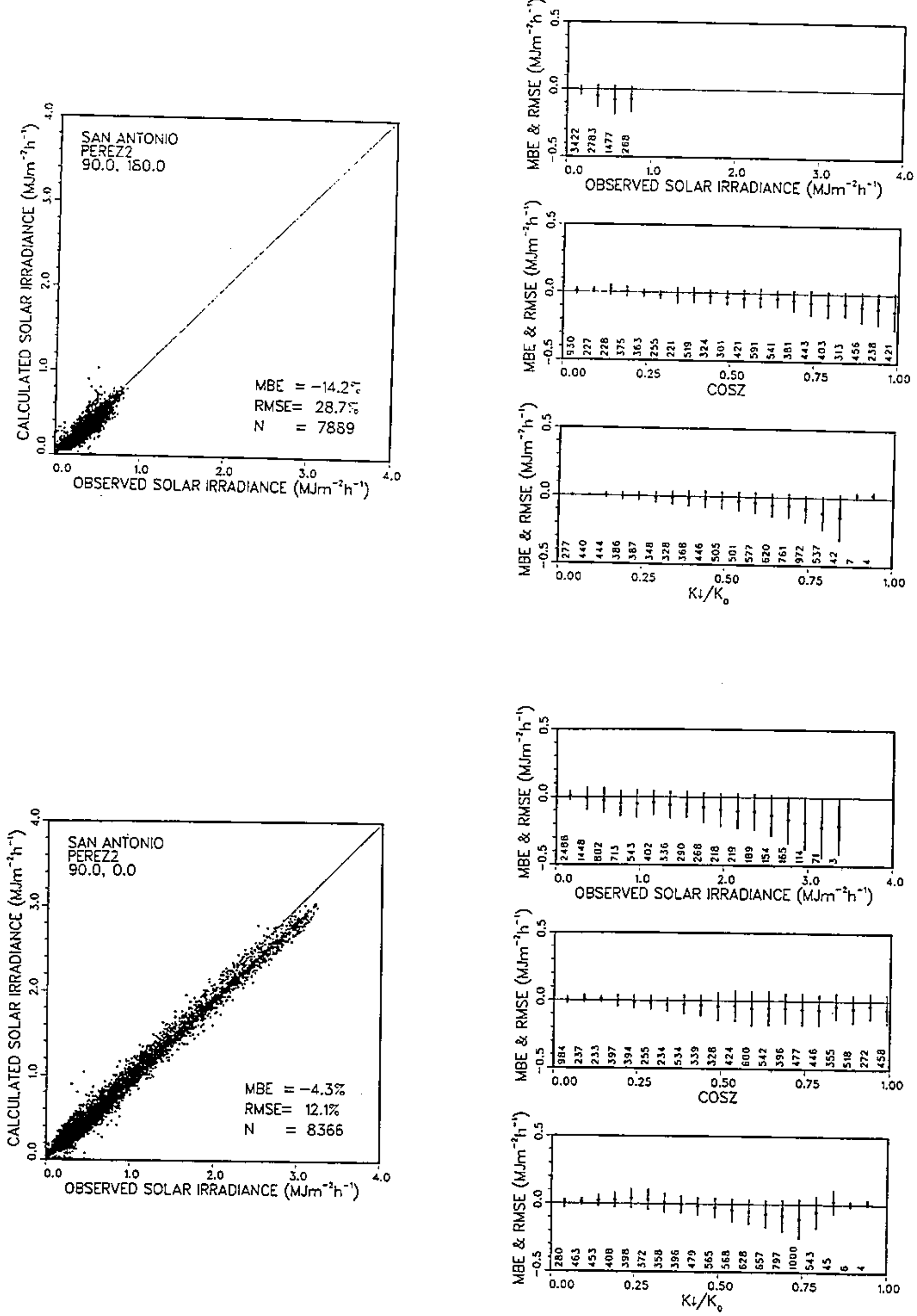


Figure 2e. As for Fig. 2a but for San Antonio.

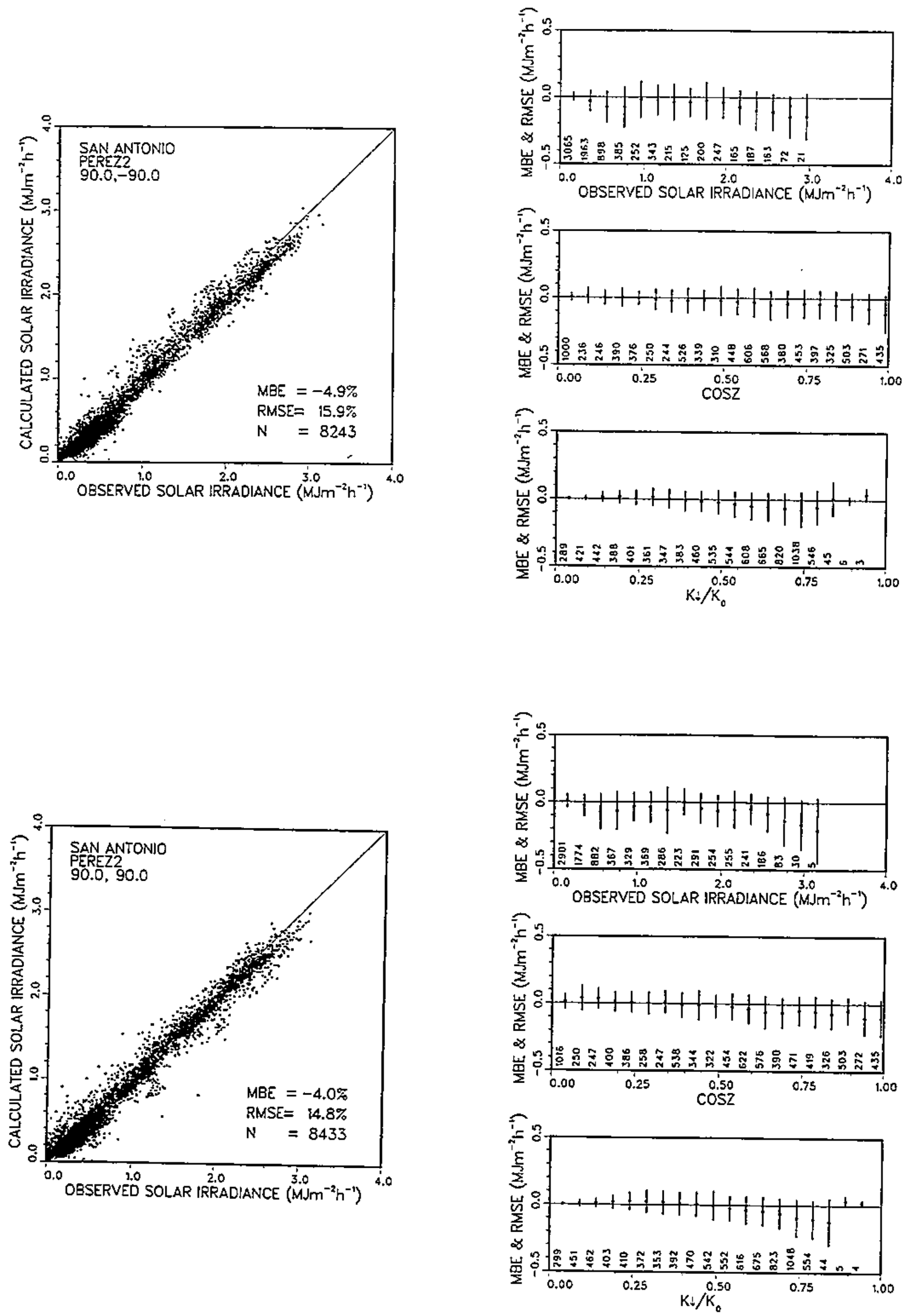


Figure 2f. As for Fig. 2b but for San Antonio.

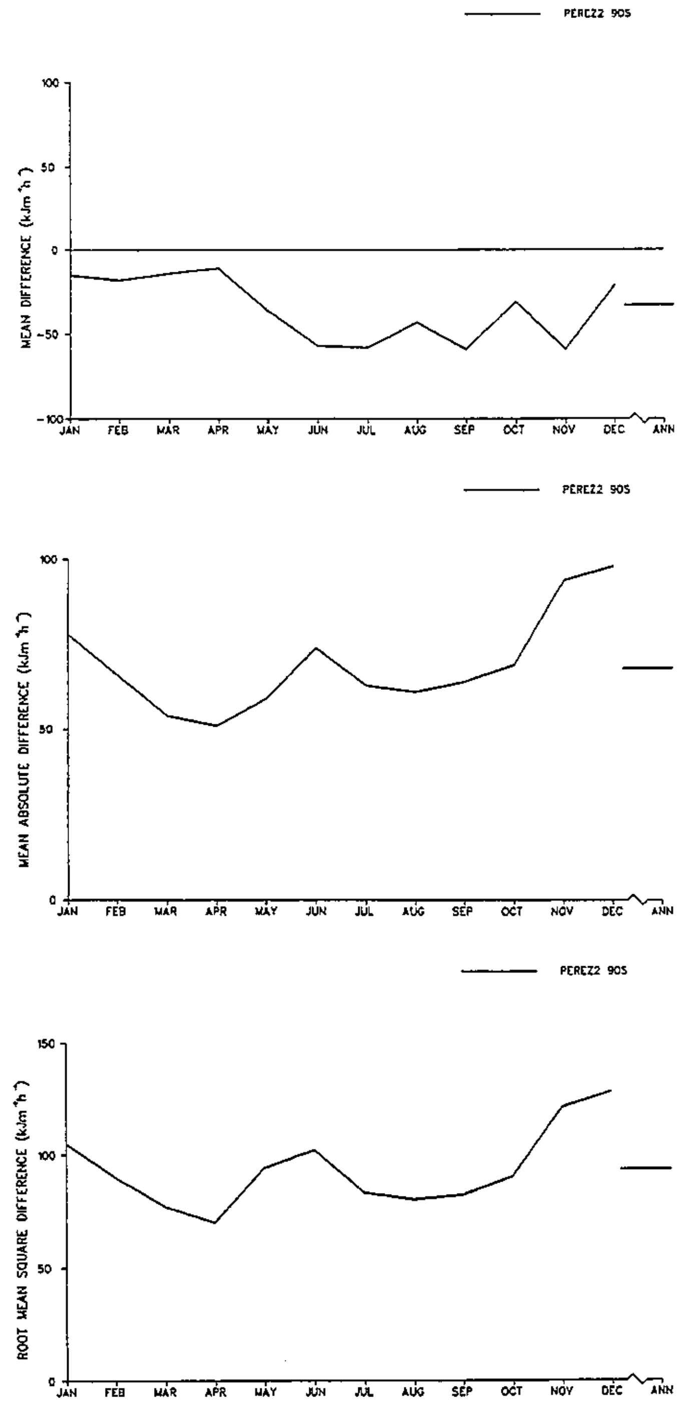


Figure 3. Monthly and total period values of the validation statistics for the Perez 2 model for a vertical south-facing surface at San Antonio.

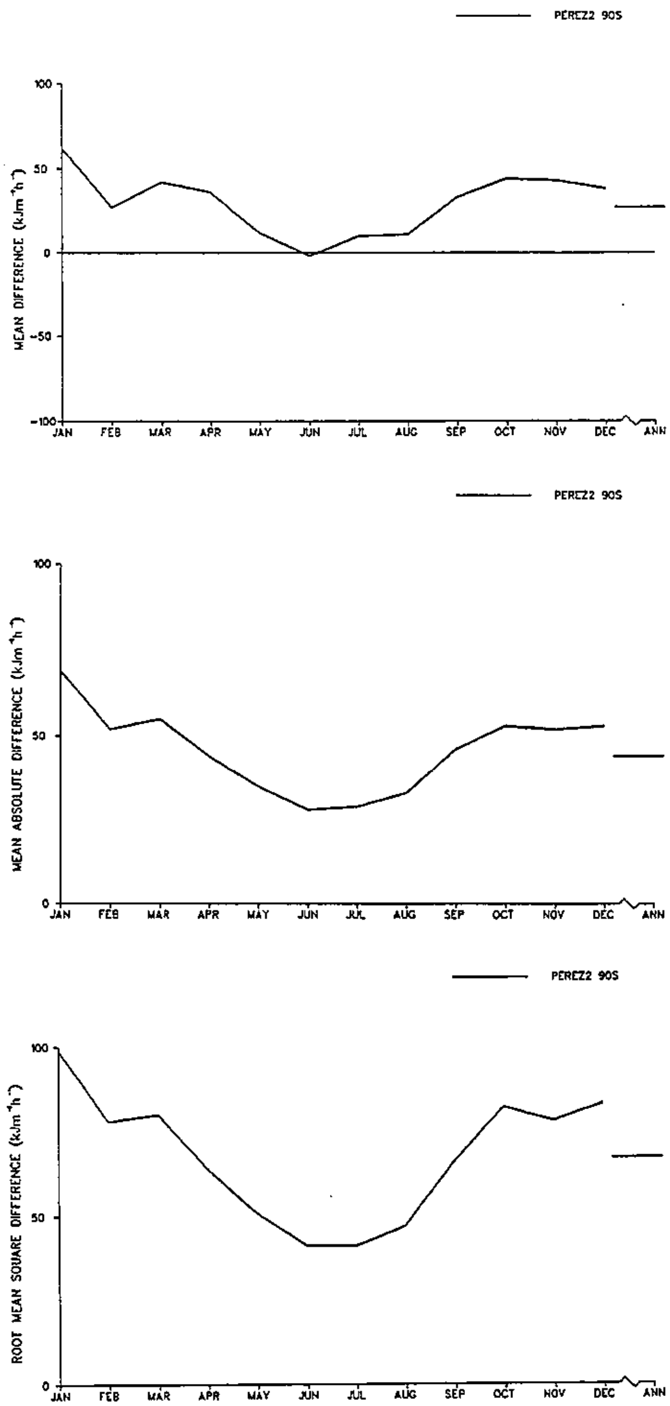


Figure 4. As for Fig. 3 but for Albany.

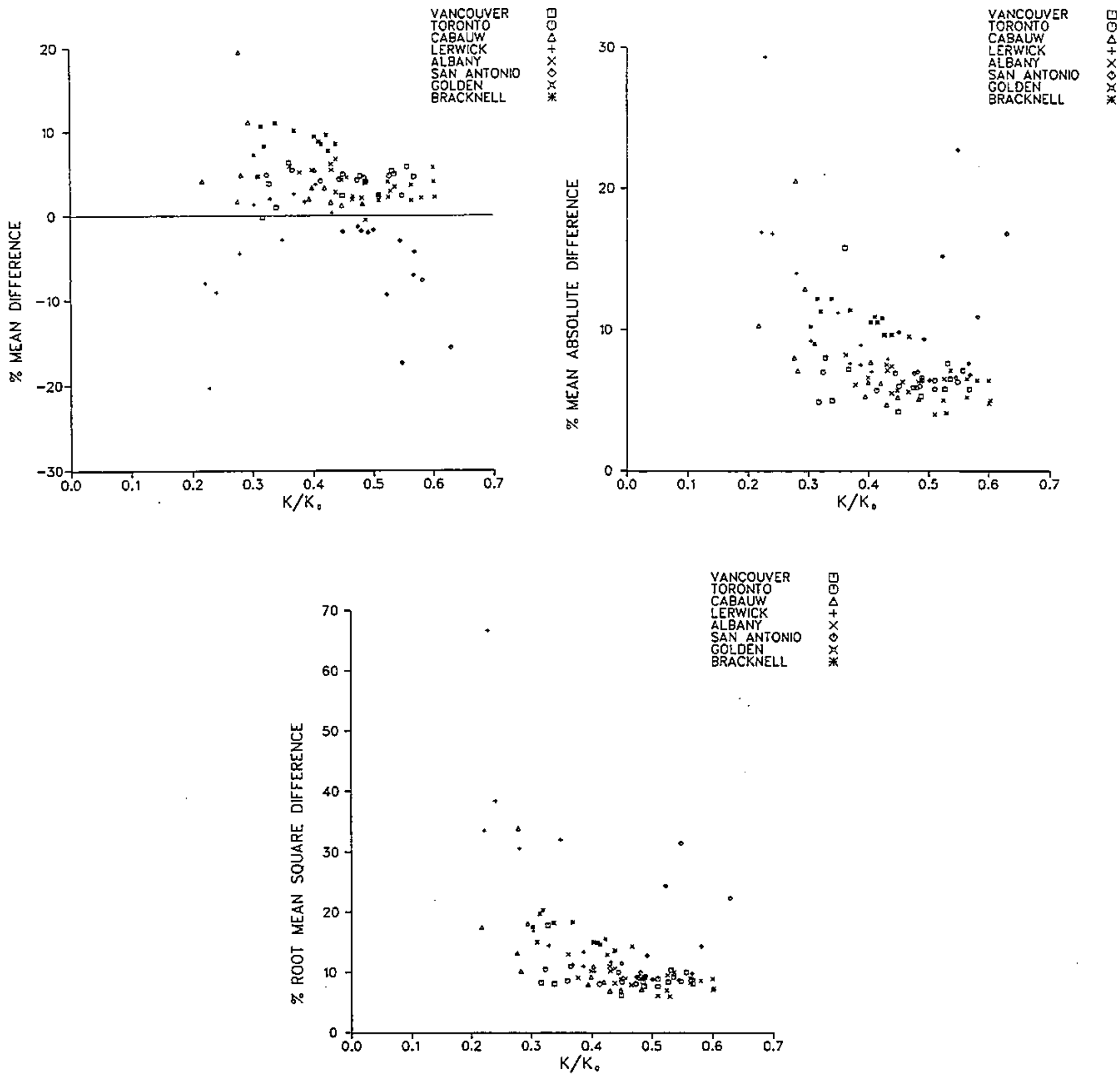


Figure 5b. As for Fig. 5a but for a vertical surface facing south.

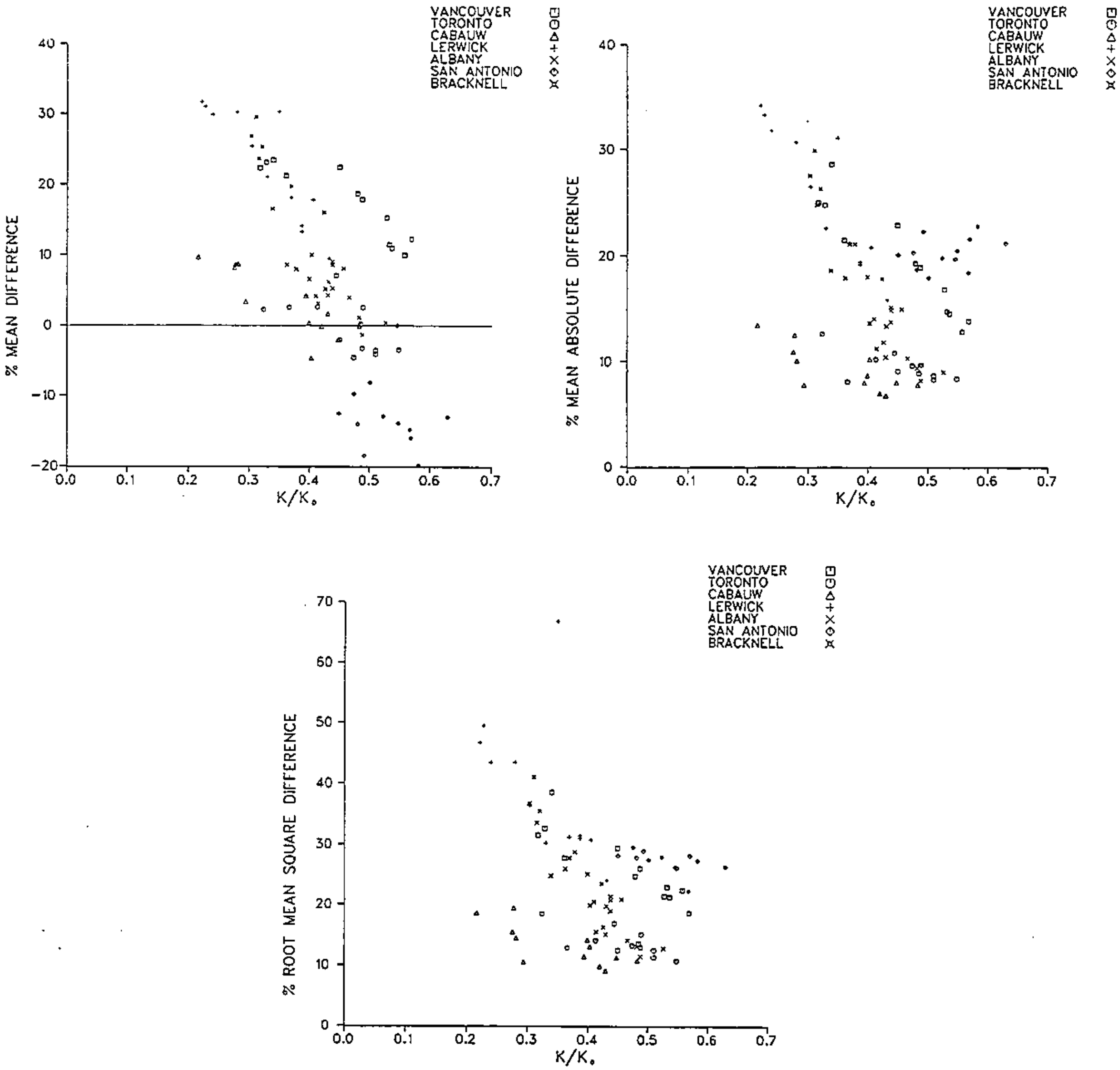


Figure 5a. The association between the overall monthly validation statistics and the clearness index ($K\downarrow/K_0$) for seven selected locations. Values are based on hourly calculations using the Perez 2 model and are presented for a vertical surface facing north.

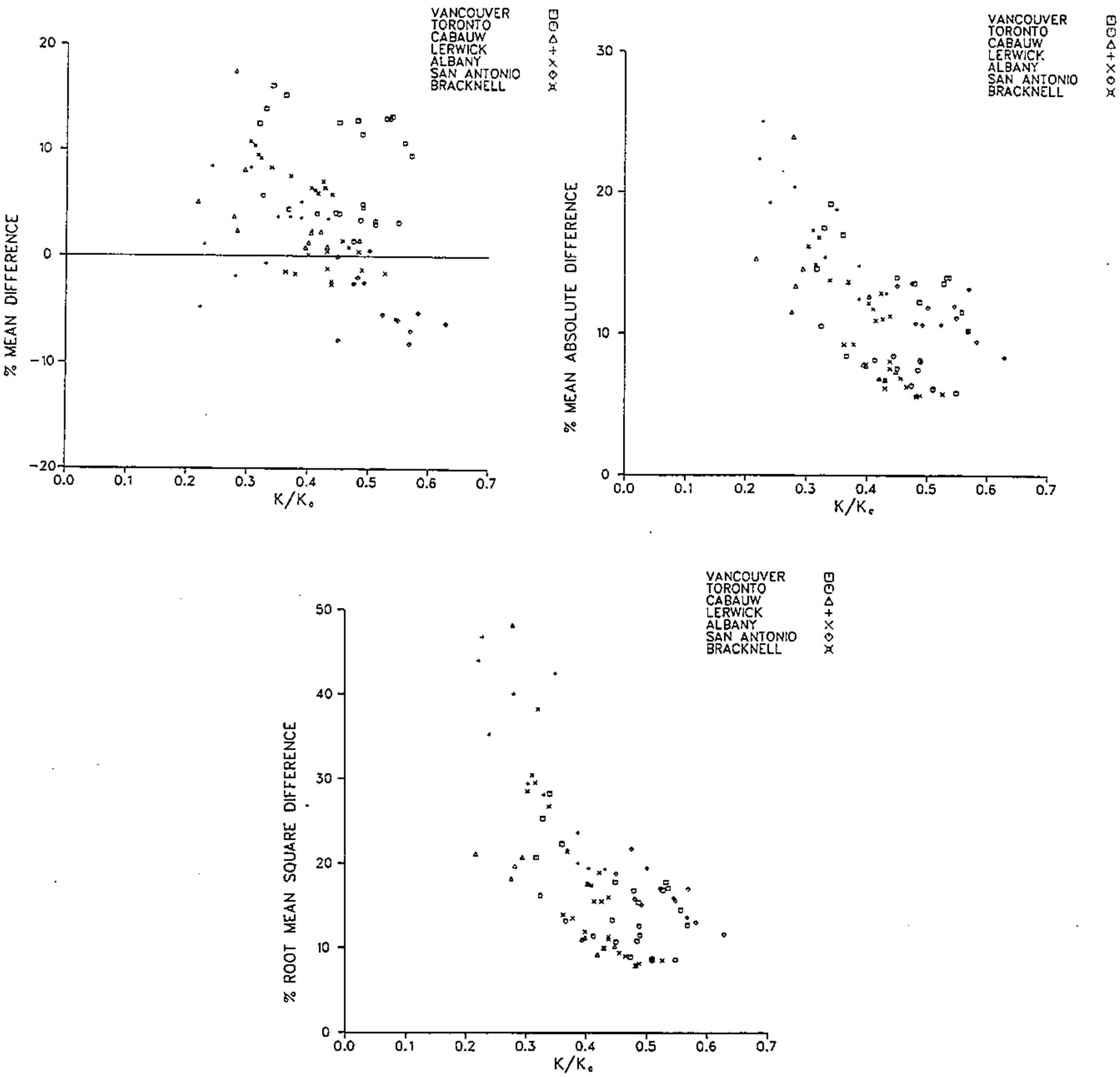


Figure 5c. As for Fig. 5a but for a vertical surface facing east.

8. VALIDATION OF DAILY MODELS

8.1 Introduction

The study recognized eight models which calculate the direct solar irradiance using daily data and therefore is was feasible to validate all of these models. However, in order to estimate the global irradiance these models must be combined with a diffuse irradiance algorithm capable of using daily data. The Isotropic model may be used for any time scale, but all other hourly diffuse irradiance algorithms require that the daily data at least be partitioned into a period representing the time the slope potentially receives direct radiation and a period when the slope can only receive diffuse radiation. Therefore the hourly model validation results presented in the preceding section cannot be used to select a daily diffuse irradiance model. Moreover, the two models which individually minimize the differences between the observed and calculated values of the individual direct and diffuse slope irradiances may not produce the smallest differences for the global irradiance.

8.2 Procedures

Given the theoretically higher quality of diffuse and direct irradiance estimates derived using pyrheliometer measurements a decision was made to limit the validation of the direct irradiance models to category A, B and C data sets. The validation results for the daily diffuse and global algorithms were further limited to category A and B locations in order to avoid the consequences associated with the need to estimate surface albedo. The preferred models will be subjected to detailed evaluation using procedures similar to those invoked in Section 7.

8.3 Results

8.3.1 Direct Models

8.3.1.1 Model Selection

Table 8 provides validation statistics and rankings for the seven daily direct irradiance models. These results are based on daily irradiance data for the 15 category A, B and C locations. Although there are specific slopes at certain locations where other models appear to be more accurate, Page is on average the best model followed by Rev2 and DPD. This selection is valid for all slope orientations although the data shows that model performance deteriorates significantly for slopes not facing the equator. There should not be any significant differences between the results for the three data set categories since the direct radiation is treated in a similar manner for all three categories.

Table 9 presents the results of a similar analysis although in this case long-term monthly mean data have been used to verify the models. This was done in order to determine whether selection of a model is dependent on the time scale of the data used in the validation. Table 9 confirms the superiority of Page at all time scales.

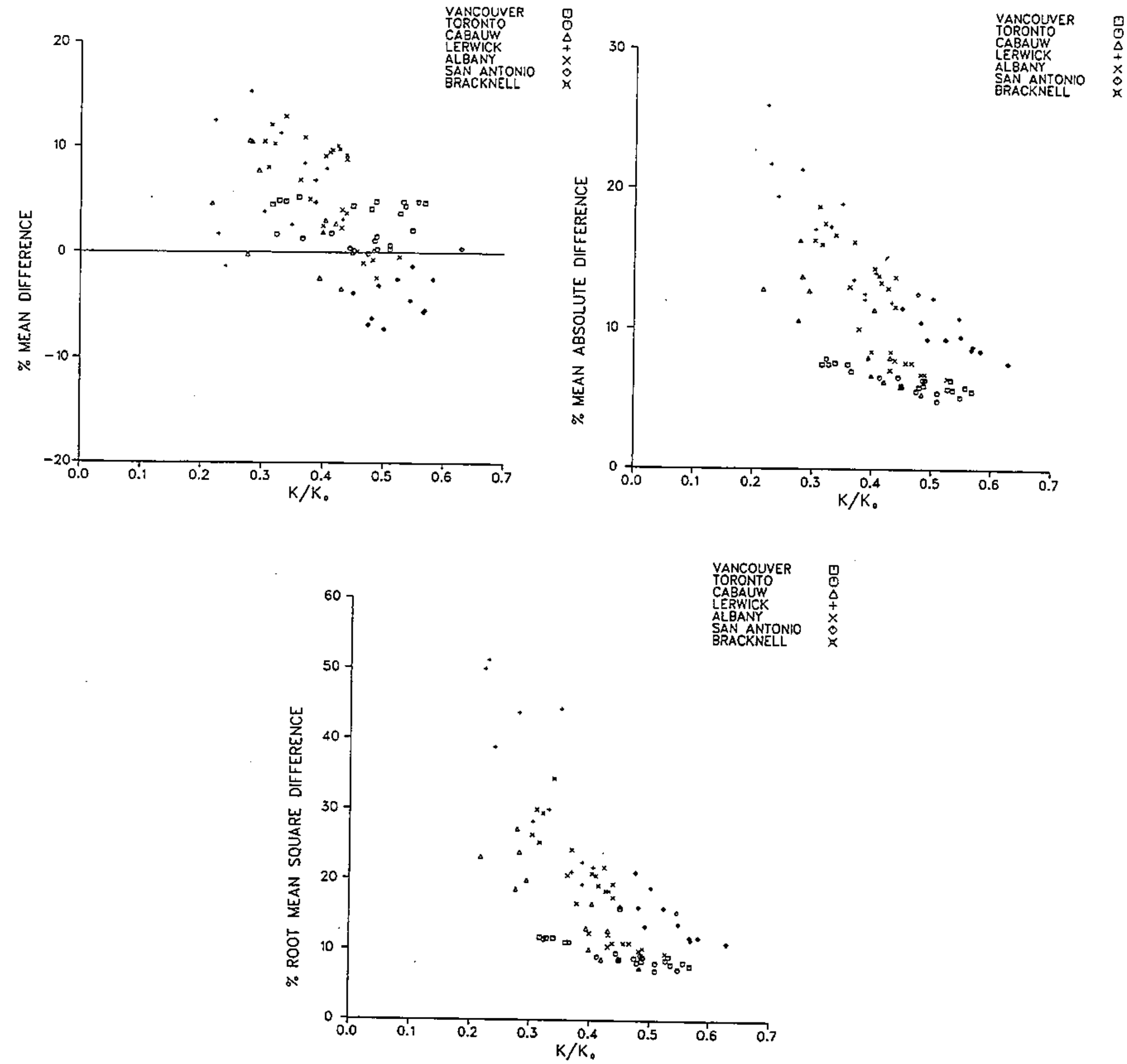


Figure 5d. As for Fig. 5a but for a vertical surface facing west.

Table 8. Validation statistics and rankings for daily direct irradiance models for 11 selected locations. Results based on daily direct irradiances (Units: kJ m^{-2} day^{-1}).

ALBANY

SLOPE	JONES MAD	JONES RMSD	REV2 MAD	REV2 RMSD	BREMER MAD	BREMER RMSD	PAGE MAD	PAGE RMSD	L&J MAD	L&J RMSD	K&T MAD	K&T RMSD	DPD MAD	DPD RMSD
33S	307	458	147	232	150	242	111	179	190	253	174	251	111	187
43S	365	541	177	276	181	286	135	217	219	293	208	299	135	224
53S	398	591	205	318	209	329	153	245	240	324	230	331	152	251
90N	368	778	95	235	103	255	72	168	162	367	169	385	111	248
90E	1467	2107	1123	1652	1133	1671	985	1515	1033	1603	1025	1598	966	1519
90S	377	585	204	304	205	304	154	234	221	312	224	330	150	239
90W	1556	2206	1065	1546	1069	1555	965	1489	1101	1647	1092	1647	958	1508
All	691	1260	431	886	436	896	368	822	452	908	446	909	369	832
Rank.1	7	7	3	3	4	4	1	1	6	5	5	6	2	2
Rank.2	7	7	3	3	4	4	2	1	6	5	5	6	1	2

BRACKNELL.2

SLOPE	JONES MAD	JONES RMSD	REV2 MAD	REV2 RMSD	BREMER MAD	BREMER RMSD	PAGE MAD	PAGE RMSD	L&J MAD	L&J RMSD	K&T MAD	K&T RMSD	DPD MAD	DPD RMSD
90N	284	669	71	179	73	187	75	186	135	351	129	343	116	278
90E	1032	1643	792	1295	797	1306	782	1269	809	1338	814	1345	801	1290
90S	290	473	137	227	140	235	137	223	214	302	213	307	158	252
90W	1101	1694	701	1117	702	1122	729	1149	855	1310	823	1290	773	1209
51.4S	294	479	128	229	131	237	137	237	222	315	208	312	159	262
All	600	1138	366	782	369	789	372	784	447	874	437	870	401	817
Rank.1	7	7	1	1	2	3	3	2	6	6	5	5	4	4
Rank.2	7	7	1	1	3	3	2	2	6	6	5	5	4	4

LERWICK

SLOPE	JONES MAD	JONES RMSD	REV2 MAD	REV2 RMSD	BREMER MAD	BREMER RMSD	PAGE MAD	PAGE RMSD	L&J MAD	L&J RMSD	K&T MAD	K&T RMSD	DPD MAD	DPD RMSD
90N	360	1003	69	206	62	193	85	251	166	535	157	521	153	451
90E	801	1635	513	1101	509	1090	534	1141	577	1243	579	1248	581	1221
90S	247	473	116	249	115	245	133	277	186	322	188	323	149	303
90W	733	1499	496	977	496	1000	512	1024	583	1160	544	1127	543	1092
60.1S	268	548	124	276	122	272	141	306	209	372	202	367	160	342
All	482	1136	264	685	261	687	281	719	344	827	334	817	317	787
Rank.1	7	7	2	1	1	2	3	3	6	6	5	5	4	4
Rank.2	7	7	2	2	1	1	3	3	6	6	5	5	4	4

LULEA

SLOPE	JONES MAD	JONES RMSD	REV2 MAD	REV2 RMSD	BREMER MAD	BREMER RMSD	PAGE MAD	PAGE RMSD	L&J MAD	L&J RMSD	K&T MAD	K&T RMSD	DPD MAD	DPD RMSD
90S	337	617	147	315	158	336	148	312	227	404	232	401	179	355
60S	352	682	151	338	166	365	150	330	235	432	239	436	183	383
30S	257	525	96	222	107	241	97	220	171	324	167	322	127	275
All	315	611	131	296	144	318	132	291	211	389	213	389	163	341
Rank.1	7	7	1	2	3	3	2	1	5	6	6	5	4	4
Rank.2	7	7	1	2	3	3	2	1	5	6	6	5	4	4

NORRKOPING

SLOPE	JONES MAD	JONES RMSD	REV2 MAD	REV2 RMSD	BREMER MAD	BREMER RMSD	PAGE MAD	PAGE RMSD	L&J MAD	L&J RMSD	K&T MAD	K&T RMSD	DPD MAD	DPD RMSD
60S	435	699	255	435	281	484	221	376	291	444	303	455	233	387
Rank.1	7	7	3	3	4	6	1	1	5	4	6	5	2	2
Rank.2	7	7	3	3	4	6	1	1	5	4	6	5	2	2

SAN ANTONIO

SLOPE	JONES MAD	JONES RMSD	REV2 MAD	REV2 RMSD	BREMER MAD	BREMER RMSD	PAGE MAD	PAGE RMSD	L&J MAD	L&J RMSD	K&T MAD	K&T RMSD	DPD MAD	DPD RMSD
20S	243	326	94	141	94	140	74	108	125	164	122	164	73	110
30S	335	446	137	209	137	208	105	153	162	214	166	223	101	150
40S	403	542	173	267	173	263	129	190	195	261	201	272	120	180
90N	260	660	55	159	58	169	57	157	124	334	123	327	83	219
90E	2149	2648	1216	1516	1210	1512	1177	1559	1338	1790	1322	1771	1178	1605
90S	423	657	214	359	210	348	150	237	201	311	225	343	131	221
90W	1646	2100	1304	1633	1306	1635	992	1357	1114	1481	1119	1489	945	1336
All	780	1357	456	866	455	865	383	795	466	906	468	905	376	804
Rank.1	7	7	4	4	3	3	2	1	5	6	6	5	1	2
Rank.2	7	7	3	4	4	3	2	1	5	5	6	6	1	2

CATEGORY A

SLOPE	JONES MAD	JONES RMSD	REV2 MAD	REV2 RMSD	BREMER MAD	BREMER RMSD	PAGE MAD	PAGE RMSD	L&J MAD	L&J RMSD	K&T MAD	K&T RMSD	DPD MAD	DPD RMSD
All	610	1173	357	770	361	776	326	737	404	833	400	830	340	763
Rank.1	7	7	3	3	4	4	1	1	6	6	5	5	2	2
Rank.2	7	7	2	2	4	4	1	1	6	5	5	6	3	3
Equat.	333	548	157	283	161	293	136	249	207	323	206	329	145	269
Rank.1	7	7	3	3	4	4	1	1	6	5	5	6	2	2
Rank.2	7	7	3	3	4	4	1	1	5	5	6	6	2	2
Other	980	1676	625	1130	627	1136	580	1088	666	1216	658	1210	601	1123
Rank.1	7	7	3	3	4	4	1	1	6	6	5	5	2	2
Rank.2	7	7	2	2	3	3	1	1	6	6	5	5	4	4

CABAUW.1

SLOPE	JONES MAD	JONES RMSD	REV2 MAD	REV2 RMSD	BREMER MAD	BREMER RMSD	PAGE MAD	PAGE RMSD	L&J MAD	L&J RMSD	K&T MAD	K&T RMSD	DPD MAD	DPD RMSD
90N	278	635	60	152	60	152	73	182	130	324	118	306	114	281
90E	927	1564	676	1225	679	1236	668	1201	727	1289	738	1298	690	1222
90S	274	474	130	231	133	235	134	238	211	313	206	314	155	265
90W	1054	1699	651	1091	650	1089	685	1146	796	1293	752	1256	732	1213
45SE	535	906	518	891	517	890	512	888	549	894	525	890	508	885
45S	257	448	117	219	120	224	121	229	209	304	190	296	140	253
45SW	595	985	530	913	530	913	533	916	572	935	556	937	545	929
45W	869	1446	669	1155	668	1152	682	1181	723	1227	728	1232	708	1219
67.5S	297	512	139	256	142	261	144	266	233	346	221	342	165	292
All	565	1070	388	806	389	807	395	816	461	877	448	872	417	843
Rank.1	7	7	1	1	2	2	3	3	6	6	5	5	4	4
Rank.2	7	7	1	1=	2	1=	3	3	6	6	5	5	4	4

CARPENTRAS

SLOPE	JONES MAD	JONES RMSD	REV2 MAD	REV2 RMSD	BREMER MAD	BREMER RMSD	PAGE MAD	PAGE RMSD	L&J MAD	L&J RMSD	K&T MAD	K&T RMSD	DPD MAD	DPD RMSD
45S	550	698	220	320	232	342	149	230	250	330	274	359	167	250
90N	613	1127	120	264	134	294	89	205	289	572	301	590	187	362
90E	1926	2429	1188	1518	1213	1554	968	1359	1143	1578	1137	1567	957	1397
90S	519	688	240	332	247	340	157	225	238	324	263	362	175	248
90W	1930	2409	1073	1435	1097	1472	871	1278	1116	1520	1151	1534	912	1324
All	1108	1669	568	964	585	990	447	852	607	1034	625	1041	480	890
Rank.1	7	7	3	3	4	4	1	1	5	5	6	6	2	2
Rank.2	7	7	3	3	4=	4	1	1	4=	5	6	6	2	2

GOLDEN

SLOPE	JONES MAD	JONES RMSD	REV2 MAD	REV2 RMSD	BREMER MAD	BREMER RMSD	PAGE MAD	PAGE RMSD	L&J MAD	L&J RMSD	K&T MAD	K&T RMSD	DPD MAD	DPD RMSD
40S	482	638	236	335	243	351	156	235	264	353	269	360	179	265
90S	544	787	260	345	263	348	184	260	306	446	315	454	219	320
All	513	716	248	340	253	350	170	248	285	402	292	410	199	294
Rank.1	7	7	3	3	4	4	1	1	5	5	6	6	2	2
Rank.2	7	7	3	3	4	4	1	1	5	5	6	6	2	2

TORONTO

SLOPE	JONES MAD	JONES RMSD	REV2 MAD	REV2 RMSD	BREMER MAD	BREMER RMSD	PAGE MAD	PAGE RMSD	L&J MAD	L&J RMSD	K&T MAD	K&T RMSD	DPD MAD	DPD RMSD
30S	275	423	131	226	136	238	105	178	192	258	170	248	116	191
90N	382	831	89	225	96	242	81	196	176	417	187	436	132	295
90E	1339	1979	1115	1650	1130	1673	979	1495	1020	1578	1020	1580	969	1493
90S	372	584	201	311	206	318	158	248	236	333	244	357	174	275
60S	399	605	214	355	222	371	168	275	265	365	257	372	184	296
90W	1529	2187	1007	1485	1016	1501	955	1439	1099	1610	1079	1608	976	1479
90SE	982	1446	909	1337	914	1343	850	1286	883	1310	877	1312	846	1285
90SW	1146	1623	870	1284	871	1285	860	1293	920	1348	944	1376	878	1320
All	803	1369	567	1042	574	1052	520	990	599	1067	597	1073	534	1006
Rank.1	7	7	3	3	4	4	1	1	6	5	5	6	2	2
Rank.2	7	7	3	3	4	4	1	1	6	5	5	6	2	2

TRAPPES

SLOPE	JONES MAD	JONES RMSD	REV2 MAD	REV2 RMSD	BREMER MAD	BREMER RMSD	PAGE MAD	PAGE RMSD	L&J MAD	L&J RMSD	K&T MAD	K&T RMSD	DPD MAD	DPD RMSD
45S	332	501	152	241	158	256	145	232	246	325	230	318	165	254
90N	421	834	93	197	98	212	92	193	193	399	198	407	164	315
90E	1302	1887	1104	1576	1121	1603	1030	1478	1106	1602	1113	1615	1028	1481
90S	324	499	168	258	174	269	162	246	241	324	240	328	182	271
90W	1393	2042	887	1251	898	1263	872	1287	996	1422	971	1420	908	1355
All	754	1336	481	918	490	932	460	894	556	996	550	1000	489	924
Rank.1	7	7	2	2	4	4	1	1	6	5	5	6	3	3
Rank.2	7	7	2	2	4	3=	1	1	6	5	5	6	3	3=

VANCOUVER

SLOPE	JONES MAD	JONES RMSD	REV2 MAD	REV2 RMSD	BREMER MAD	BREMER RMSD	PAGE MAD	PAGE RMSD	L&J MAD	L&J RMSD	K&T MAD	K&T RMSD	DPD MAD	DPD RMSD
30S	328	510	127	212	135	230	102	196	212	305	193	287	122	212
60S	465	702	197	317	207	340	159	284	278	401	278	406	183	311
90S	416	626	188	288	195	303	151	259	245	358	251	368	174	283
90E	1893	2775	926	1455	929	1441	975	1620	1240	1936	1226	1923	1081	1754
90W	1353	2002	1044	1649	1071	1691	880	1460	1003	1590	977	1568	866	1446
90N	527	1108	74	171	82	189	87	208	276	613	274	614	193	408
60N	570	1202	135	302	147	329	138	335	307	656	312	661	217	470
All	793	1489	384	861	395	873	356	853	509	1033	502	1025	405	908
Rank.1	7	7	2	2	3	3	1	1	6	6	5	5	4	4
Rank.2	7	7	2	2	4	4	1	1	6	5	5	6	3	3

CATEGORY B

SLOPE	JONES MAD	JONES RMSD	REV2 MAD	REV2 RMSD	BREMER MAD	BREMER RMSD	PAGE MAD	PAGE RMSD	L&J MAD	L&J RMSD	K&T MAD	K&T RMSD	DPD MAD	DPD RMSD
All	761	1341	457	895	465	906	419	861	525	973	522	974	448	892
Rank.1	7	7	3	3	4	4	1	1	6	5	5	6	2	2
Rank.2	7	7	2	2	4	4	1	1	6	5	5	6	3	3
Equat.	479	785	292	576	297	581	261	554	345	605	342	611	278	567
Rank.1	7	7	3	3	4	4	1	1	6	5	5	6	2	2
Rank.2	7	7	2=	2=	4	4	1	1	6	5	5	6	2=	2=
Other	1077	1766	642	1151	652	1166	596	1107	726	1264	722	1262	637	1152
Rank.1	7	7	3	2	4	4	1	1	6	6	5	5	2	3
Rank.2	7	7	2	2	4	3=	1	1	5=	5	5=	6	3	3=

ATLANTA

SLOPE	JONES MAD	JONES RMSD	REV2 MAD	REV2 RMSD	BREMER MAD	BREMER RMSD	PAGE MAD	PAGE RMSD	L&J MAD	L&J RMSD	K&T MAD	K&T RMSD	DPD MAD	DPD RMSD
34S	315	430	163	246	164	246	109	167	170	220	153	211	97	151
Rank.1	7	7	4	5=	5	5=	2	2	6	4	3	3	1	1
Rank.2	7	7	4	5=	5	5=	2	2	6	4	3	3	1	1

BERGEN

SLOPE	JONES MAD	JONES RMSD	REV2 MAD	REV2 RMSD	BREMER MAD	BREMER RMSD	PAGE MAD	PAGE RMSD	L&J MAD	L&J RMSD	K&T MAD	K&T RMSD	DPD MAD	DPD RMSD
45S	336	642	144	288	152	310	152	305	254	434	241	422	176	352
90S	324	576	162	310	171	331	168	321	241	399	239	399	185	349
90W	989	1721	758	1372	783	1412	746	1351	805	1443	808	1448	762	1375
90E	1097	2002	757	1372	746	1341	779	1447	851	1607	845	1601	820	1533
90N	410	1092	83	213	77	194	105	274	233	662	232	667	185	492
All	631	1335	381	893	386	898	390	915	477	1044	473	1043	426	972
Rank.1	7	7	1	1	2	2	3	3	6	6	5	5	4	4
Rank.2	7	7	1	1	2=	3	2=	2	6	5=	5	5=	4	4

LOS ALAMOS

SLOPE	JONES MAD	JONES RMSD	REV2 MAD	REV2 RMSD	BREMER MAD	BREMER RMSD	PAGE MAD	PAGE RMSD	L&J MAD	L&J RMSD	K&T MAD	K&T RMSD	DPD MAD	DPD RMSD
45SSE	669	956	395	644	394	644	405	672	532	722	516	714	419	687
90S	516	781	227	316	226	315	160	242	345	534	353	542	212	309
All	593	873	311	507	310	507	283	505	439	635	435	634	316	533
Rank.1	7	7	3	3	2	2	1	1	6	6	5	5	4	4
Rank.2	7	7	3=	3	1=	1=	1=	1=	5=	5=	5=	5=	3=	4

CATEGORY C

SLOPE	JONES MAD	JONES RMSD	REV2 MAD	REV2 RMSD	BREMER MAD	BREMER RMSD	PAGE MAD	PAGE RMSD	L&J MAD	L&J RMSD	K&T MAD	K&T RMSD	DPD MAD	DPD RMSD
All	582	1152	336	755	339	759	328	769	429	888	423	887	357	815
Rank.1	7	7	2	1	3	2	1	3	6	6	5	5	4	4
Rank.2	7	7	2	2	3	3	1	1	6	6	5	5	4	4
Equat.	432	700	218	388	221	395	199	383	308	490	300	487	218	409
Rank.1	7	7	3	2	4	3	1	1	6	6	5	5	2	4
Rank.2	7	7	2	2	3	3=	1	1	6	6	5	5	4	3=
Other	832	1649	533	1127	535	1130	543	1154	630	1304	628	1304	589	1222
Rank.1	7	7	1	1	2	2	3	3	6	5	5	6	4	4
Rank.2	7	7	1=	1=	1=	1=	3	3	6	5	5	6	4	4

ALL LOCATIONS

SLOPE	JONES MAD	JONES RMSD	REV2 MAD	REV2 RMSD	BREMER MAD	BREMER RMSD	PAGE MAD	PAGE RMSD	L&J MAD	L&J RMSD	K&T MAD	K&T RMSD	DPD MAD	DPD RMSD
All	683	1258	405	833	410	842	373	805	467	912	463	911	396	836
Rank.1	7	7	3	2	4	4	1	1	6	6	5	5	2	3
Rank.2	7	7	2	2	4	4	1	1	6	5	5	6	3	3
Equat.	415	689	229	457	233	463	203	435	285	496	283	500	217	450
Rank.1	7	7	3	3	4	4	1	1	6	5	5	6	2	2
Rank.2	7	7	2	3	4	4	1	1	6	5	5	6	3	2
Other	1017	1722	625	1141	632	1152	585	1105	695	1250	689	1247	619	1148
Rank.1	7	7	3	2	4	4	1	1	6	6	5	5	2	3
Rank.2	7	7	2	2	3	3	1	1	6	5	5	6	4	4

Table 9. Validation statistics and rankings for daily direct irradiance models for 9 selected locations. Results based on long-term monthly mean daily direct irradiances (Units: kJ m^{-2} day^{-1}).

ALBANY

SLOPE	JONES MAD	JONES RMSD	REV2 MAD	REV2 RMSD	BREMER MAD	BREMER RMSD	PAGE MAD	PAGE RMSD	L&J MAD	L&J RMSD	K&T MAD	K&T RMSD	DPD MAD	DPD RMSD
33S	294	328	98	113	105	126	35	42	55	70	60	76	53	61
43S	346	382	118	134	125	147	44	54	60	76	69	80	61	70
53S	375	408	138	156	146	170	46	55	63	79	68	84	60	68
90N	371	633	66	120	78	141	16	33	107	191	123	215	98	166
90E	1145	1224	407	470	430	507	155	201	275	336	258	319	224	274
90W	1161	1264	391	406	414	433	159	202	215	296	252	335	232	280
90S	347	385	134	148	138	150	50	56	53	69	56	71	52	61
All	577	762	193	261	205	281	72	115	118	192	127	202	111	168
Rank.1	7	7	5	5	6	6	1	1	3	3	4	4	2	2
Rank.2	7	7	5	5	6	6	1	1	3	3	4	4	2	2

BRACKNELL.2

SLOPE	JONES MAD	JONES RMSD	REV2 MAD	REV2 RMSD	BREMER MAD	BREMER RMSD	PAGE MAD	PAGE RMSD	L&J MAD	L&J RMSD	K&T MAD	K&T RMSD	DPD MAD	DPD RMSD
90N	270	455	33	56	44	76	15	28	17	33	17	34	81	137
90E	674	742	210	255	238	289	91	125	113	146	120	155	162	190
90S	239	256	58	77	66	93	32	38	40	60	41	58	67	76
90W	761	845	149	173	179	210	139	165	126	147	133	154	237	278
51.4S	241	260	63	88	74	109	27	33	41	63	40	59	60	66
All	437	567	103	150	120	175	61	96	67	102	70	106	121	169
Rank.1	7	7	4	4	5	6	1	1	2	2	3	3	6	5
Rank.2	7	7	4	4	6	6	1	1	2	2	3	3	5	5

LERWICK

SLOPE	JONES MAD	JONES RMSD	REV2 MAD	REV2 RMSD	BREMER MAD	BREMER RMSD	PAGE MAD	PAGE RMSD	L&J MAD	L&J RMSD	K&T MAD	K&T RMSD	DPD MAD	DPD RMSD
90N	391	703	23	59	16	26	57	119	65	139	67	142	157	293
90E	685	874	113	160	81	107	206	273	157	216	167	218	314	412
90S	231	281	24	48	21	28	71	102	51	65	76	88	103	133
90W	659	832	110	139	103	131	166	236	156	198	177	216	278	372
60.1S	256	335	25	54	24	34	72	111	52	73	75	91	110	155
All	444	654	59	104	49	79	114	183	96	151	112	161	192	295
Rank.1	7	7	2	2	1	1	5	5	3	3	4	4	6	6
Rank.2	7	7	2	2	1	1	4	5	3	3	5	4	6	6

SAN ANTONIO

SLOPE	JONES MAD	JONES RMSD	REV2 MAD	REV2 RMSD	BREMER MAD	BREMER RMSD	PAGE MAD	PAGE RMSD	L&J MAD	L&J RMSD	K&T MAD	K&T RMSD	DPD MAD	DPD RMSD
20S	255	295	75	94	77	93	55	78	79	109	86	114	53	77
30S	317	358	118	143	118	142	59	81	81	102	94	115	52	69
40S	392	437	146	180	146	177	78	104	105	129	116	138	65	82
90N	467	822	49	89	58	103	86	174	195	375	198	374	146	267
90E	2188	2268	195	258	175	233	712	832	1085	1159	1054	1130	860	932
90S	395	492	174	248	171	239	84	112	96	118	110	139	51	62
90W	1173	1273	984	1024	994	1032	400	480	310	407	275	349	278	344
All	741	1075	249	422	248	422	211	376	279	493	276	479	215	393
Rank.1	7	7	4	3	3	4	1	1	6	6	5	5	2	2
Rank.2	7	7	3	5=	4=	3	2	2	4=	4	6	5=	1	1

CATEGORY A

SLOPE	JONES MAD	JONES RMSD	REV2 MAD	REV2 RMSD	BREMER MAD	BREMER RMSD	PAGE MAD	PAGE RMSD	L&J MAD	L&J RMSD	K&T MAD	K&T RMSD	DPD MAD	DPD RMSD
All	568	814	163	281	168	288	119	232	150	298	156	294	161	278
Rank.1	7	7	5	3	6	4	1	1	2	6	3	5	4	2
Rank.2	7	7	4	5	6	6	1	1	2	2	5	4	3	3
Equat.	307	358	98	135	101	138	54	78	65	87	74	96	66	87
Rank.1	7	7	5	5	6	6	1	1	2	3	4	4	3	2
Rank.2	7	7	5	5=	6	5=	1	1	3	3	4	4	2	2
Other	765	1051	210	358	216	368	169	307	217	396	219	388	236	369
Rank.1	7	7	2	2	3	3	1	1	4	6	5	5	6	4
Rank.2	7	7	2	2	4	4	1	1	3	3	5	5	6	6

CARPENTRAS

SLOPE	JONES MAD	JONES RMSD	REV2 MAD	REV2 RMSD	BREMER MAD	BREMER RMSD	PAGE MAD	PAGE RMSD	L&J MAD	L&J RMSD	K&T MAD	K&T RMSD	DPD MAD	DPD RMSD
45S	502	555	153	183	166	209	54	73	136	161	159	185	100	113
90N	565	961	78	139	96	172	39	76	216	368	249	431	163	277
90E	1684	1828	450	574	489	637	255	281	601	692	579	665	384	452
90S	482	529	172	194	179	207	49	61	117	144	133	167	86	110
90W	1610	1781	525	566	563	624	160	210	421	521	488	608	312	366
All	969	1267	276	385	299	427	111	166	298	432	322	460	209	297
Rank.1	7	7	3	3	5	4	1	1	4	5	6	6	2	2
Rank.2	7	7	3	3	6	5=	1	1	4	4	5	5=	2	2

TORONTO

SLOPE	JONES		REV2		BREMER		PAGE		L&J		K&T		DPD	
	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD
30S	259	291	94	126	102	144	14	20	32	43	33	42	42	50
90N	397	681	72	134	85	158	15	31	111	193	132	229	104	176
90E	995	1063	524	618	553	667	140	185	106	147	101	138	128	152
90S	312	343	130	150	137	164	18	22	27	33	31	38	65	83
60S	351	376	153	197	164	228	25	32	24	34	31	38	65	76
90W	1207	1314	313	367	341	414	124	181	205	270	251	330	271	316
90SE	493	511	306	353	316	369	127	164	92	110	88	106	107	133
90SW	724	755	98	126	100	133	128	176	174	215	203	253	230	263
All	592	750	211	307	225	334	74	126	96	156	109	180	127	179
Rank.1	7	7	5	5	6	6	1	1	2	2	3	4	4	3
Rank.2	7	7	5	5	6	6	1	1	2	2	3	3	4	4

TRAPPES

SLOPE	JONES		REV2		BREMER		PAGE		L&J		K&T		DPD	
	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD
45S	236	266	64	88	73	105	32	44	52	80	54	80	63	74
90N	262	467	25	50	35	69	22	41	44	89	44	88	83	147
90E	572	691	379	511	405	543	240	328	291	428	295	435	242	305
90S	230	270	79	104	86	118	42	57	68	100	70	104	72	93
90W	862	998	93	125	106	137	203	257	173	214	177	225	298	347
All	432	606	128	244	141	262	108	190	126	225	128	230	152	223
Rank.1	7	7	3=	5	5	6	1	1	2	3	3=	4	6	2
Rank.2	7	7	3=	2=	6	6	1	1	2	2=	3=	5	5	2=

VANCOUVER

SLOPE	JONES		REV2		BREMER		PAGE		L&J		K&T		DPD	
	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD
30S	322	379	72	92	86	119	32	46	89	120	84	109	80	91
60S	448	495	108	132	127	168	49	72	101	123	104	126	107	116
90S	392	411	102	118	116	143	42	59	77	85	77	85	89	96
90E	1724	2012	204	289	157	218	518	702	782	1010	759	989	734	907
90W	919	1010	688	839	732	913	287	380	123	150	104	129	174	209
90N	536	907	38	66	57	100	53	98	218	377	224	382	177	301
60N	613	1012	84	138	265	542	69	130	226	383	228	384	180	302
All	708	1033	185	349	220	422	150	310	231	442	226	435	220	393
Rank.1	7	7	2	2	3	4	1	1	6	6	5	5	4	3
Rank.2	7	7	2	3	6	6	1	1	5	5	4	4	3	2

CATEGORY B

SLOPE	JONES MAD	JONES RMSD	REV2 MAD	REV2 RMSD	BREMER MAD	BREMER RMSD	PAGE MAD	PAGE RMSD	L&J MAD	L&J RMSD	K&T MAD	K&T RMSD	DPD MAD	DPD RMSD
All	668	934	200	325	221	369	109	212	180	332	188	341	174	285
Rank.1	7	7	5	3	6	6	1	1	3	4	4	5	2	2
Rank.2	7	7	4	4	6	6	1	1	2	3	5	5	3	2
Equat.	396	453	128	170	138	189	51	84	82	116	89	127	92	120
Rank.1	7	7	5	5	6	6	1	1	2	2	3	4	4	3
Rank.2	7	7	5	5	6	6	1	1	2	2	3	4	4	3
Other	919	1220	267	420	299	478	163	282	271	446	279	457	250	377
Rank.1	7	7	3	3	6	6	1	1	4	4	5	5	2	2
Rank.2	7	7	2	2	6	5	1	1	4	4	5	6	3	3

BERGEN

SLOPE	JONES MAD	JONES RMSD	REV2 MAD	REV2 RMSD	BREMER MAD	BREMER RMSD	PAGE MAD	PAGE RMSD	L&J MAD	L&J RMSD	K&T MAD	K&T RMSD	DPD MAD	DPD RMSD
45S	330	410	24	34	60	79	66	86	84	136	84	132	125	155
90S	322	360	36	44	69	88	69	81	66	90	69	96	120	134
90W	761	846	225	301	291	407	166	196	118	147	139	176	223	255
90N	567	1024	26	60	18	36	75	151	226	436	225	450	223	414
All	495	718	78	156	110	213	94	137	124	244	129	255	173	264
Rank.1	7	7	1	2	3	3	2	1	4	4	5	5	6	6
Rank.2	7	7	1	1	2=	3	2=	2	4	4	5	5	6	6

CATEGORY C

SLOPE	JONES MAD	JONES RMSD	REV2 MAD	REV2 RMSD	BREMER MAD	BREMER RMSD	PAGE MAD	PAGE RMSD	L&J MAD	L&J RMSD	K&T MAD	K&T RMSD	DPD MAD	DPD RMSD
All	495	718	78	156	110	213	94	137	124	244	129	255	173	264
Rank.1	7	7	1	2	3	3	2	1	4	4	5	5	6	6
Rank.2	7	7	1	1	2=	3	2=	2	4	4	5	5	6	6
Equat.	326	386	30	39	65	84	68	84	75	115	77	115	123	145
Rank.1	7	7	1	1	2	3	3	2	4	4	5	5	6	6
Rank.2	7	7	1	1	2	2=	3=	2=	3=	4=	5	4=	6	6
Other	664	939	126	217	155	289	121	175	172	325	182	342	223	344
Rank.1	7	7	2	2	3	3	1	1	4	4	5	5	6	6
Rank.2	7	7	2=	3=	2=	3=	1	1=	2=	1=	2=	5=	6	5=

ALL LOCATIONS

SLOPE	JONES		REV2		BREMER		PAGE		L&J		K&T		DPD	
	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD
All	610	866	174	295	189	324	113	217	162	311	169	314	168	280
Rank.1	7	7	5	3	6	6	1	1	2	4	4	5	3	2
Rank.2	7	7	3	4	6	6	1	1	2	2	5	5	4	3
Equat.	350	407	106	148	115	161	54	81	74	104	81	113	82	108
Rank.1	7	7	5	5	6	6	1	1	2	2	3	4	4	3
Rank.2	7	7	5	5	6	6	1	1	2	3	4	4	3	2
Other	829	1126	231	381	250	418	163	288	239	415	244	419	242	371
Rank.1	7	7	2	3	6	5	1	1	3	4	5	6	4	2
Rank.2	7	7	2	2	4	5	1	1	3	3	5	6	6	4

8.3.1.2 Model Performance

Figure 6 demonstrates that the Page model is capable of providing accurate estimates of the daily direct irradiance for equator-facing surfaces, but the validity of the estimates is substantially lower for other orientations. This is particularly true for individual daily estimates since for some slopes the mean differences remain relatively small and similar to those for equator-facing slopes.

Monthly variations in the validation statistics are shown in Figure 7. Data are presented for Albany and are generally representative of the other locations. Absolute errors are small on both the poleward and equatorward- facing slopes while large errors occur for the east and west orientations.

Figure 8 shows that, at least in a relative sense, accurate daily estimates of the direct irradiance for an inclined surface are possible using the Page algorithm. Again there is often a weak dependency on the clearness index, especially for the root mean square and mean absolute differences. Relative errors tend to decrease as the index increases.

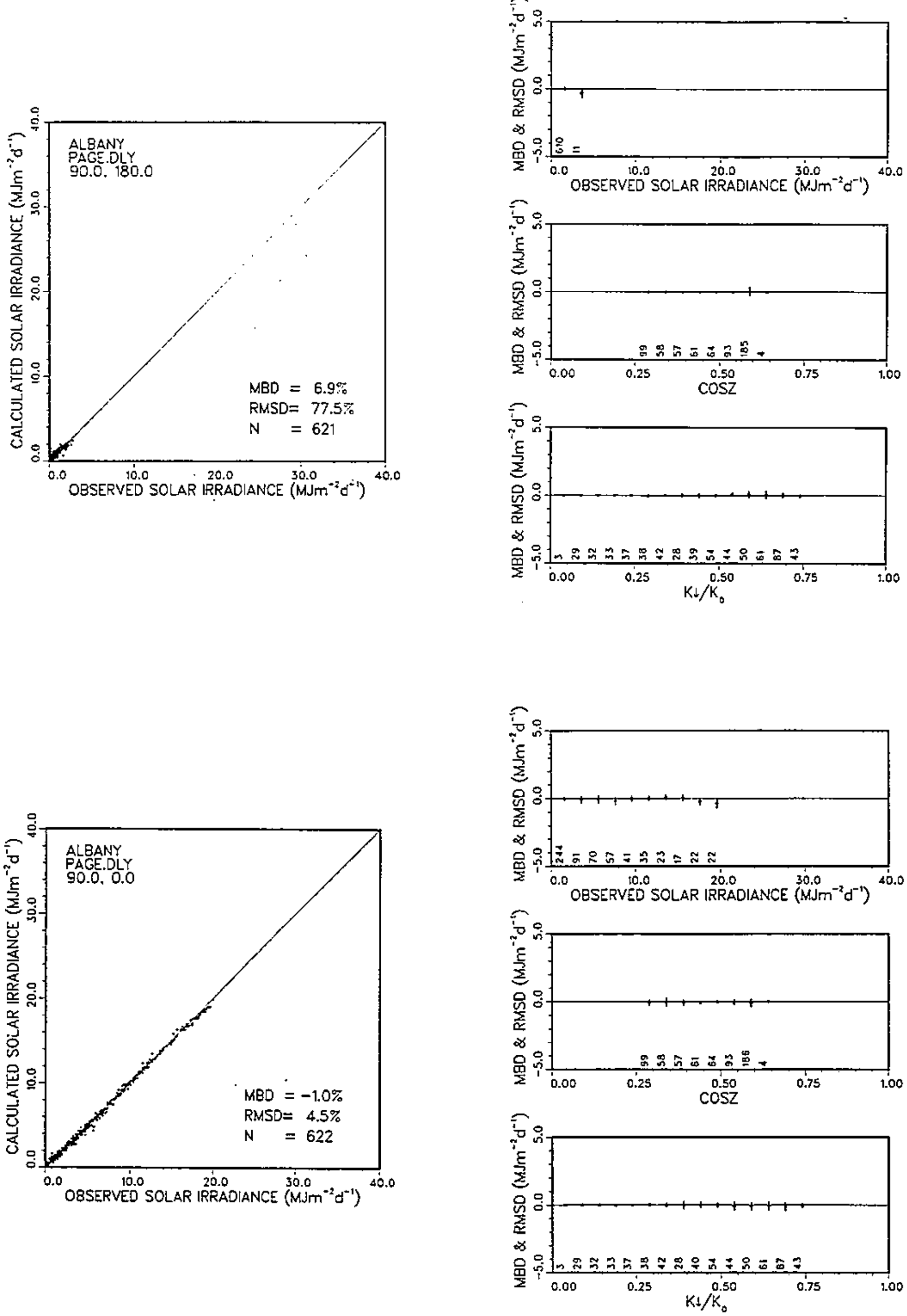


Figure 6a. Scatter diagrams of daily estimated (using Page) and observed direct solar irradiances for north (top) and south (bottom) facing vertical surfaces at Albany. Also shown are the average and root mean square values of the differences between the estimated and observed direct irradiances. These latter values are presented as a function of the solar irradiance for the slope, the cosine of the solar zenith angle and of the clearness index ($K{\downarrow}/K_0$).

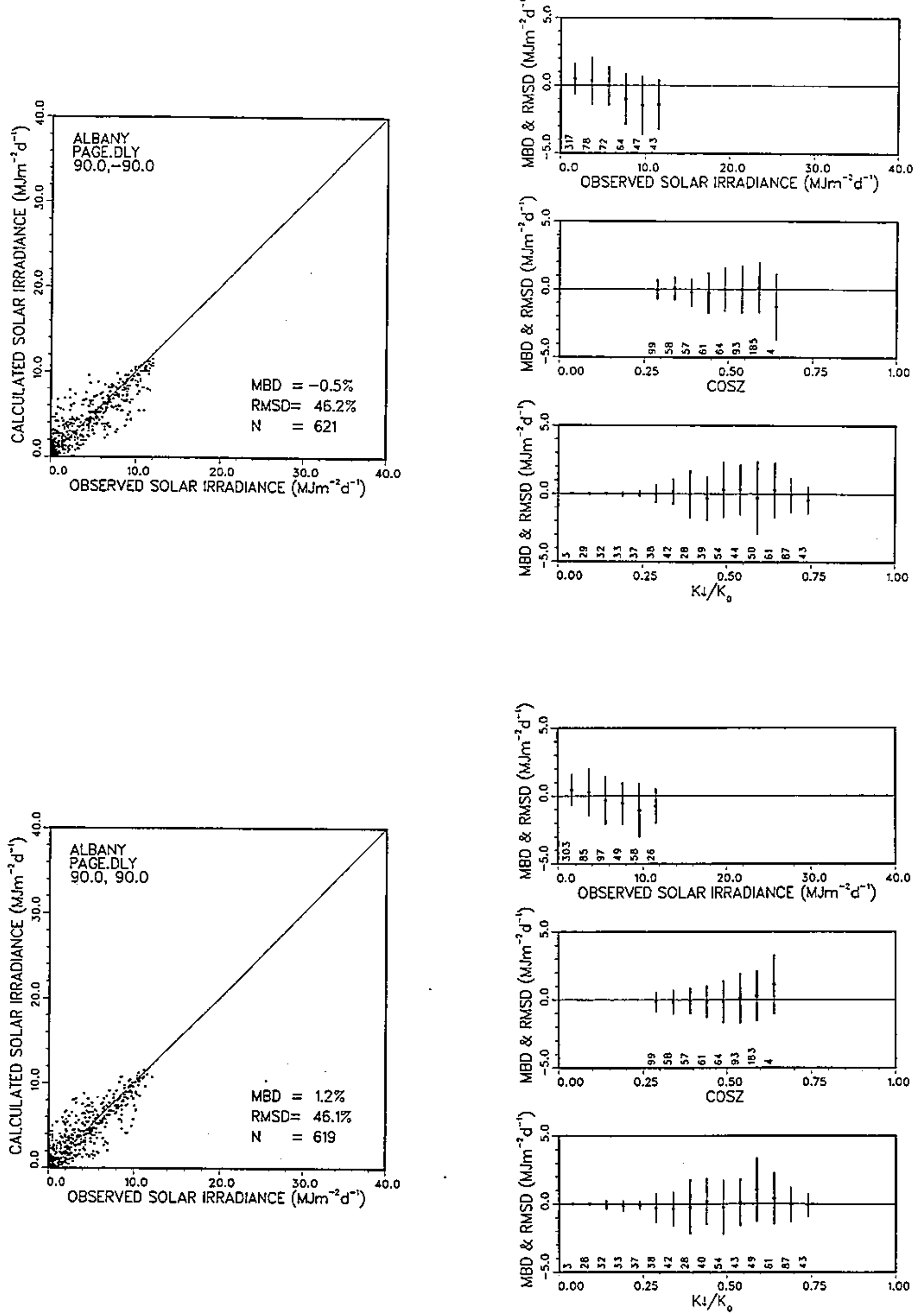


Figure 6b. As for Fig. 6a but for east (top) and west (bottom) facing vertical surfaces.

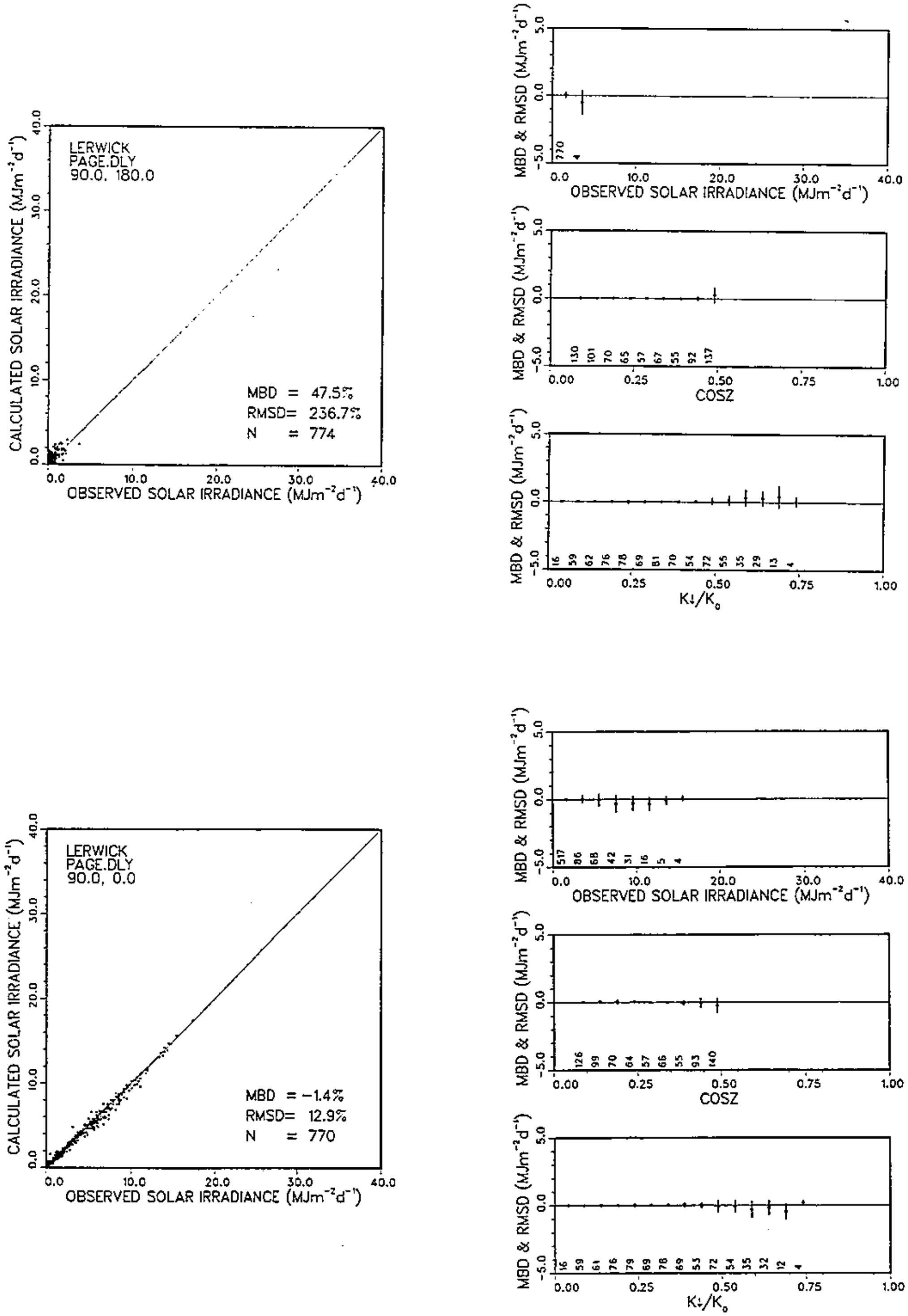


Figure 6c. As for Fig. 6a but for Lerwick.

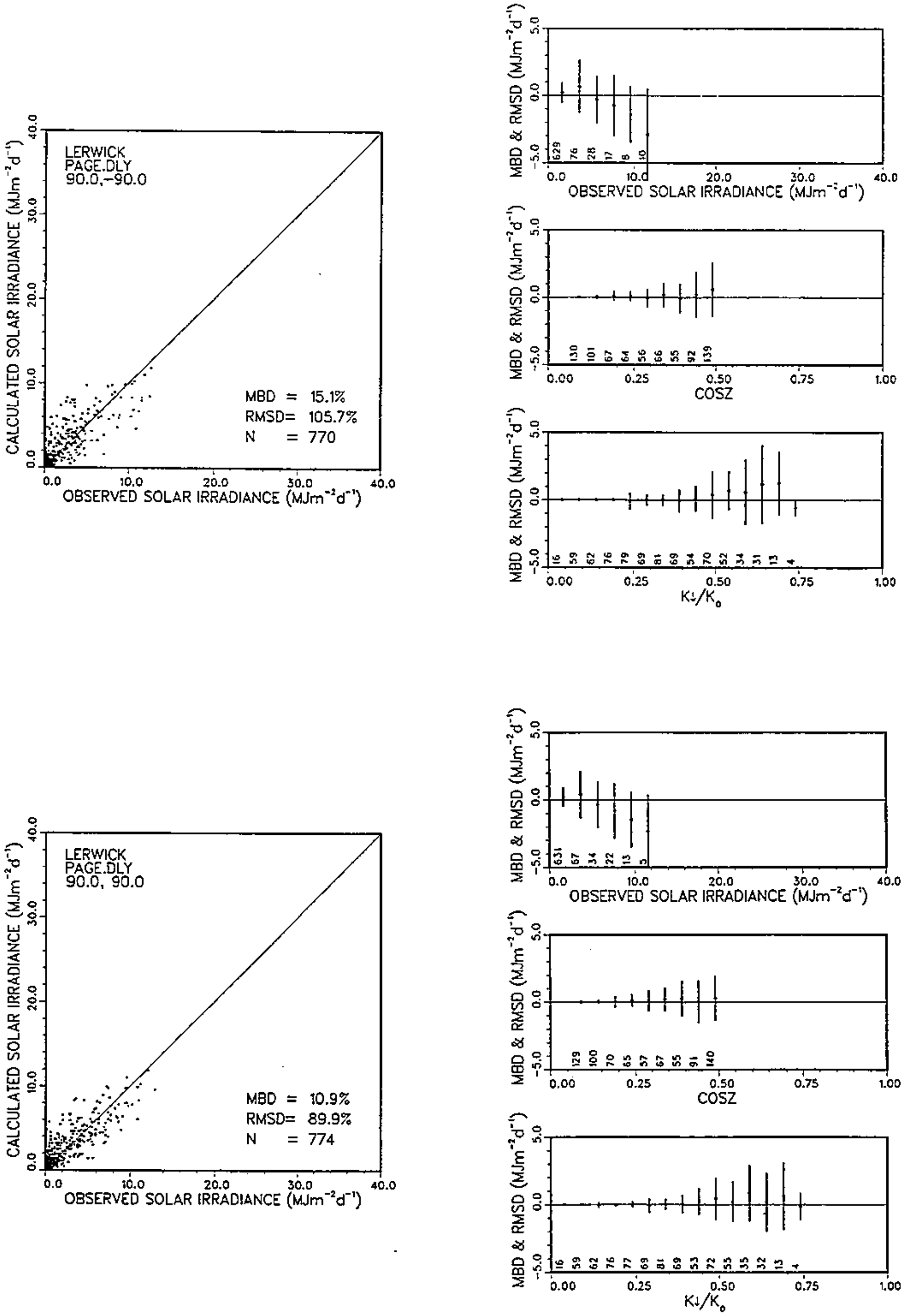


Figure 6d. As for Fig. 6b but for Lerwick.

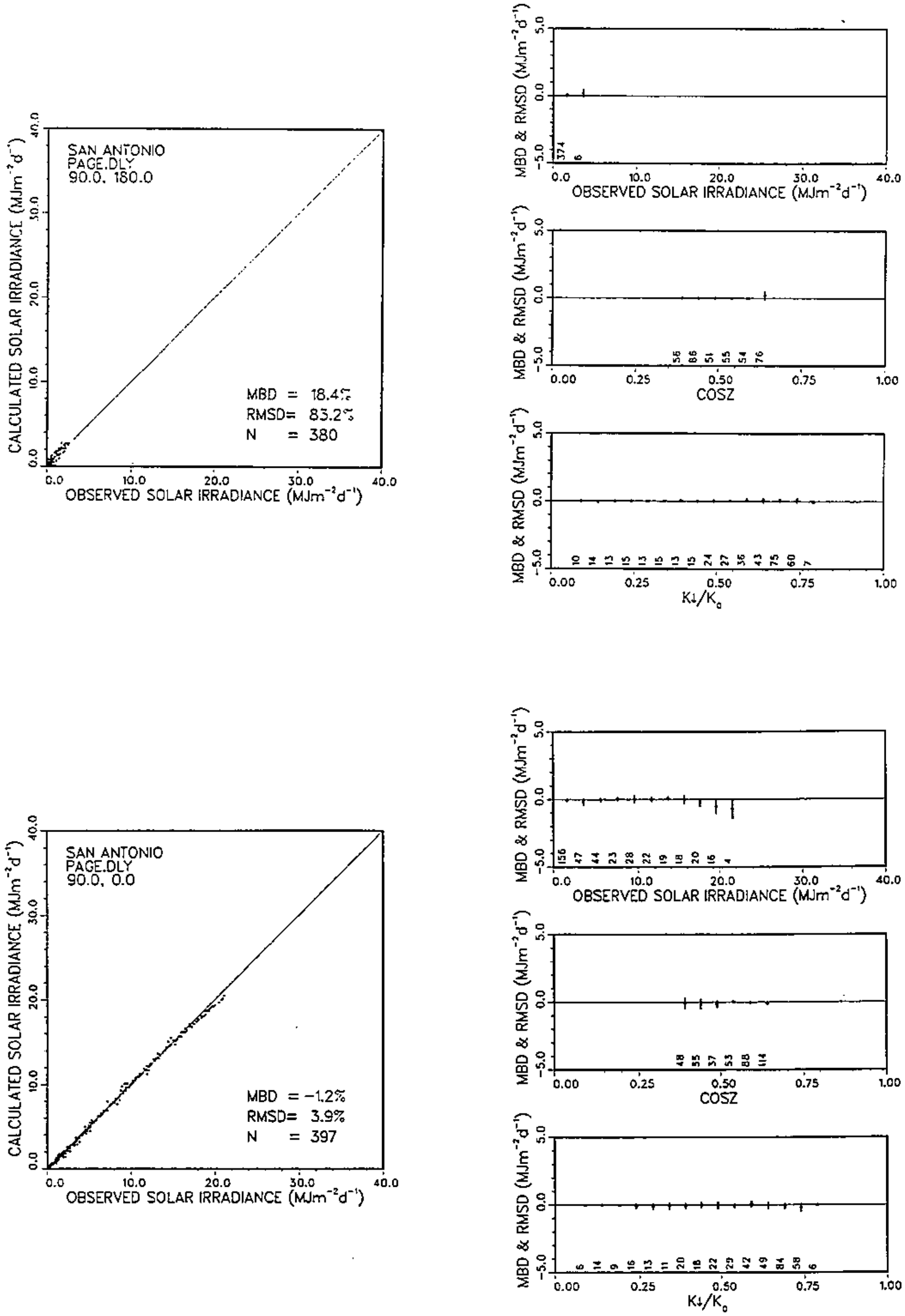


Figure 6e. As for Fig. 6a but for San Antonio.

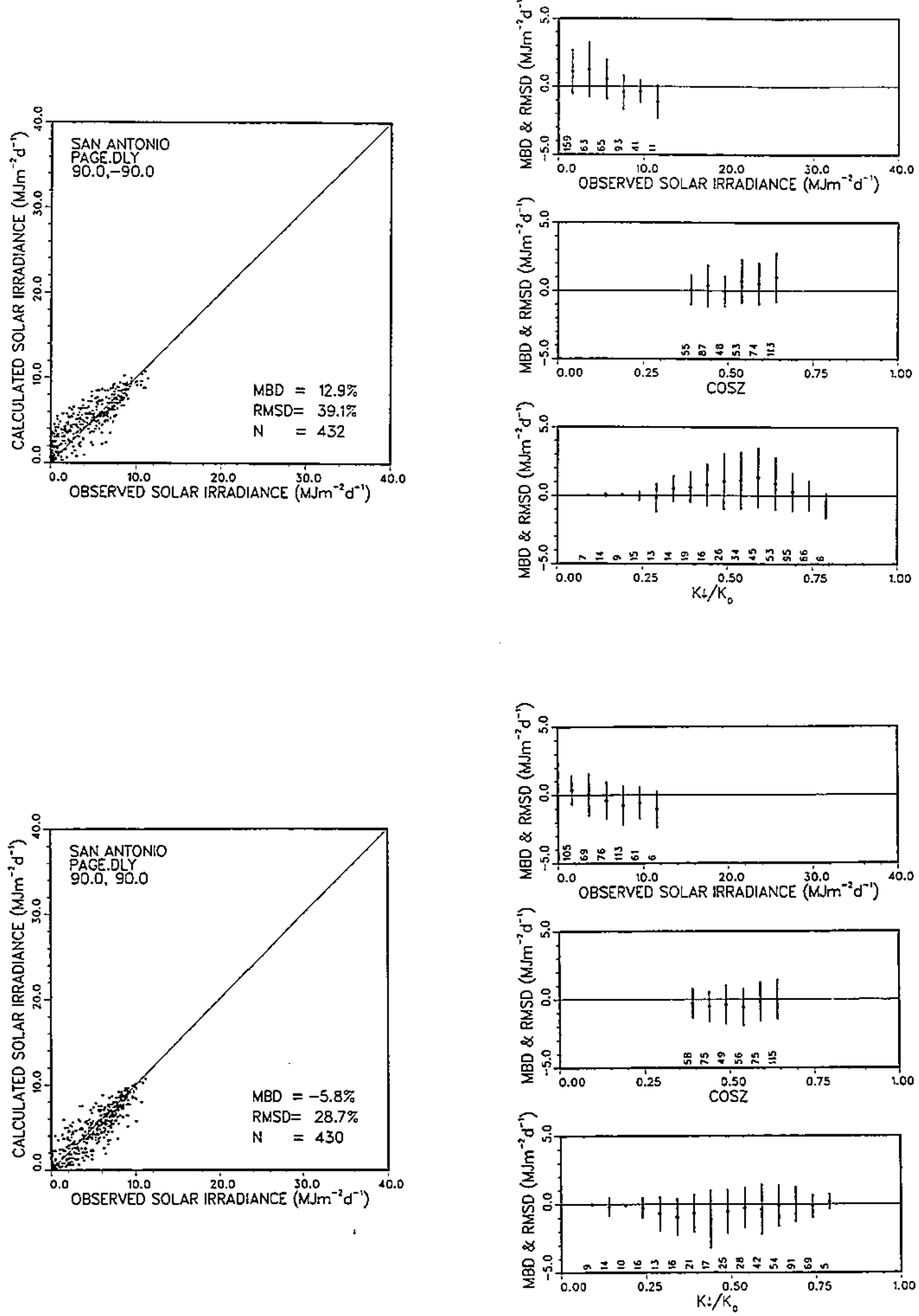


Figure 6f. As for Fig. 6b but for San Antonio.

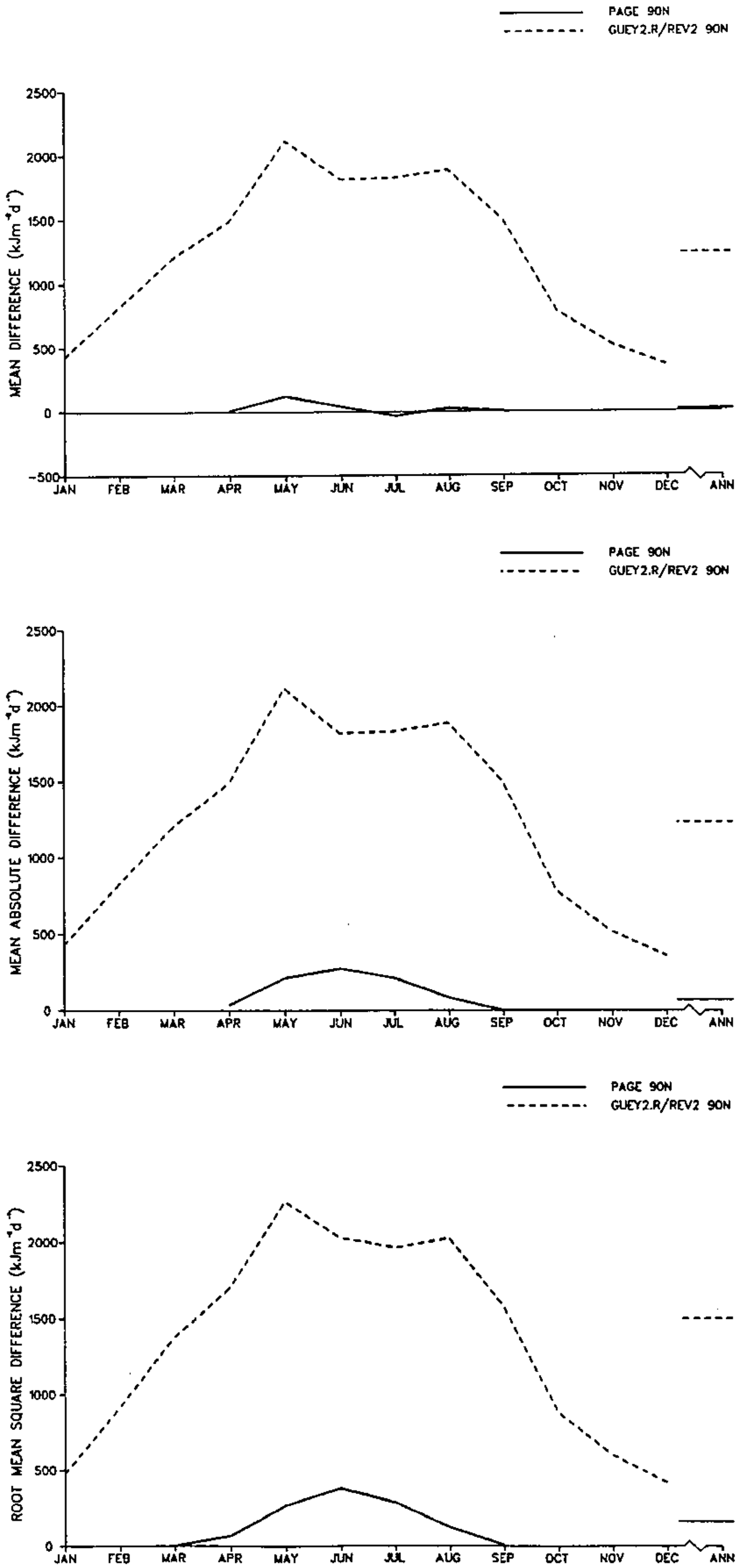


Figure 7a. Monthly and total period values of the validation statistics for the Perez 2 model for a vertical north-facing surface at Albany. Data are presented for both the Page (direct irradiance) and Guey 2.R/Rev 2 (total irradiance) models.

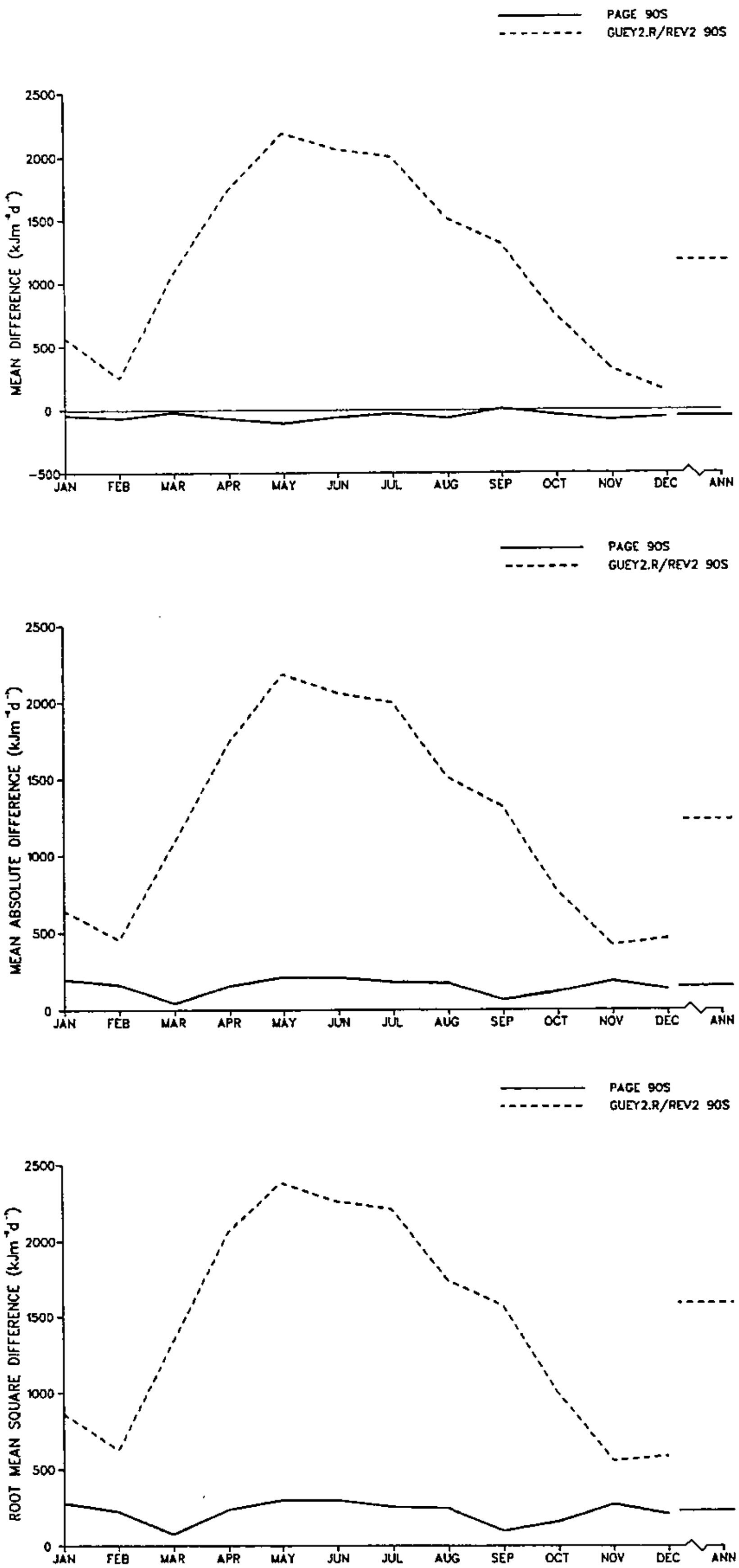


Figure 7b. As for Fig. 7a but for a vertical south-facing surface.

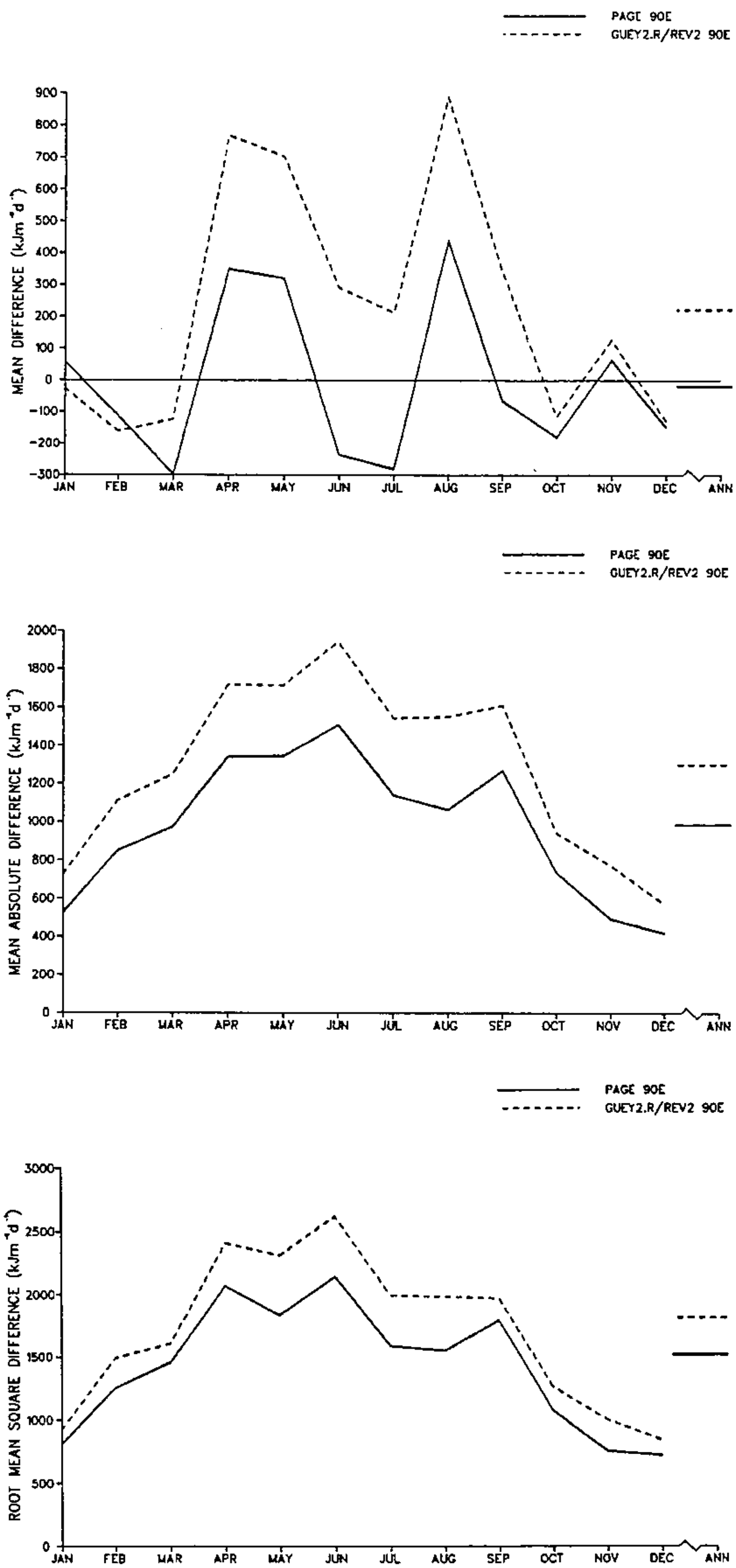


Figure 7c. As for Fig. 7a but for a vertical east-facing surface.

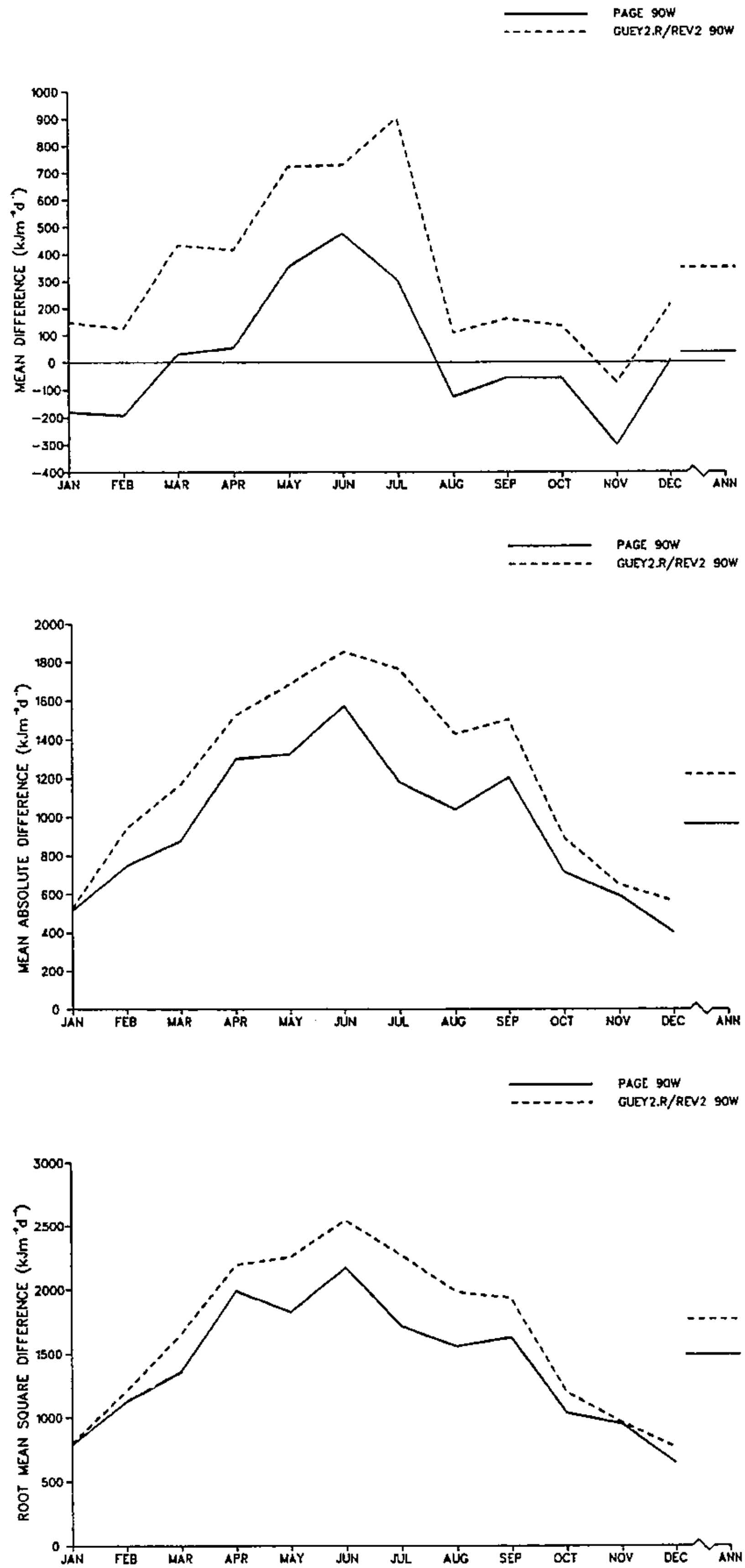


Figure 7d. As for Fig. 7a but for a vertical west-facing surface.

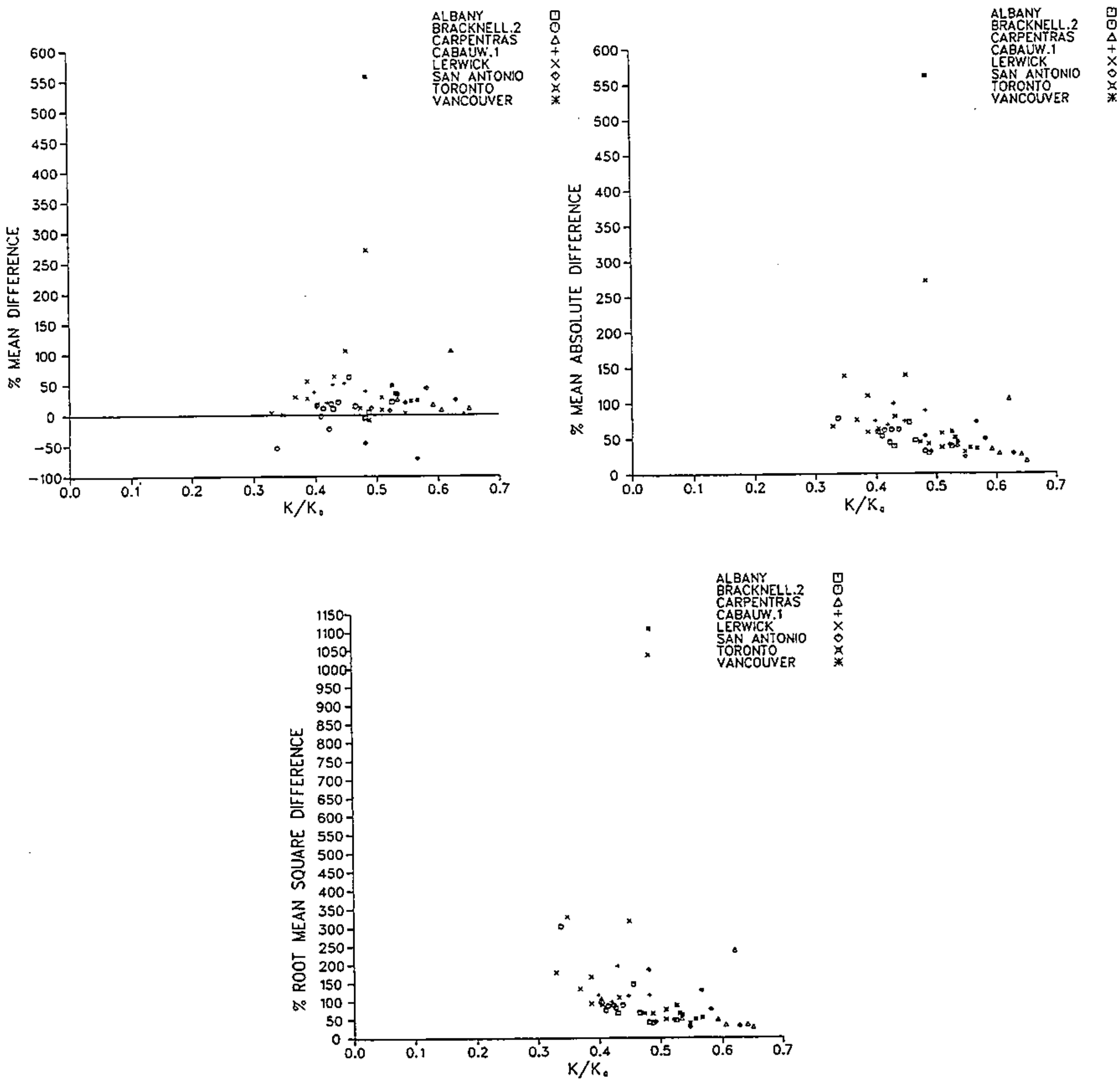


Figure 8a. The association between the overall monthly validation statistics and the clearness index ($K\downarrow/K_0$) for seven selected locations. Values are based on daily calculations using the Page model and are presented for a vertical surface facing north.

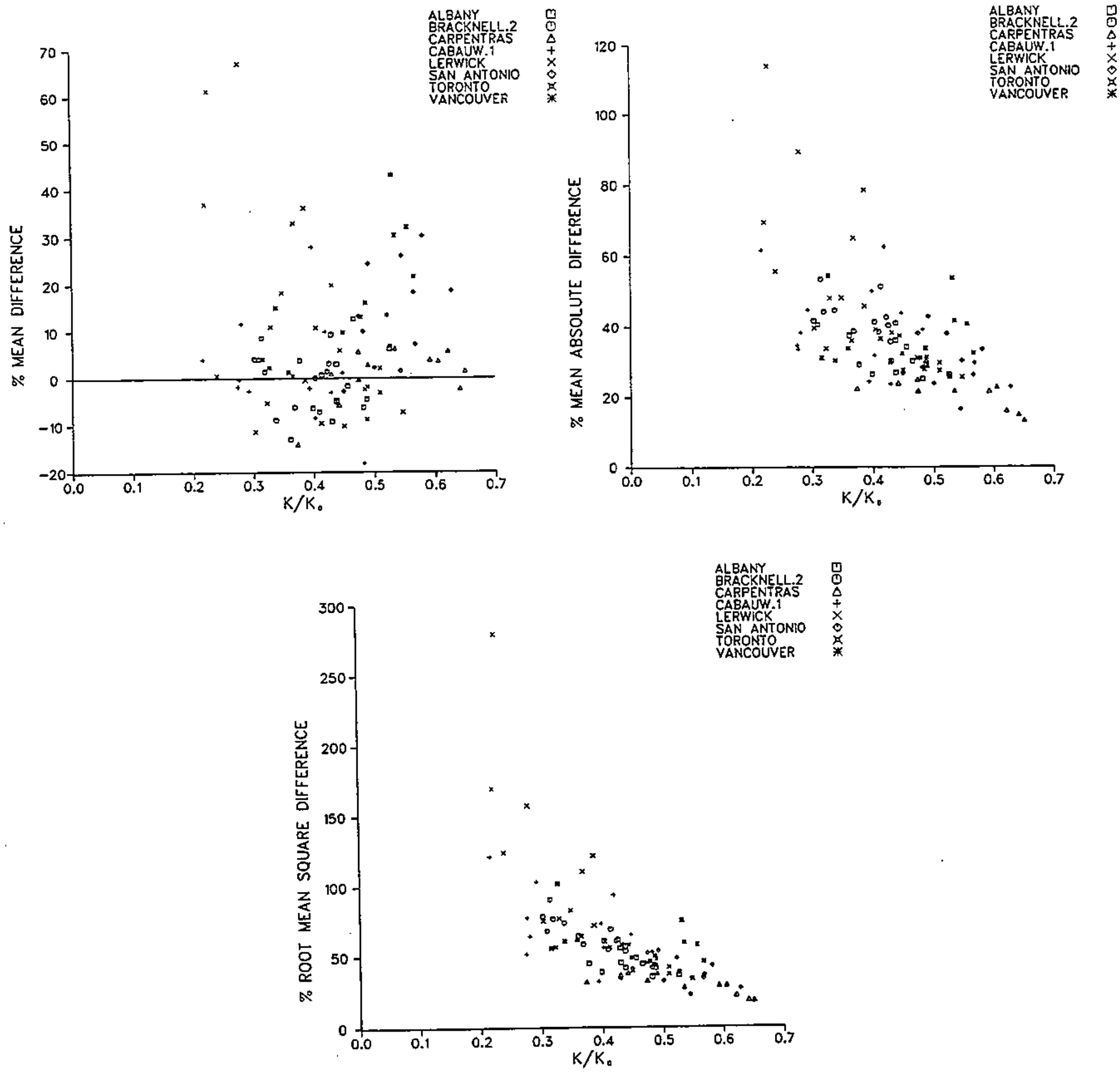


Figure 8b. As for Fig. 8a but for a vertical surface facing south.

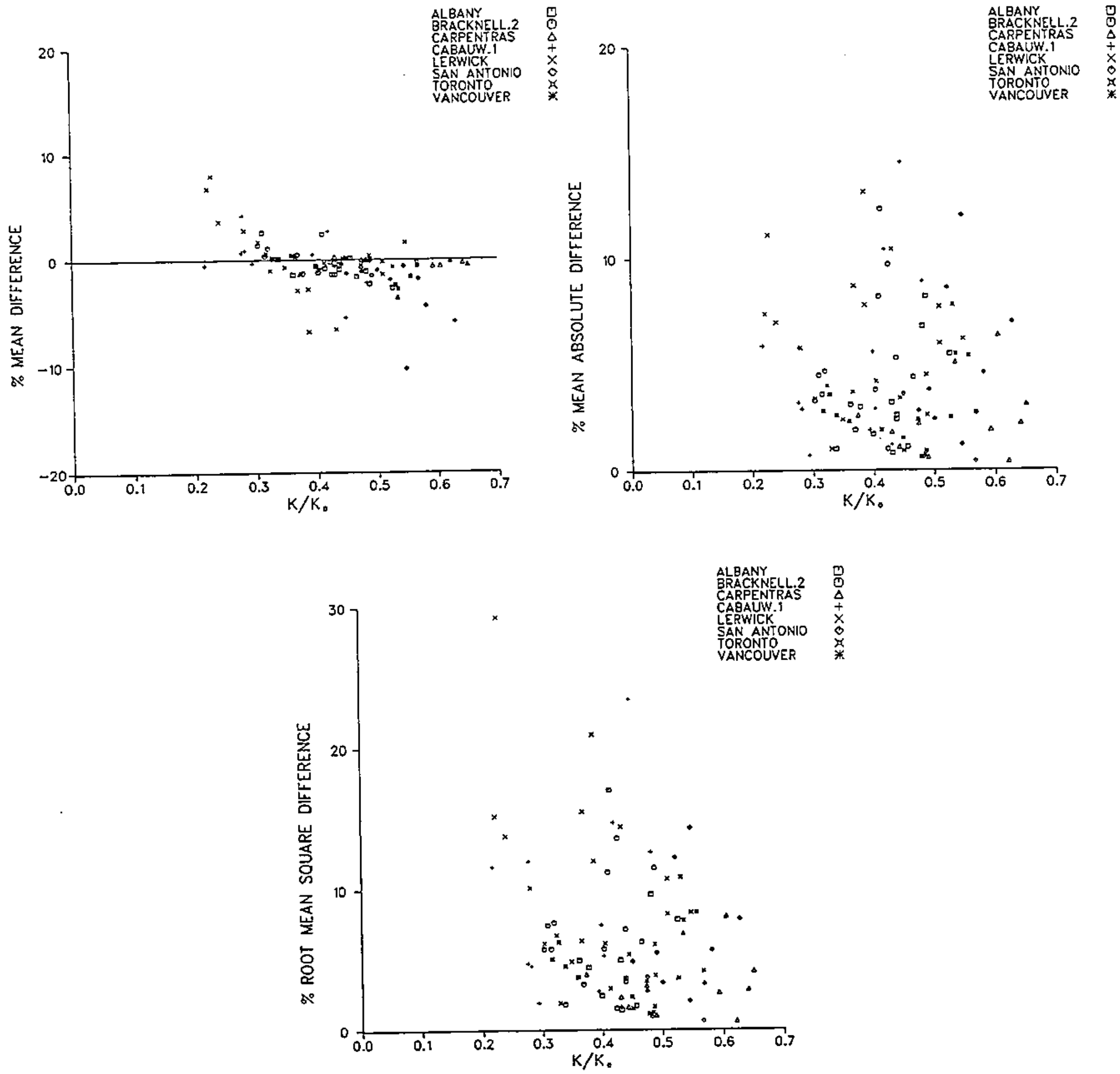


Figure 8c. As for Fig. 8a but for a vertical surface facing east.

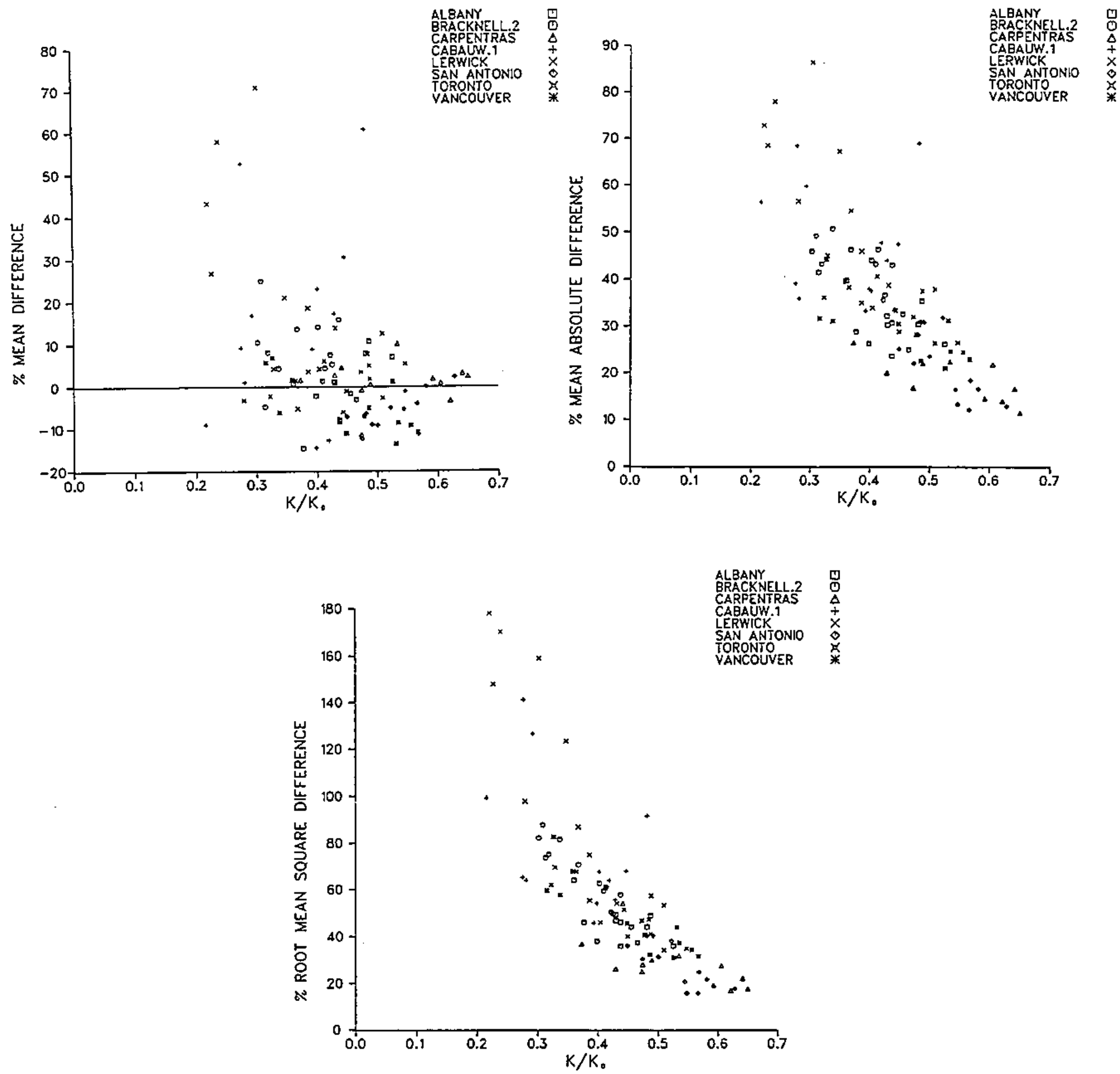


Figure 8d. As for Fig. 8a but for a vertical surface facing west.

8.3.1.3 Conclusions

The validation results presented here support a recommendation for the use of the direct irradiance algorithm developed by Page. This is an efficient model now that it has been integrated thereby avoiding the need to make iterative calculations at small time steps during the day.

8.3.2 Diffuse Models

8.3.2.1 Model Selection

Table 10 presents validation results for the six daily diffuse irradiance models. It is apparent that, apart from the Isotropic model, all have a similar ability to estimate the diffuse irradiance using individual daily data. Similar conclusions are valid for the long-term mean data (Table 11). Consequently the ranking data are somewhat inconclusive although in general and for poleward-facing slopes in particular the Guey2.P and Guey2.R model have the best performances.

8.3.2.2 Model Performance

No graphical analyses of the validation statistics for the daily diffuse irradiance models were undertaken since the characteristics of the model will become apparent when the total irradiance models are assessed.

8.3.2.3 Conclusions

There is very little to distinguish between the Guey2 variants, although the data presented in Tables 10 and 11 would tend to suggest the selection of Guey2.P or Guey2.R over the other options. Certainly the Isotropic algorithm cannot be recommended.

Table 10. Validation statistics and rankings for six daily diffuse irradiance models. Results based on daily diffuse irradiance data (Units: kJ m^{-2} day^{-1}).

ALBANY

SLOPE	ISOTROPIC		GUEY1		GUEY2.K		GUEY2.R		GUEY2.P		GUEY2.D	
	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD
33S	475	630	250	335	234	325	232	322	238	328	240	332
43S	543	726	272	377	256	365	260	364	261	367	263	370
53S	566	732	414	521	397	486	413	507	395	486	396	487
90N	1738	2022	1275	1579	1273	1550	1265	1538	1267	1542	1270	1547
90E	914	1157	1007	1289	760	978	703	915	735	955	746	967
90S	1048	1295	1221	1531	1206	1490	1205	1496	1196	1484	1198	1486
90W	975	1142	1079	1308	825	988	765	922	798	962	810	975
All	894	1187	788	1117	707	1002	692	984	699	993	703	998
Rank.1	6	6	5	5	4	4	1	1	2	2	3	3
Rank.1	5	5	6	6	4	3	1	1	2	2	3	4

BRACKNELL.2

SLOPE	ISOTROPIC		GUEY1		GUEY2.K		GUEY2.R		GUEY2.P		GUEY2.D	
	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD
90N	1696	2044	1185	1502	1185	1477	1177	1467	1178	1469	1180	1472
90E	978	1241	934	1236	749	977	710	936	731	963	743	977
90S	990	1236	1011	1325	1004	1287	1001	1293	987	1273	984	1270
90W	1098	1383	1062	1411	860	1124	821	1079	844	1110	857	1127
51.5S	633	864	388	546	382	520	392	538	379	522	377	519
All	1079	1407	916	1251	836	1125	820	1109	824	1114	828	1120
Rank.1	6	6	5	5	4	4	1	1	2	2	3	3
Rank.2	6	5	5	6	4	4	3	1=	1	1=	2	3

LERWICK

SLOPE	ISOTROPIC		GUEY1		GUEY2.K		GUEY2.R		GUEY2.P		GUEY2.D	
	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD
90N	1311	1864	927	1399	923	1364	912	1346	913	1347	915	1352
90E	650	1008	613	1000	500	796	472	760	481	775	491	790
90S	677	965	552	875	530	816	532	827	525	816	521	811
90W	669	986	649	1008	524	792	497	755	507	770	517	787
60.1S	742	1097	463	779	449	749	458	762	463	769	467	774
All	810	1233	641	1034	585	933	574	919	578	924	582	930
Rank.1	6	6	5	5	4	4	1	1	2	2	3	3
Rank.2	6	6	5	5	4	4	1	1	2	2	3	3

LULEA

SLOPE	ISOTROPIC MAD	ISOTROPIC RMSD	GUEY1 MAD	GUEY1 RMSD	GUEY2.K MAD	GUEY2.K RMSD	GUEY2.R MAD	GUEY2.R RMSD	GUEY2.P MAD	GUEY2.P RMSD	GUEY2.D MAD	GUEY2.D RMSD
90S	545	795	481	747	441	657	455	689	448	675	439	660
60S	653	964	311	468	293	427	305	450	302	447	300	444
30S	479	714	207	339	203	339	207	340	208	343	212	353
All	559	831	333	545	312	493	322	514	319	508	317	502
Rank.1	6	6	5	5	1	1	4	4	3	3	2	2
Rank.2	6	6	5	4=	1	1	3=	4=	3=	3	2	2

NORRKOPING

SLOPE	ISOTROPIC MAD	ISOTROPIC RMSD	GUEY1 MAD	GUEY1 RMSD	GUEY2.K MAD	GUEY2.K RMSD	GUEY2.R MAD	GUEY2.R RMSD	GUEY2.P MAD	GUEY2.P RMSD	GUEY2.D MAD	GUEY2.D RMSD
60S	518	742	401	549	366	493	388	522	379	510	376	506
Rank.1	6	6	5	5	1	1	4	4	3	3	2	2
Rank.2	6	6	5	5	1	1	4	4	3	3	2	2

SAN ANTONIO

SLOPE	ISOTROPIC MAD	ISOTROPIC RMSD	GUEY1 MAD	GUEY1 RMSD	GUEY2.K MAD	GUEY2.K RMSD	GUEY2.R MAD	GUEY2.R RMSD	GUEY2.P MAD	GUEY2.P RMSD	GUEY2.D MAD	GUEY2.D RMSD
20S	434	560	209	269	191	255	198	259	193	257	193	258
30S	567	730	236	293	218	281	222	282	219	282	220	284
40S	729	902	296	411	279	378	291	393	283	383	283	383
90N	1551	1734	1099	1305	1110	1300	1100	1283	1104	1291	1108	1297
90E	917	1160	1113	1349	782	995	715	932	759	980	768	987
90S	1177	1494	1105	1424	1096	1401	1086	1397	1088	1396	1091	1398
90W	877	1133	1063	1341	774	1005	707	933	749	982	756	988
All	893	1167	732	1047	636	921	617	897	628	913	631	917
Rank.1	6	6	5	5	4	4	1	1	2	2	3	3
Rank.2	6	6	5	5	3=	3	2	2	1	1	3=	4

CATEGORY A

SLOPE	ISOTROPIC MAD	ISOTROPIC RMSD	GUEY1 MAD	GUEY1 RMSD	GUEY2.K MAD	GUEY2.K RMSD	GUEY2.R MAD	GUEY2.R RMSD	GUEY2.P MAD	GUEY2.P RMSD	GUEY2.D MAD	GUEY2.D RMSD
All	863	1188	708	1048	636	938	625	923	630	930	633	935
Rank.1	6	6	5	5	4	4	1	1	2	2	3	3
Rank.2	6	6	5	5	4	3	2	2	1	1	3	4
Equat.	674	937	489	784	472	753	478	761	473	754	473	754
Rank.1	6	6	5	5	1	1	4	4	3	3	2	2
Rank.2	6	6	5	5	1	1	4	4	2	2	3	3
Other	1115	1457	1001	1321	855	1138	820	1103	839	1123	847	1132
Rank.1	6	6	5	5	4	4	1	1	2	2	3	3
Rank.2	6	5=	5	5=	4	4	1	1	2	2	3	3

CABAUW.1

SLOPE	ISOTROPIC MAD	ISOTROPIC RMSD	GUEY1 MAD	GUEY1 RMSD	GUEY2.K MAD	GUEY2.K RMSD
90N	542	733	217	327	208	318
90E	500	650	343	494	492	695
90S	864	1214	446	614	452	615
90W	572	823	461	680	596	891
45E	349	494	296	451	351	522
45SE	806	1109	540	737	580	795
45S	912	1272	558	742	553	747
45SW	859	1197	598	805	633	860
45W	415	602	371	550	430	645
67.5S	990	1395	567	774	573	780
All	681	997	440	635	487	706
Rank.1	6	6	1	1	2	3
Rank.2	6	6	1	1	2	3

SLOPE	GUEY2.R MAD	GUEY2.R RMSD	GUEY2.P MAD	GUEY2.P RMSD	GUEY2.D MAD	GUEY2.D RMSD
90N	208	317	208	317	208	317
90E	507	721	490	696	480	682
90S	454	620	466	631	468	633
90W	627	928	609	902	598	888
45E	362	537	351	520	341	508
45SE	584	800	586	803	581	797
45S	544	735	562	755	568	763
45SW	637	865	640	867	635	861
45W	448	669	435	649	424	633
67.5S	568	777	587	795	592	800
All	494	714	487	705	496	719
Rank.1	4	4	3	2	5	5
Rank.2	4	5	3	2	5	4

CARPENTRAS

SLOPE	ISOTROPIC MAD	ISOTROPIC RMSD	GUEY1 MAD	GUEY1 RMSD	GUEY2.K MAD	GUEY2.K RMSD
45S	1039	1295	422	531	402	522
90N	2177	2454	1742	2030	1714	1976
90E	1007	1207	1394	1631	969	1155
90S	1256	1445	1300	1621	1254	1551
90W	947	1200	1327	1589	906	1119
All	1285	1593	1237	1563	1049	1354
Rank.1	6	6	5	5	4	4
Rank.2	5	5	6	6	4	3=

SLOPE	GUEY2.R MAD	GUEY2.R RMSD	GUEY2.P MAD	GUEY2.P RMSD	GUEY2.D MAD	GUEY2.D RMSD
45S	424	532	412	528	412	530
90N	1701	1959	1705	1964	1710	1972
90E	882	1058	934	1117	954	1137
90S	1262	1571	1248	1552	1250	1552
90W	820	1029	871	1087	891	1105
All	1018	1324	1034	1340	1043	1348
Rank.1	1	1	2	2	3	3
Rank.2	2=	2	1	1	2=	3=

GOLDEN

SLOPE	ISOTROPIC MAD	ISOTROPIC RMSD	GUEY1 MAD	GUEY1 RMSD	GUEY2.K MAD	GUEY2.K RMSD
40S	715	917	462	611	447	593
90S	889	1176	433	565	407	545
All	802	1054	448	588	427	570
Rank.1	6	6	5	5	1	1
Rank.2	6	6	5	4=	2=	1

SLOPE	GUEY2.R MAD	GUEY2.R RMSD	GUEY2.P MAD	GUEY2.P RMSD	GUEY2.D MAD	GUEY2.D RMSD
40S	461	612	452	601	450	598
90S	412	549	405	545	405	545
All	437	581	429	574	428	572
Rank.1	4	4	3	3	2	2
Rank.2	4	4=	2=	3	1	2

TORONTO

SLOPE	ISOTROPIC MAD	ISOTROPIC RMSD	GUEY1 MAD	GUEY1 RMSD	GUEY2.K MAD	GUEY2.K RMSD	GUEY2.R MAD	GUEY2.R RMSD	GUEY2.P MAD	GUEY2.P RMSD	GUEY2.D MAD	GUEY2.D RMSD
30S	523	683	453	627	452	607	470	637	453	611	450	607
90N	585	733	324	450	326	455	328	459	328	458	326	456
90E	493	629	341	477	404	542	435	579	412	550	404	542
90S	832	1114	325	461	312	444	316	448	313	446	313	447
60S	1486	1889	884	1095	899	1124	888	1106	905	1128	907	1130
90W	627	790	385	528	578	758	625	820	595	782	583	768
90SE	829	1029	386	517	489	632	512	658	493	636	486	627
90SW	757	982	356	488	401	533	423	557	406	539	398	529
All	767	1052	432	614	483	670	500	688	488	677	483	672
Rank.1	6	6	1	1	2	2	5	5	4	4	3	3
Rank.2	6	6	1	1	2	2	5	5	4	4	3	3

TRAPPES

SLOPE	ISOTROPIC MAD	ISOTROPIC RMSD	GUEY1 MAD	GUEY1 RMSD	GUEY2.K MAD	GUEY2.K RMSD	GUEY2.R MAD	GUEY2.R RMSD	GUEY2.P MAD	GUEY2.P RMSD	GUEY2.D MAD	GUEY2.D RMSD
45S	779	1029	439	564	410	548	415	554	426	563	429	566
90N	2029	2348	1492	1812	1479	1770	1469	1757	1471	1761	1474	1766
90E	795	1045	816	1116	582	791	537	740	563	774	573	788
90S	1120	1301	918	1172	905	1124	900	1129	885	1108	884	1107
90W	1154	1431	1238	1593	937	1204	880	1138	915	1184	931	1202
All	1175	1510	981	1323	863	1164	840	1141	852	1153	858	1160
Rank.1	6	6	5	5	4	4	1	1	2	2	3	3
Rank.2	6	6	5	5	4	4	1	1	2	2	3	3

VANCOUVER

SLOPE	ISOTROPIC MAD	ISOTROPIC RMSD	GUEY1 MAD	GUEY1 RMSD	GUEY2.K MAD	GUEY2.K RMSD	GUEY2.R MAD	GUEY2.R RMSD	GUEY2.P MAD	GUEY2.P RMSD	GUEY2.D MAD	GUEY2.D RMSD
30S	718	949	334	462	327	453	323	453	329	458	332	461
60S	934	1285	446	608	411	572	434	594	424	585	423	585
90S	879	1218	408	553	369	511	386	528	377	521	376	520
90E	591	830	638	867	431	607	414	582	420	596	424	604
90W	441	567	302	458	349	489	393	539	368	509	356	495
90N	921	1162	488	686	476	657	468	646	469	648	472	652
60N	1290	1574	686	943	717	962	670	897	696	937	715	965
All	825	1126	472	677	440	628	441	620	440	625	443	631
Rank.1	6	6	5	5	1	3	3	1	2	2	4	4
Rank.2	6	6	5	5	2	1=	1	1=	3	3	4	4

CATEGORY B

SLOPE	ISOTROPIC		GUEY1		GUEY2.K		GUEY2.R		GUEY2.P		GUEY2.D	
	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD
All	882	1208	625	929	601	869	600	863	599	864	602	871
Rank.1	6	6	5	5	3	3	2	1	1	2	4	4
Rank.1	6	6	5	4	1	1	4	5	2	2	3	3
Equat.	905	1209	541	768	541	765	551	775	546	770	542	766
Rank.1	6	6	1	3	2	1	5	5	4	4	3	2
Rank.2	6	6	4	4	1	1	5	5	3	3	2	2
Other	858	1207	715	1073	664	966	651	946	655	956	665	968
Rank.1	6	6	5	5	3	3	1	1	2	2	4	4
Rank.2	6	6	3	3	4	4=	1	2	2	1	5	4=

ALL LOCATIONS

SLOPE	ISOTROPIC		GUEY1		GUEY2.K		GUEY2.R		GUEY2.P		GUEY2.D	
	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD
All	873	1199	661	982	616	899	610	889	612	893	615	899
Rank.1	6	6	5	5	4	4	1	1	2	2	3	3
Rank.2	6	6	5	5	2	2	3	3	1	1	4	4
Equat.	799	1093	517	776	509	759	517	769	512	763	510	761
Rank.1	6	6	4	5	1	1	5	4	3	3	2	2
Rank.2	6	6	5	5	1	1	4	4	3	3	2	2
Other	960	1312	829	1178	740	1038	719	1012	729	1026	738	1037
Rank.1	6	6	5	5	4	4	1	1	2	2	3	3
Rank.2	6	6	5	5	4	4	1	1	2	2	3	3

Table 11. Validation statistics and rankings for six daily diffuse irradiance models. Results based on long-term monthly mean daily diffuse irradiance data (Units: kJ m^{-2} day^{-1}).

ALBANY

SLOPE	ISOTROPIC MAD	ISOTROPIC RMSD	GUEY1 MAD	GUEY1 RMSD	GUEY2.K MAD	GUEY2.K RMSD	GUEY2.R MAD	GUEY2.R RMSD	GUEY2.P MAD	GUEY2.P RMSD	GUEY2.D MAD	GUEY2.D RMSD
33S	435	479	124	170	116	170	121	167	117	168	117	170
43S	472	537	165	194	139	173	156	186	142	174	142	175
53S	440	498	421	479	372	418	406	457	377	423	374	421
90N	1754	1936	1324	1519	1312	1490	1306	1482	1308	1485	1311	1489
90E	877	1028	1073	1222	767	893	711	831	750	876	764	889
90S	974	1211	1299	1471	1257	1417	1271	1434	1258	1417	1257	1417
90W	937	1028	1133	1228	827	897	771	836	810	879	824	894
All	841	1075	791	1053	684	931	677	919	680	925	684	930
Rank.1	6	6	5	5	4	4	1	1	2	2	3	3
Rank.2	5	5	6	6	1=	3=	4	2	1=	1	1=	3=

BRACKNELL.2

SLOPE	ISOTROPIC MAD	ISOTROPIC RMSD	GUEY1 MAD	GUEY1 RMSD	GUEY2.K MAD	GUEY2.K RMSD	GUEY2.R MAD	GUEY2.R RMSD	GUEY2.P MAD	GUEY2.P RMSD	GUEY2.D MAD	GUEY2.D RMSD
90N	1687	1936	1199	1399	1180	1369	1179	1367	1179	1368	1181	1370
90E	946	1125	926	1089	684	814	672	799	695	827	708	841
90S	829	1076	932	1173	901	1126	907	1133	891	1113	887	1110
90W	1089	1303	1069	1265	827	991	816	976	839	1003	852	1017
51.4S	489	633	436	577	424	565	427	571	424	561	425	558
All	1008	1286	912	1136	803	1011	800	1007	806	1011	811	1016
Rank.1	6	6	5	5	2	2	1	1	3	3	4	4
Rank.2	5	5	6	6	2=	3	2=	1	1	2	4	4

LERWICK

SLOPE	ISOTROPIC MAD	ISOTROPIC RMSD	GUEY1 MAD	GUEY1 RMSD	GUEY2.K MAD	GUEY2.K RMSD	GUEY2.R MAD	GUEY2.R RMSD	GUEY2.P MAD	GUEY2.P RMSD	GUEY2.D MAD	GUEY2.D RMSD
90N	1508	1882	1089	1385	1059	1336	1058	1334	1059	1336	1060	1338
90E	723	967	664	901	472	658	472	656	485	673	498	689
90S	540	616	482	578	441	521	444	522	435	508	433	503
90W	742	955	683	890	488	644	488	643	501	660	514	677
60.1S	627	693	340	397	362	401	365	408	383	422	394	433
All	828	1118	652	896	564	783	565	783	573	789	580	795
Rank.1	6	6	5	5	1	2	2	1	3	3	4	4
Rank.2	6	6	5	5	1	2	2	1	3	3	4	4

SAN ANTONIO

SLOPE	ISOTROPIC MAD	ISOTROPIC RMSD	GUEY1 MAD	GUEY1 RMSD	GUEY2.K MAD	GUEY2.K RMSD	GUEY2.R MAD	GUEY2.R RMSD	GUEY2.P MAD	GUEY2.P RMSD	GUEY2.D MAD	GUEY2.D RMSD
20S	386	471	232	270	221	273	225	266	220	269	221	270
30S	539	612	252	323	225	302	223	297	224	301	225	303
40S	654	764	430	563	378	507	392	520	380	508	380	509
90N	1675	1762	1254	1368	1255	1357	1237	1337	1245	1346	1251	1353
90E	902	1027	1228	1310	820	919	729	841	792	897	804	908
90S	1017	1276	1383	1498	1360	1469	1349	1461	1351	1462	1356	1466
90W	814	974	1139	1279	731	875	644	788	703	851	715	860
All	855	1063	845	1066	713	928	686	901	702	918	707	923
Rank.1	6	5	5	6	4	4	1	1	2	2	3	3
Rank.2	5	5	6	6	4	4	1=	1	1=	2	4	4

CATEGORY A

SLOPE	ISOTROPIC MAD	ISOTROPIC RMSD	GUEY1 MAD	GUEY1 RMSD	GUEY2.K MAD	GUEY2.K RMSD	GUEY2.R MAD	GUEY2.R RMSD	GUEY2.P MAD	GUEY2.P RMSD	GUEY2.D MAD	GUEY2.D RMSD
All	877	1128	803	1045	692	919	682	907	690	915	696	921
Rank.1	6	6	5	5	3	3	1	1	2	2	4	4
Rank.2	6	6	5	5	3	3	1=	1	1=	2	4	4
Equat.	617	788	541	785	516	755	524	760	517	752	518	753
Rank.1	6	6	5	5	1	3	4	4	2	1	3	2
Rank.2	5	6	6	5	1	2=	4	4	2	1	3	2=
Other	1138	1387	1065	1252	869	1058	840	1032	864	1054	874	1062
Rank.1	6	6	5	5	3	3	1	1	2	2	4	4
Rank.2	6	6	5	5	3	3	1	1	2	2	4	4

CABAUW.1

SLOPE	ISOTROPIC MAD	ISOTROPIC RMSD	GUEY1 MAD	GUEY1 RMSD	GUEY2.K MAD	GUEY2.K RMSD	GUEY2.R MAD	GUEY2.R RMSD	GUEY2.P MAD	GUEY2.P RMSD	GUEY2.D MAD	GUEY2.D RMSD
90N	562	641	99	139	91	130	91	130	91	130	89	130
90E	203	259	199	255	420	504	428	516	406	491	393	477
90S	717	874	397	440	425	460	422	455	438	469	442	473
90W	343	427	382	430	622	692	630	704	608	679	595	664
45E	121	142	111	141	218	268	228	282	208	260	192	242
45SE	724	801	466	506	535	579	536	581	540	585	534	580
45S	889	983	516	553	533	570	527	563	551	585	559	593
45SW	837	916	578	616	647	686	648	688	652	692	647	686
45W	185	250	187	249	343	398	353	412	331	389	313	370
67.5S	907	1041	528	571	554	593	549	586	572	607	579	614
All	549	710	346	426	439	517	440	519	434	514	441	520
Rank.1	6	6	1	1	3	3	4	4	2	2	5	5
Rank.2	6	6	1	1	3	3	4=	4=	2	2	4=	4=

CARPENTRAS

SLOPE	ISOTROPIC MAD	ISOTROPIC RMSD	GUEY1 MAD	GUEY1 RMSD	GUEY2.K MAD	GUEY2.K RMSD	GUEY2.R MAD	GUEY2.R RMSD	GUEY2.P MAD	GUEY2.P RMSD	GUEY2.D MAD	GUEY2.D RMSD
45S	1039	1295	422	531	402	522	424	532	412	528	406	463
90N	2177	2454	1742	2030	1714	1976	1701	1959	1705	1964	1678	1882
90E	1007	1207	1394	1631	969	1155	882	1058	934	1117	917	1063
90S	1256	1445	1300	1621	1254	1551	1262	1571	1248	1552	1229	1548
90W	947	1200	1327	1589	906	1119	820	1029	871	1087	844	1010
All	1285	1593	1237	1563	1049	1354	1018	1324	1034	1340	1015	1289
Rank.1	6	6	5	5	4	4	2	2	3	3	1	1
Rank.2	5	5	6	6	4	4	2=	2	2=	3	1	1

TORONTO

SLOPE	ISOTROPIC MAD	ISOTROPIC RMSD	GUEY1 MAD	GUEY1 RMSD	GUEY2.K MAD	GUEY2.K RMSD	GUEY2.R MAD	GUEY2.R RMSD	GUEY2.P MAD	GUEY2.P RMSD	GUEY2.D MAD	GUEY2.D RMSD
30S	422	460	455	577	417	532	452	579	424	541	418	535
90N	554	593	176	197	150	187	144	185	146	186	149	186
90E	281	356	446	532	254	306	258	302	256	305	256	309
90S	605	712	220	265	175	219	191	235	176	220	175	219
60S	1299	1351	548	600	609	661	572	623	604	656	608	660
90W	271	323	260	330	321	397	355	444	328	410	323	400
90SE	454	568	422	519	391	469	403	471	394	469	394	472
90SW	426	587	473	543	381	443	389	437	384	441	383	444
All	539	689	375	469	337	429	346	435	339	430	338	430
Rank.1	6	6	5	5	1	1	4	4	3	3	2	2
Rank.2	6	6	5	5	1	1=	4	3	3	1=	2	4

TRAPPES

SLOPE	ISOTROPIC MAD	ISOTROPIC RMSD	GUEY1 MAD	GUEY1 RMSD	GUEY2.K MAD	GUEY2.K RMSD	GUEY2.R MAD	GUEY2.R RMSD	GUEY2.P MAD	GUEY2.P RMSD	GUEY2.D MAD	GUEY2.D RMSD
45S	642	708	341	410	355	418	349	414	362	421	363	422
90N	1620	1875	1141	1349	1125	1324	1124	1322	1125	1324	1127	1326
90E	562	670	582	684	406	454	392	436	410	458	417	468
90S	821	942	856	1030	824	987	832	998	816	978	814	975
90W	873	1116	874	1116	644	838	628	818	650	847	660	861
All	904	1149	759	976	671	873	665	869	673	873	676	877
Rank.1	6	6	5	5	2	2	1	1	3	3	4	4
Rank.2	6	5=	5	5=	2	2	1	1	3	3	4	4

VANCOUVER

SLOPE	ISOTROPIC MAD	ISOTROPIC RMSD	GUEY1 MAD	GUEY1 RMSD	GUEY2.K MAD	GUEY2.K RMSD	GUEY2.R MAD	GUEY2.R RMSD	GUEY2.P MAD	GUEY2.P RMSD	GUEY2.D MAD	GUEY2.D RMSD
30S	644	685	185	220	176	221	188	224	174	219	174	221
60S	759	871	397	436	341	363	377	409	348	372	344	367
90S	673	788	398	437	337	363	362	392	342	368	338	365
90E	581	805	868	1098	535	737	484	673	517	713	532	730
90W	290	357	355	528	249	319	247	321	249	318	248	315
90N	893	1004	467	572	439	521	432	512	434	515	438	520
60N	1342	1502	737	894	769	938	702	831	735	885	759	922
All	740	917	487	659	407	549	399	518	400	532	405	544
Rank.1	6	6	5	5	4	4	1	1	2	2	3	3
Rank.2	6	6	5	5	4	4	2=	3	1	1	2=	2

CATEGORY B

SLOPE	ISOTROPIC MAD	ISOTROPIC RMSD	GUEY1 MAD	GUEY1 RMSD	GUEY2.K MAD	GUEY2.K RMSD	GUEY2.R MAD	GUEY2.R RMSD	GUEY2.P MAD	GUEY2.P RMSD	GUEY2.D MAD	GUEY2.D RMSD
All	741	986	567	821	529	741	525	729	525	735	526	725
Rank.1	6	6	5	5	4	4	1	2	2	3	3	1
Rank.2	6	6	5	5	2=	2	4	3	1	1	2=	4
Equat.	771	924	500	658	492	642	503	652	497	646	490	638
Rank.1	6	6	4	5	2	2	5	4	3	3	1	1
Rank.2	6	6	4	4	1=	1	5	5	3	3	1=	2
Other	712	1041	630	950	565	824	545	796	552	810	560	799
Rank.1	6	6	5	5	4	4	1	1	2	3	3	2
Rank.2	6	6	5	5	3=	4	1	1	2	2	3=	3

ALL LOCATIONS

SLOPE	ISOTROPIC MAD	ISOTROPIC RMSD	GUEY1 MAD	GUEY1 RMSD	GUEY2.K MAD	GUEY2.K RMSD	GUEY2.R MAD	GUEY2.R RMSD	GUEY2.P MAD	GUEY2.P RMSD	GUEY2.D MAD	GUEY2.D RMSD
All	796	1046	663	919	596	818	589	806	592	813	595	810
Rank.1	6	6	5	5	4	4	1	1	2	3	3	2
Rank.2	6	6	5	5	2	3	3	1=	1	1=	4	4
Equat.	707	870	517	713	502	691	512	699	505	692	501	688
Rank.1	6	6	5	5	2	2	4	4	3	3	1	1
Rank.2	6	6	5	5	1	1	4	4	3	3	2	2
Other	882	1191	804	1081	687	924	663	898	677	915	685	913
Rank.1	6	6	5	5	4	4	1	1	2	3	3	2
Rank.2	6	6	5	5	3	3	1	1	2	2	4	4

8.3.3 Global Irradiance Models

8.3.3.1 Model Selection

The validation results for individual daily and long-term daily data are presented in Tables 12 and 13, respectively. Based on the results presented in Sections 8.3.1 and 8.3.2 one would predict that the most accurate hybrid model would be either Guey2.P/Page or Guey2.R/Rev2 unless cancellation of systematic errors in the component algorithms results in another hybrid being associated with smaller errors when the global irradiance is calculated.

Both models do receive high rankings. Although Guey2.R/Rev2 has a low ranking for equator-facing slopes, the differences between the two models for this orientation are typically small. However, the Guey2.R/Rev2 algorithm is decidedly superior for poleward-facing slopes.

Table 12. Validation statistics and rankings for six daily total irradiance models. Results based on daily total irradiance data (Units: kJ m^{-2} day^{-1}).

ALBANY

SLOPE	GUEYMARD.1 MAD	GUEYMARD.1 RMSD	GUEYMARD.2 MAD	GUEYMARD.2 RMSD	MCFAR MAD	MCFAR RMSD	GUEY2.D/DPD MAD	GUEY2.D/DPD RMSD	GUEY2.R/REV2 MAD	GUEY2.R/REV2 RMSD	GUEY2.P/PAGE MAD	GUEY2.P/PAGE RMSD
33S	331	459	380	510	593	756	297	409	278	375	275	377
43S	378	527	422	570	764	991	332	457	321	436	307	420
53S	488	635	472	627	956	1176	423	541	474	638	396	504
90N	1452	1884	1450	1850			1406	1761	1238	1501	1323	1628
90E	1724	2390	1524	2145	1599	2194	1397	2019	1298	1811	1337	1943
90S	1342	1640	1297	1590	2050	2392	1249	1550	1238	1598	1191	1489
90W	1877	2536	1674	2274	1657	2262	1479	2087	1218	1767	1366	1986
All	1085	1659	1031	1545	1270	1760	940	1444	866	1306	885	1371
Rank.1	5	5	4	4	6	6	3	3	1	1	2	2
Rank.2	5	5	4	4	6	6	3	3	2	2	1	1

BRACKNELL.2

SLOPE	GUEYMARD.1 MAD	GUEYMARD.1 RMSD	GUEYMARD.2 MAD	GUEYMARD.2 RMSD	MCFAR MAD	MCFAR RMSD	GUEY2.D/DPD MAD	GUEY2.D/DPD RMSD	GUEY2.R/REV2 MAD	GUEY2.R/REV2 RMSD	GUEY2.P/PAGE MAD	GUEY2.P/PAGE RMSD
90N	1240	1661	1238	1629			1264	1645	1147	1444	1194	1522
90E	1408	2065	1276	1869	1421	1959	1306	1890	1159	1682	1239	1799
90S	1098	1396	1067	1352	2384	2702	994	1284	1042	1371	987	1277
90W	1529	2197	1357	1939	1463	1992	1382	1952	1125	1604	1277	1815
51.4S	426	576	442	591	1226	1395	381	523	447	620	396	541
All	1140	1681	1076	1555	1624	2065	1065	1550	984	1397	1019	1468
Rank.1	5	5	4	4	6	6	3	3	1	1	2	2
Rank.2	5	5	4	4	6	6	3	3	2	2	1	1

LERWICK

SLOPE	GUEYMARD.1 MAD	GUEYMARD.1 RMSD	GUEYMARD.2 MAD	GUEYMARD.2 RMSD	MCFAR MAD	MCFAR RMSD	GUEY2.D/DPD MAD	GUEY2.D/DPD RMSD	GUEY2.R/REV2 MAD	GUEY2.R/REV2 RMSD	GUEY2.P/PAGE MAD	GUEY2.P/PAGE RMSD
90N	1053	1738	1047	1683			1060	1684	930	1409	967	1482
90E	1044	1938	951	1738	1051	1728	979	1763	869	1544	916	1638
90S	545	839	547	835	2064	2749	485	775	536	860	500	800
90W	1001	1792	899	1590	982	1550	926	1609	815	1378	858	1478
60.1S	496	798	556	874	1495	1990	539	876	517	839	528	856
All	828	1505	800	1403	1398	2056	798	1407	733	1242	754	1299
Rank.1	5	5	4	3	6	6	3	4	1	1	2	2
Rank.2	5	5	4	3	6	6	3	4	1	1	2	2

LULEA

SLOPE	GUEYMARD.1 MAD	GUEYMARD.1 RMSD	GUEYMARD.2 MAD	GUEYMARD.2 RMSD	MCFAR MAD	MCFAR RMSD	GUEY2.D/DPD MAD	GUEY2.D/DPD RMSD	GUEY2.R/REV2 MAD	GUEY2.R/REV2 RMSD	GUEY2.P/PAGE MAD	GUEY2.P/PAGE RMSD
90S	470	704	455	663	2527	3602	431	658	506	810	466	730
60S	344	558	387	601	2026	2878	361	593	386	625	360	588
30S	255	464	301	522	1123	1603	273	505	250	450	248	451
All	356	584	381	598	1892	2818	355	589	381	645	358	601
Rank.1	2	1	5	3	6	6	1	2	4	5	3	4
Rank.2	2=	1	5	4=	6	6	2=	2=	4	4=	1	2=

NORRKOPING

SLOPE	GUEYMARD.1 MAD	GUEYMARD.1 RMSD	GUEYMARD.2 MAD	GUEYMARD.2 RMSD	MCFAR MAD	MCFAR RMSD	GUEY2.D/DPD MAD	GUEY2.D/DPD RMSD	GUEY2.R/REV2 MAD	GUEY2.R/REV2 RMSD	GUEY2.P/PAGE MAD	GUEY2.P/PAGE RMSD
60S	492	704	496	701	2147	2586	491	677	553	782	500	687
Rank.1	2	4	3	3	6	6	1	1	5	5	4	2
Rank.2	2	4	3	3	6	6	1	1	5	5	4	2

SAN ANTONIO

SLOPE	GUEYMARD.1 MAD	GUEYMARD.1 RMSD	GUEYMARD.2 MAD	GUEYMARD.2 RMSD	MCFAR MAD	MCFAR RMSD	GUEY2.D/DPD MAD	GUEY2.D/DPD RMSD	GUEY2.R/REV2 MAD	GUEY2.R/REV2 RMSD	GUEY2.P/PAGE MAD	GUEY2.P/PAGE RMSD
20S	188	247	239	346	903	1142	195	258	268	339	211	279
30S	242	315	299	410	904	1108	235	303	310	394	244	322
40S	307	403	313	445	1368	1674	298	383	427	557	322	412
90N	1218	1511	1226	1495			1194	1432	1071	1240	1154	1367
90E	2274	2850	1937	2492	2227	2775	1712	2289	1485	1871	1666	2205
90S	1248	1514	1205	1476	1802	2346	1141	1442	1175	1484	1112	1402
90W	1751	2271	1526	2007	1632	2112	1285	1786	1325	1700	1291	1768
All	1033	1611	964	1471	1473	1958	866	1356	866	1237	857	1319
Rank.1	5	5	4	4	6	6	2	3	3	1	1	2
Rank.2	4	4	5	5	6	6	1	1	3	3	2	2

CATEGORY A

SLOPE	GUEYMARD.1 MAD	GUEYMARD.1 RMSD	GUEYMARD.2 MAD	GUEYMARD.2 RMSD	MCFAR MAD	MCFAR RMSD	GUEYMARD.2 DPD MAD	GUEYMARD.2 DPD RMSD	GUEYMARD.2 REV2 MAD	GUEYMARD.2 REV2 RMSD	GUEYMARD.2 PAGE MAD	GUEYMARD.2 PAGE RMSD
All	936	1517	892	1406	1515	2102	840	1348	800	1224	808	1283
Rank.1	5	5	4	4	6	6	3	3	1	1	2	2
Rank.2	5	5	4	4	6	6	3	3	2	2	1	1
Equat.	541	842	555	843	1521	2103	508	800	546	853	503	789
Rank.1	3	3	5	4	6	6	2	2	4	5	1	1
Rank.2	3	3	5	4=	6	6	2	2	4	4=	1	1
Other	1464	2103	1342	1914	1504	2100	1283	1840	1140	1590	1216	1735
Rank.1	5	6	4	4	6	5	3	3	1	1	2	2
Rank.1	6	6	4	4	5	5	3	3	1	1	2	2

CABAUW.1

SLOPE	GUEYMARD.1 MAD	GUEYMARD.1 RMSD	GUEYMARD.2 MAD	GUEYMARD.2 RMSD	MCFAR MAD	MCFAR RMSD	GUEY2.D/DPD MAD	GUEY2.D/DPD RMSD	GUEY2.R/REV2 MAD	GUEY2.R/REV2 RMSD	GUEY2.P/PAGE MAD	GUEY2.P/PAGE RMSD
90N	290	481	271	448			274	455	246	377	251	394
90E	909	1518	944	1592	1027	1564	893	1486	1030	1668	937	1535
90S	445	610	496	666	1105	1355	478	656	477	656	493	670
90W	907	1451	919	1490	958	1452	891	1407	990	1561	921	1446
45E	881	1477	894	1517	921	1522	864	1463	923	1540	883	1489
45SE	827	1264	888	1331	1060	1447	865	1316	908	1362	897	1351
45S	539	749	613	827	806	1097	594	815	556	765	591	807
45SW	782	1180	841	1249	975	1364	803	1212	845	1257	831	1244
45W	879	1434	888	1447	893	1435	866	1413	899	1452	876	1421
67.5S	555	771	623	838	1022	1335	614	839	586	812	620	845
All	701	1157	738	1205	974	1403	714	1163	746	1223	730	1184
Rank.1	1	1	4	4	6	6	2	2	5	5	3	3
Rank.2	1	1	4	4=	6	6	2	2	5	4=	3	3

CARPENTRAS

SLOPE	GUEYMARD.1 MAD	GUEYMARD.1 RMSD	GUEYMARD.2 MAD	GUEYMARD.2 RMSD	MCFAR MAD	MCFAR RMSD	GUEY2.D/DPD MAD	GUEY2.D/DPD RMSD	GUEY2.R/REV2 MAD	GUEY2.R/REV2 RMSD	GUEY2.P/PAGE MAD	GUEY2.P/PAGE RMSD
45S	385	510	434	562	1059	1460	414	531	582	704	449	564
90N	2070	2519	2044	2461			1937	2290	165	1914	1798	2093
90E	2216	2778	1829	2344	1673	2231	1498	2043	1053	1523	1313	1873
90S	1384	1625	1335	1555	2513	2831	1288	1569	1386	1748	1235	1533
90W	2160	2683	1777	2251	1628	2151	1465	1947	995	1466	1277	1783
All	1643	2198	1484	1967	1718	2222	1320	1786	1133	1529	1214	1657
Rank.1	5	5	4	4	6	6	3	3	1	1	2	2
Rank.2	5	5	4	4	6	6	2=	3	2=	2	1	1

GOLDEN

SLOPE	GUEYMARD.1 MAD	GUEYMARD.1 RMSD	GUEYMARD.2 MAD	GUEYMARD.2 RMSD	MCFAR MAD	MCFAR RMSD	GUEY2.D/DPD MAD	GUEY2.D/DPD RMSD	GUEY2.R/REV2 MAD	GUEY2.R/REV2 RMSD	GUEY2.P/PAGE MAD	GUEY2.P/PAGE RMSD
40S	528	680	536	685	944	1229	467	617	550	717	467	619
90S	571	722	559	725	1625	1914	466	605	534	662	438	574
All	550	701	548	705	1285	1608	467	611	542	690	453	597
Rank.1	5	4	4	5	6	6	2	2	3	3	1	1
Rank.2	3=	3	3=	5	6	6	2	1=	3=	4	1	1=

TORONTO

SLOPE	GUEYMARD.1 MAD	GUEYMARD.1 RMSD	GUEYMARD.2 MAD	GUEYMARD.2 RMSD	MCFAR MAD	MCFAR RMSD	GUEY2.D/DPD MAD	GUEY2.D/DPD RMSD	GUEY2.R/REV2 MAD	GUEY2.R/REV2 RMSD	GUEY2.P/PAGE MAD	GUEY2.P/PAGE RMSD
30S	491	640	487	638	939	1125	454	615	541	757	460	628
90N	402	573	379	536			363	507	389	559	362	503
90E	1155	1742	1124	1719	1371	1896	1150	1678	1420	1978	1201	1718
90S	418	579	436	610	1308	1684	362	507	419	562	360	500
60S	869	1113	948	1203	1286	1706	900	1142	882	1116	924	1168
90W	1163	1718	1121	1682	1417	1975	1145	1643	1406	1957	1202	1695
90SE	1036	1520	1102	1578	1413	1905	1106	1556	1262	1707	1143	1586
90SW	1064	1517	1033	1486	1437	1963	1005	1431	1092	1489	1025	1437
All	825	1270	829	1275	2395	3905	811	1234	926	1384	835	1258
Rank.1	2	3	3	4	6	6	1	1	5	5	4	2
Rank.2	4	4	3	3	6	6	1	1	5	5	2	2

TRAPPES

SLOPE	GUEYMARD.1 MAD	GUEYMARD.1 RMSD	GUEYMARD.2 MAD	GUEYMARD.2 RMSD	MCFAR MAD	MCFAR RMSD	GUEY2.D/DPD MAD	GUEY2.D/DPD RMSD	GUEY2.R/REV2 MAD	GUEY2.R/REV2 RMSD	GUEY2.P/PAGE MAD	GUEY2.P/PAGE RMSD
45S	424	559	483	618	779	1031	459	590	475	606	465	595
90N	1616	2065	1603	2019			1603	1991	1427	1718	1503	1833
90E	1464	2095	1376	1927	1373	1863	1285	1814	1269	1714	1255	1758
90S	992	1221	970	1177	2111	2371	883	1113	974	1249	877	1110
90W	1853	2596	1573	2241	1656	2299	1542	2205	1174	1756	1402	2054
All	1270	1854	1201	1708	1480	1965	1154	1656	1064	1476	1100	1566
Rank.1	5	5	4	4	6	6	3	3	1	1	2	2
Rank.2	5	5	4	4	6	6	3	3	2	2	1	1

VANCOUVER

SLOPE	GUEYMARD.1 MAD	GUEYMARD.1 RMSD	GUEYMARD.2 MAD	GUEYMARD.2 RMSD	MCFAR MAD	MCFAR RMSD	GUEY2.D/DPD MAD	GUEY2.D/DPD RMSD	GUEY2.R/REV2 MAD	GUEY2.R/REV2 RMSD	GUEY2.P/PAGE MAD	GUEY2.P/PAGE RMSD
30S	356	481	416	554	739	931	357	487	375	513	356	489
60S	423	581	470	637	1414	1683	426	584	547	722	449	610
90S	391	544	409	568	1680	1980	372	509	486	640	387	531
90E	1802	2599	1531	2256	1467	2152	1378	2129	1228	1811	1263	1990
90W	1136	1766	1049	1732	1150	1689	1013	1648	1344	1922	1107	1715
90N	728	1098	714	1040			646	918	474	668	533	753
60N	924	1380	951	1395			894	1280	642	898	779	1104
All	823	1407	791	1318	1290	1738	727	1229	728	1160	696	1170
Rank.1	5	5	4	4	6	6	2	3	3	2	1	1
Rank.2	4	4	5	5	6	6	2	1	3	3	1	2

CATEGORY B

SLOPE	GUEYMARD.1 MAD	GUEYMARD.1 RMSD	GUEYMARD.2 MAD	GUEYMARD.2 RMSD	MCFAR MAD	MCFAR RMSD	GUEY2.D/DPD MAD	GUEY2.D/DPD RMSD	GUEY2.R/REV2 MAD	GUEY2.R/REV2 RMSD	GUEY2.P/PAGE MAD	GUEY2.P/PAGE RMSD
All	947	1493	921	1420	1554	2469	865	1342	866	1307	847	1305
Rank.1	5	5	4	4	6	6	2	3	3	2	1	1
Rank.2	3	3	5	5	6	6	1	1	4	4	2	2
Equat.	657	964	688	990	1274	1669	648	955	709	1026	656	963
Rank.1	3	3	4	4	6	6	1	1	5	5	2	2
Rank.2	2	2	4	4	6	6	1	1	5	5	3	3
Other	1253	1898	1166	1763	1963	3308	1095	1656	1031	1550	1048	1587
Rank.1	5	5	4	4	6	6	3	3	1	1	2	2
Rank.2	5	6	4	4	6	5	1	2	3	3	2	1

ALL LOCATIONS

SLOPE	GUEYMARD.1 MAD	GUEYMARD.1 RMSD	GUEYMARD.2 MAD	GUEYMARD.2 RMSD	MCFAR MAD	MCFAR RMSD	GUEY2.D/DPD MAD	GUEY2.D/DPD RMSD	GUEY2.R/REV2 MAD	GUEY2.R/REV2 RMSD	GUEY2.P/PAGE MAD	GUEY2.P/PAGE RMSD
All	942	1503	908	1414	1538	2319	854	1345	838	1272	830	1295
Rank.1	5	5	4	4	6	6	3	3	2	1	1	2
Rank.2	4	4	5	5	6	6	2	2	3	3	1	1
Equat.	604	910	627	926	1387	1880	584	887	634	951	586	888
Rank.1	3	3	4	4	6	6	1	1	5	5	2	2
Rank.2	3	3	5	4	6	6	1	1	4	5	2	2
Other	1338	1983	1236	1825	1788	2908	1170	1732	1075	1566	1115	1648
Rank.1	5	5	4	4	6	6	3	3	1	1	2	2
Rank.2	5	6	4	4	6	5	3	3	2	2	1	1

Table 13. Validation statistics and rankings for six daily total irradiance models. Results based on long-term mean daily total irradiance data (Units: kJ m^{-2} day^{-1}).

ALBANY

	GUEYMARD.1		GUEYMARD.2		MCFAR		GUEY2.D/DPD		GUEY2.R/REV2		GUEY2.P/PAGE	
SLOPE	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD
33S	138	205	154	211	491	561	144	202	141	173	115	162
43S	161	216	142	203	660	752	138	197	169	222	115	151
53S	420	461	356	396	661	752	363	403	440	538	336	375
90N	1447	1702	1435	1672			1409	1633	1240	1387	1324	1508
90E	1322	1500	991	1153	1053	1266	954	1100	375	470	766	946
90S	1315	1466	1264	1408	1488	1917	1266	1410	1283	1481	1218	1371
90W	1397	1553	1066	1200	1130	1317	1030	1149	427	488	857	987
All	886	1196	773	1055	914	1187	758	1030	582	840	676	942
Rank.1	5	6	4	4	6	5	3	3	1	1	2	2
Rank.2	5	5	4	4	6	6	3	2=	2	2=	1	1

BRACKNELL.2

	GUEYMARD.1		GUEYMARD.2		MCFAR		GUEY2.D/DPD		GUEY2.R/REV2		GUEY2.P/PAGE	
SLOPE	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD
90N	1217	1427	1196	1392			1261	1489	1146	1320	1192	1387
90E	854	1013	595	726	910	1071	851	984	483	589	710	844
90S	946	1212	911	1162	1796	2155	900	1099	937	1194	883	1103
90W	1084	1277	825	986	1140	1329	1080	1248	713	845	940	1105
51.4S	461	617	447	601	709	931	445	574	455	616	438	577
All	912	1144	795	1015	1139	1451	907	1121	747	960	833	1040
Rank.1	5	5	2	2	6	6	4	4	1	1	3	3
Rank.2	5	5	3	3	6	6	4	4	2	1	1	2

LERWICK

	GUEYMARD.1		GUEYMARD.2		MCFAR		GUEY2.D/DPD		GUEY2.R/REV2		GUEY2.P/PAGE	
SLOPE	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD
90N	1143	1484	1108	1427			1217	1597	1076	1368	1115	1432
90E	720	1060	523	813	793	1059	800	1092	537	783	666	933
90S	474	553	462	516	1683	2174	338	383	424	490	368	418
90W	712	976	501	722	786	970	793	1015	530	692	659	850
60.1S	364	411	414	446	1017	1362	465	505	382	422	434	470
All	683	975	602	858	1070	1470	723	1017	590	822	648	899
Rank.1	4	4	2	2	6	6	5	5	1	1	3	3
Rank.2	4	4	2	2	6	6	5	5	1	1	3	3

SAN ANTONIO

	GUEYMARD.1		GUEYMARD.2		MCFAR		GUEY2.D/DPD		GUEY2.R/REV2		GUEY2.P/PAGE	
SLOPE	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD
20S	244	309	243	327	889	1030	223	298	238	270	214	289
30S	287	358	270	344	996	1071	244	311	220	273	210	281
40S	467	569	421	515	1437	1566	387	498	372	526	338	461
90N	1453	1632	1453	1612			1397	1534	1188	1274	1329	1443
90E	2316	2391	1874	1938	2210	2314	1665	1748	768	906	1504	1621
90S	1454	1555	1419	1519	1676	2290	1363	1460	1231	1383	1269	1374
90W	1212	1438	771	1021	1106	1363	586	835	530	597	553	803
All	1062	1384	922	1207	1386	1689	838	1113	650	857	774	1043
Rank.1	5	5	4	4	6	6	3	3	1	1	2	2
Rank.2	5	5	4	4	6	6	3	3	1=	1	1=	2

CATEGORY A

	GUEYMARD.1		GUEYMARD.2		MCFAR		GUEY2.D/DPD		GUEY2.R/REV2		GUEY2.P/PAGE	
SLOPE	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD
All	900	1203	785	1057	1132	1460	805	1071	638	868	731	985
Rank.1	5	5	3	3	6	6	4	4	1	1	2	2
Rank.2	5	5	3	3=	6	6	4	3=	2	2	1	1
Equat.	561	803	542	775	1125	1503	523	749	524	770	495	723
Rank.1	5	5	4	4	6	6	2	2	3	3	1	1
Rank.2	5	5	4	4	6	6	2	2	3	3	1	1
Other	1240	1499	1028	1279	1141	1393	1087	1317	751	955	968	1190
Rank.1	6	6	3	3	5	5	4	4	1	1	2	2
Rank.2	5	6	3	3	6	5	4	4	1	1	2	2

CARPENTRAS

	GUEYMARD.1		GUEYMARD.2		MCFAR		GUEY2.D/DPD		GUEY2.R/REV2		GUEY2.P/PAGE	
SLOPE	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD
45S	311	401	317	418	1052	1328	334	422	565	589	373	452
90N	1953	2297	1929	2248			1841	2116	1592	1763	1711	1928
90E	1952	2199	1496	1699	1339	1562	1287	1446	440	530	1043	1202
90S	1311	1581	1242	1499	2185	2419	1255	1539	1354	1695	1216	1509
90W	1806	2114	1349	1617	1219	1500	1140	1362	396	499	911	1138
All	1467	1857	1267	1611	1449	1754	1171	1481	869	1171	1051	1337
Rank.1	6	6	4	4	5	5	3	3	1	1	2	2
Rank.2	5	5	4	4	6	6	3	3	2	2	1	1

TORONTO

	GUEYMARD.1		GUEYMARD.2		MCFAR		GUEY2.D/DPD		GUEY2.R/REV2		GUEY2.P/PAGE	
SLOPE	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD
30S	444	544	401	498	497	635	419	515	515	688	424	537
90N	290	358	263	318			236	276	190	220	158	194
90E	518	621	322	368	492	592	341	399	594	724	343	384
90S	235	281	184	228	839	900	204	242	290	342	181	224
60S	535	585	600	650	716	849	566	626	503	559	596	646
90W	498	589	296	386	577	718	314	405	603	785	341	425
90SE	460	540	438	510	611	718	459	541	547	646	460	538
90SW	612	722	455	556	715	825	452	567	426	475	432	513
All	449	547	370	458	635	756	374	465	459	585	367	457
Rank.1	4	4	2	2	6	6	3	3	5	5	1	1
Rank.2	4=	4=	1	1=	6	6	2=	3	4=	4=	2=	1=

TRAPPES

	GUEYMARD.1		GUEYMARD.2		MCFAR		GUEY2.D/DPD		GUEY2.R/REV2		GUEY2.P/PAGE	
SLOPE	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD
45S	363	424	373	434	503	600	366	413	334	417	367	421
90N	1173	1397	1157	1371			1209	1446	1099	1287	1147	1355
90E	543	650	481	540	491	587	461	544	355	470	406	478
90S	919	1093	886	1050	1526	1869	819	984	894	1083	823	989
90W	993	1293	743	998	1035	1331	946	1209	570	800	811	1075
All	798	1041	728	944	889	1222	760	999	650	879	711	935
Rank.1	5	5	3	3	6	6	4	4	1	1	2	2
Rank.2	5	5	4	4	6	6	3	3	1	1	2	2

VANCOUVER

	GUEYMARD.1		GUEYMARD.2		MCFAR		GUEY2.D/DPD		GUEY2.R/REV2		GUEY2.P/PAGE	
SLOPE	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD	MAD	RMSD
30S	166	197	194	228	497	549	166	204	256	279	164	215
60S	300	320	247	261	990	1100	248	262	480	532	303	322
90S	319	360	264	291	1240	1381	255	292	462	501	302	328
90E	1653	2075	1276	1665	1240	1381	1248	1581	590	920	1012	1371
90W	349	480	240	291	372	469	251	295	766	938	347	477
90N	690	924	662	869			615	792	394	461	487	596
60N	968	1254	997	1295			939	1203	618	721	805	1001
All	635	1017	554	886	868	1053	532	833	509	662	489	729
Rank.1	5	5	4	4	6	6	3	3	2	1	1	2
Rank.2	5	5	3	3	6	6	1=	1	4	4	1=	2

CATEGORY B

SLOPE	GUEYMARD.1 MAD	GUEYMARD.1 RMSD	GUEYMARD.2 MAD	GUEYMARD.2 RMSD	MCFAR MAD	MCFAR RMSD	GUEY2.D/DPD MAD	GUEY2.D/DPD RMSD	GUEY2.R/REV2 MAD	GUEY2.R/REV2 RMSD	GUEY2.P/PAGE MAD	GUEY2.P/PAGE RMSD
All	774	1136	672	992	907	1179	655	950	593	813	607	865
Rank.1	5	5	4	4	6	6	3	3	1	1	2	2
Rank.2	5	5	3	2=	6	6	2	2=	4	4	1	1
Equat.	498	697	467	659	948	1225	462	659	552	749	470	658
Rank.1	4	4	2	2	6	6	1	3	5	5	3	1
Rank.2	4	4	2=	1	6	6	1	2	5	5	2=	3
Other	1030	1426	862	1221	846	1107	833	1155	631	868	732	1019
Rank.1	6	6	5	5	4	3	3	4	1	1	2	2
Rank.2	6	6	4	4	5	5	3	3	1=	1=	1=	1=

ALL LOCATIONS

SLOPE	GUEYMARD.1 MAD	GUEYMARD.1 RMSD	GUEYMARD.2 MAD	GUEYMARD.2 RMSD	MCFAR MAD	MCFAR RMSD	GUEY2.D/DPD MAD	GUEY2.D/DPD RMSD	GUEY2.R/REV2 MAD	GUEY2.R/REV2 RMSD	GUEY2.P/PAGE MAD	GUEY2.P/PAGE RMSD
All	836	1169	728	1024	1019	1327	728	1011	615	840	668	926
Rank.1	5	5	3	4	6	6	4	3	1	1	2	2
Rank.2	5	5	4	3=	6	6	3	3=	2	2	1	1
Equat.	529	752	504	719	1036	1371	492	705	538	760	482	692
Rank.1	4	4	3	3	6	6	2	2	5	5	1	1
Rank.2	5	5	3	3	6	6	2	2	4	4	1	1
Other	1131	1462	942	1249	993	1258	955	1235	689	911	845	1105
Rank.1	6	6	3	4	5	5	4	3	1	1	2	2
Rank.2	6	6	3	3	5	5	4	4	1	1	2	2

8.3.3.2 Model Performance

Figure 9 shows that incorporation of the diffuse component into the slope irradiance calculations leads to a significant decrease in the ability to estimate the irradiance for an inclined surface. Significant overestimates are typical for all slopes other than those at San Antonio. It should be recalled that the better hourly diffuse irradiance models underestimate the slope irradiance at San Antonio. When this characteristics is combined with the tendency for the global irradiance model to overestimate the irradiance the unusually good agreement at San Antonio is readily understood.

Figure 7 shows that the overestimates associated with the Guey2.R/Rev2 model tend to occur throughout the year. Comparison with the validation statistics for the Page model (also shown in Figure 7) indicates that the diffuse algorithm is the major contributor to the deterioration in model performance.

An overall assessment of model performance is contained in Figure 10. The data confirm the large relative errors in estimating the global irradiance for a slope given only daily data. The previously mentioned positive bias in the estimates does not show at all locations included in this analysis but neither the clearness index nor station category appears to be associated with the extent of the apparent bias in the model.

8.3.3.3 Conclusions

Large errors occur in both short and long-term estimates of the global irradiance when daily rather than hourly data are used. Of the six potential models considered in the present study the Guey2.R/Rev2 algorithm provides the best overall performance.

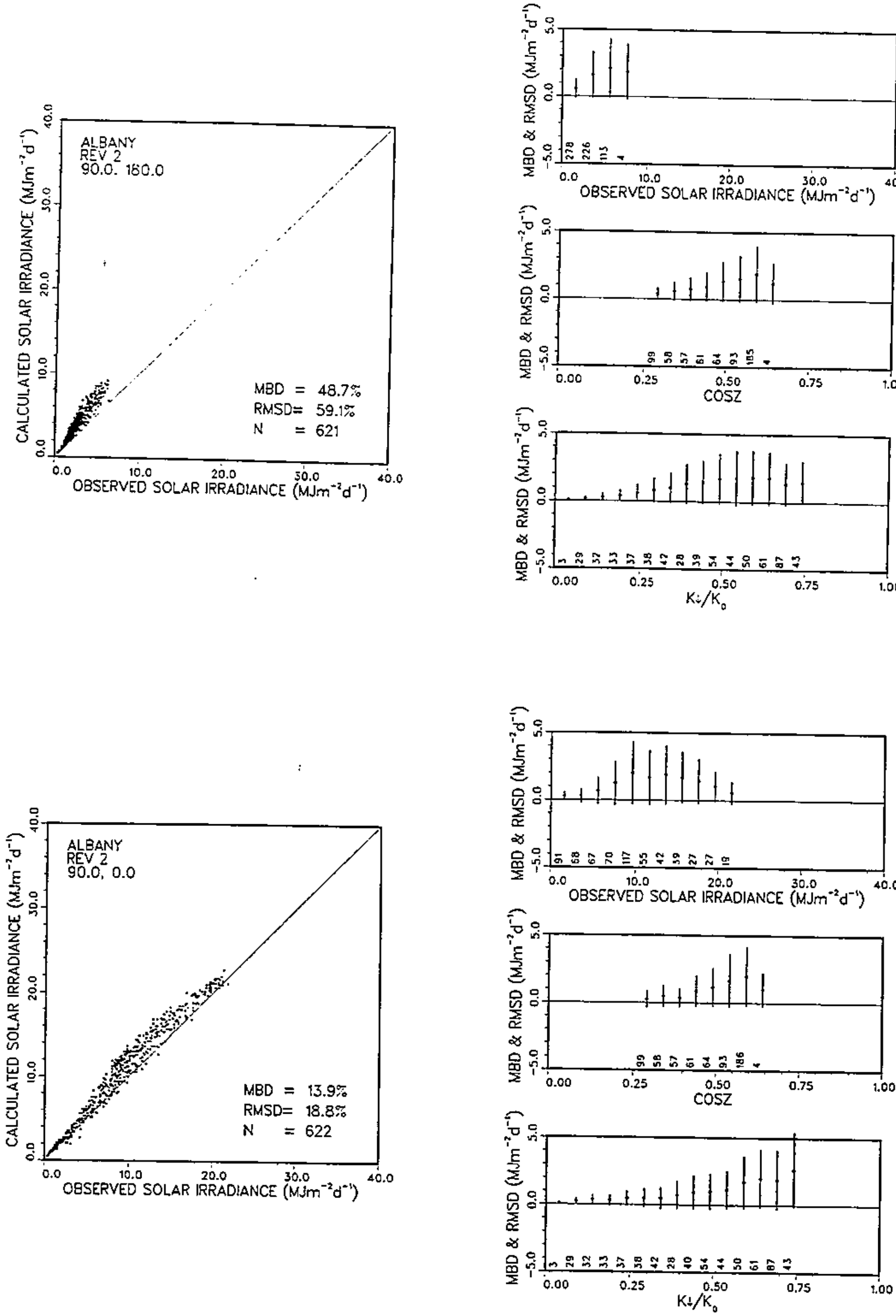


Figure 9a. Scatter diagrams of hourly estimated (using Guey 2.R/Rev 2) and observed total solar irradiances for north (top) and south (bottom) facing vertical surfaces at Albany. Also shown are the average and root mean square values of the differences between the estimated and observed irradiances. These latter values are presented as a function of the solar irradiance for the slope, the cosine of the solar zenith angle and of the clearness index (K↓/K_0).

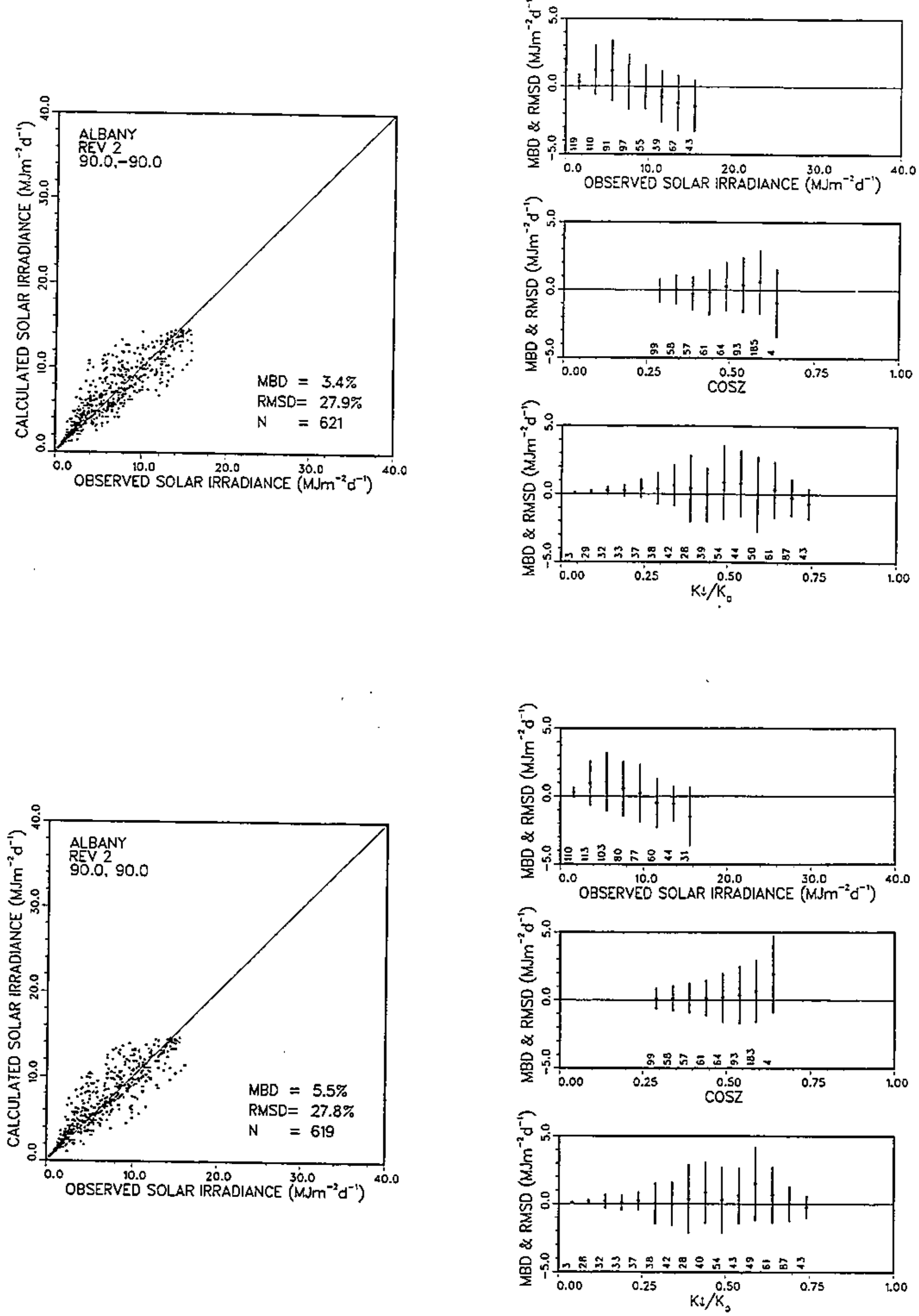


Figure 9b. As for Fig. 9a but for east (top) and west (bottom) facing vertical surfaces.

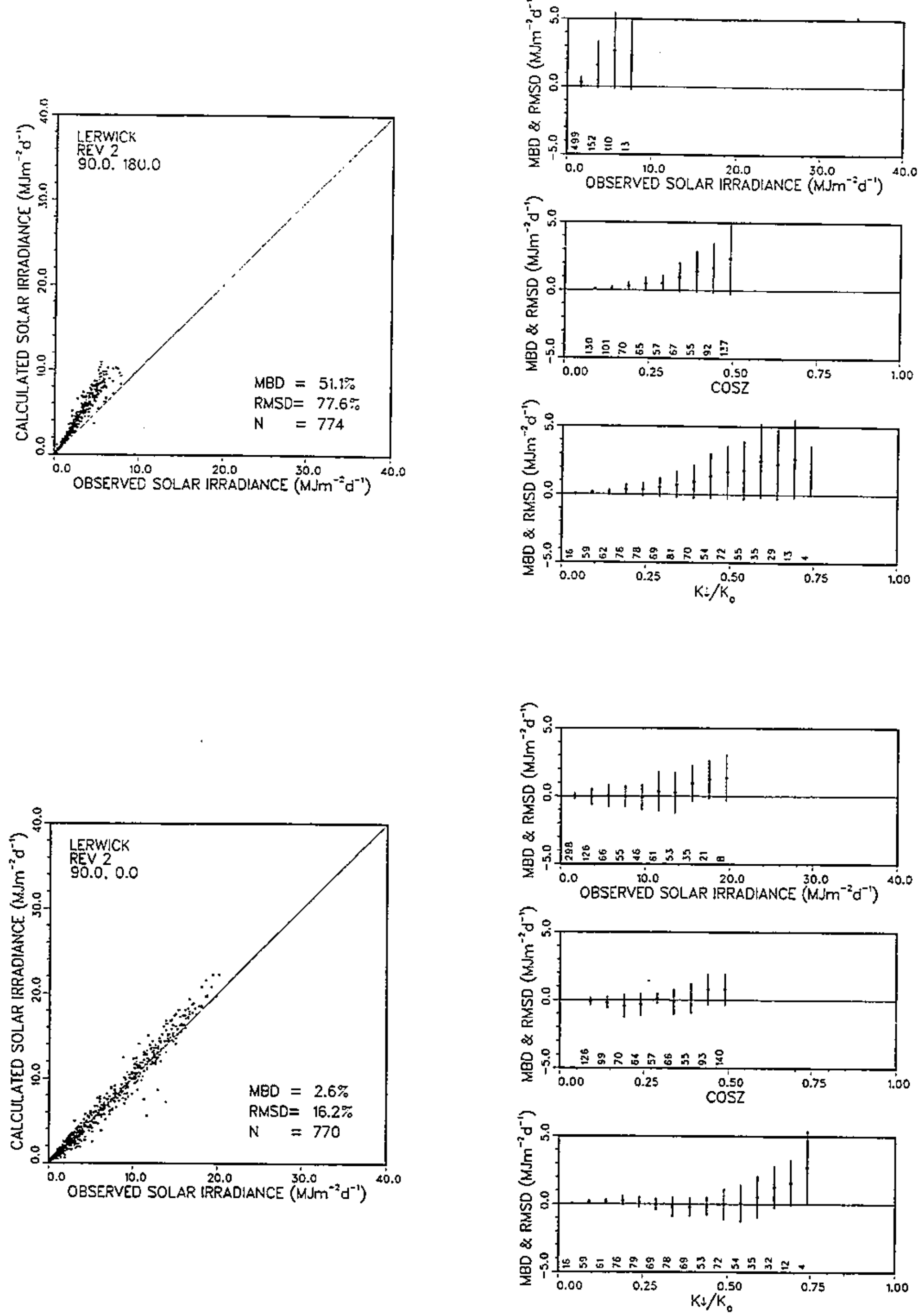


Figure 9c. As for Fig. 9a but for Lerwick.

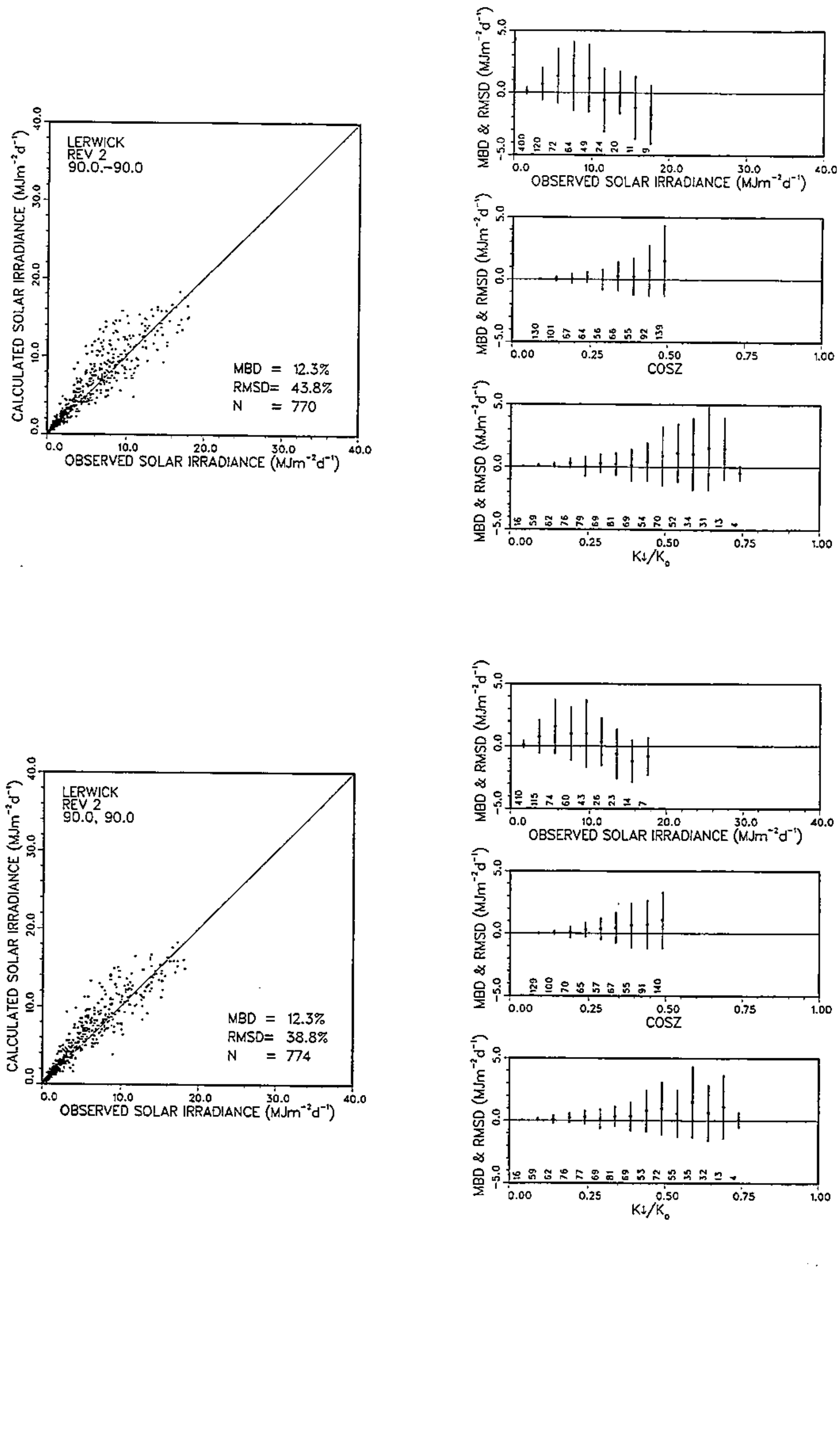


Figure 9d. As for Fig. 9b but for Lerwick.

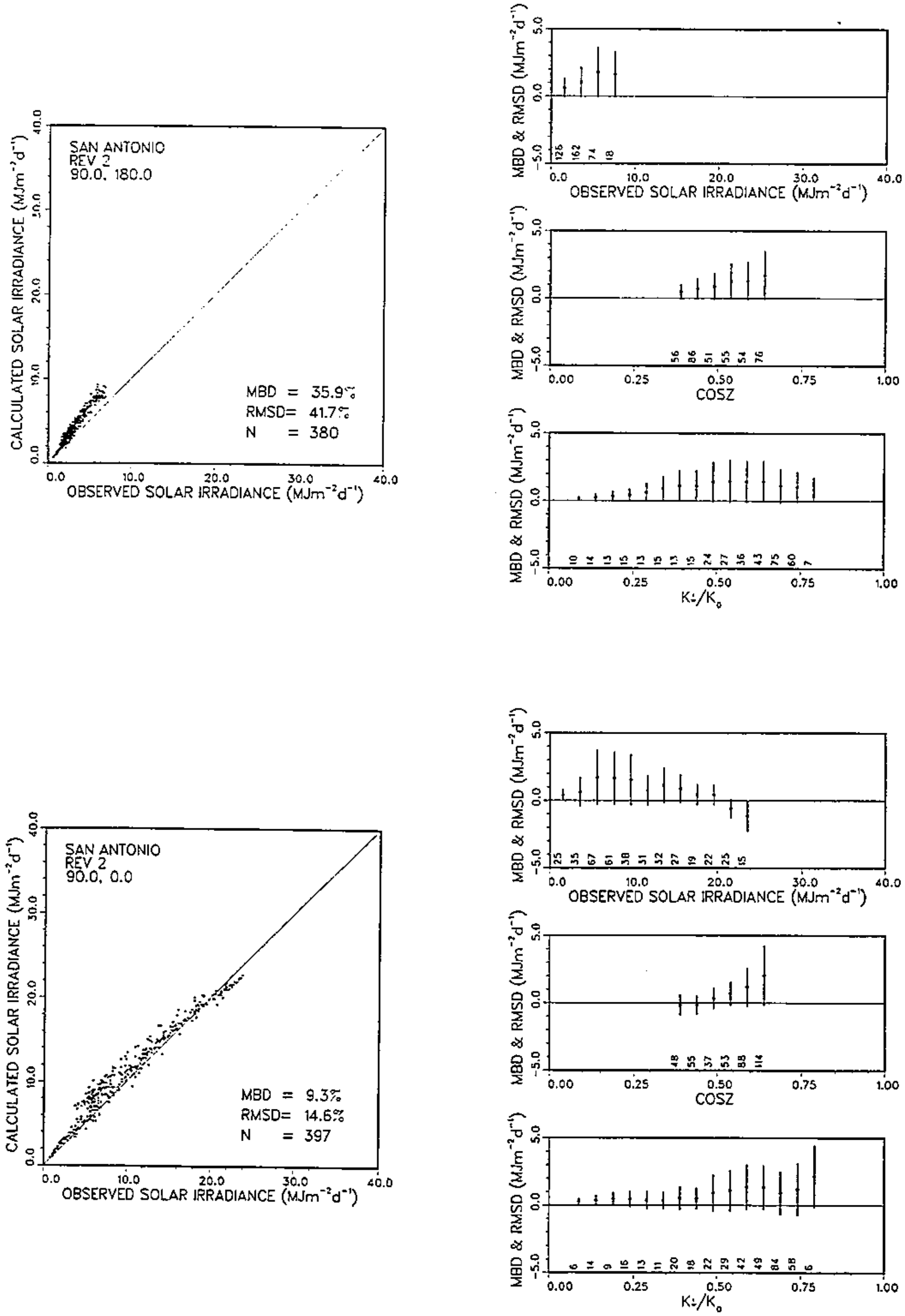


Figure 9e. As for Fig. 9a but for San Antonio.

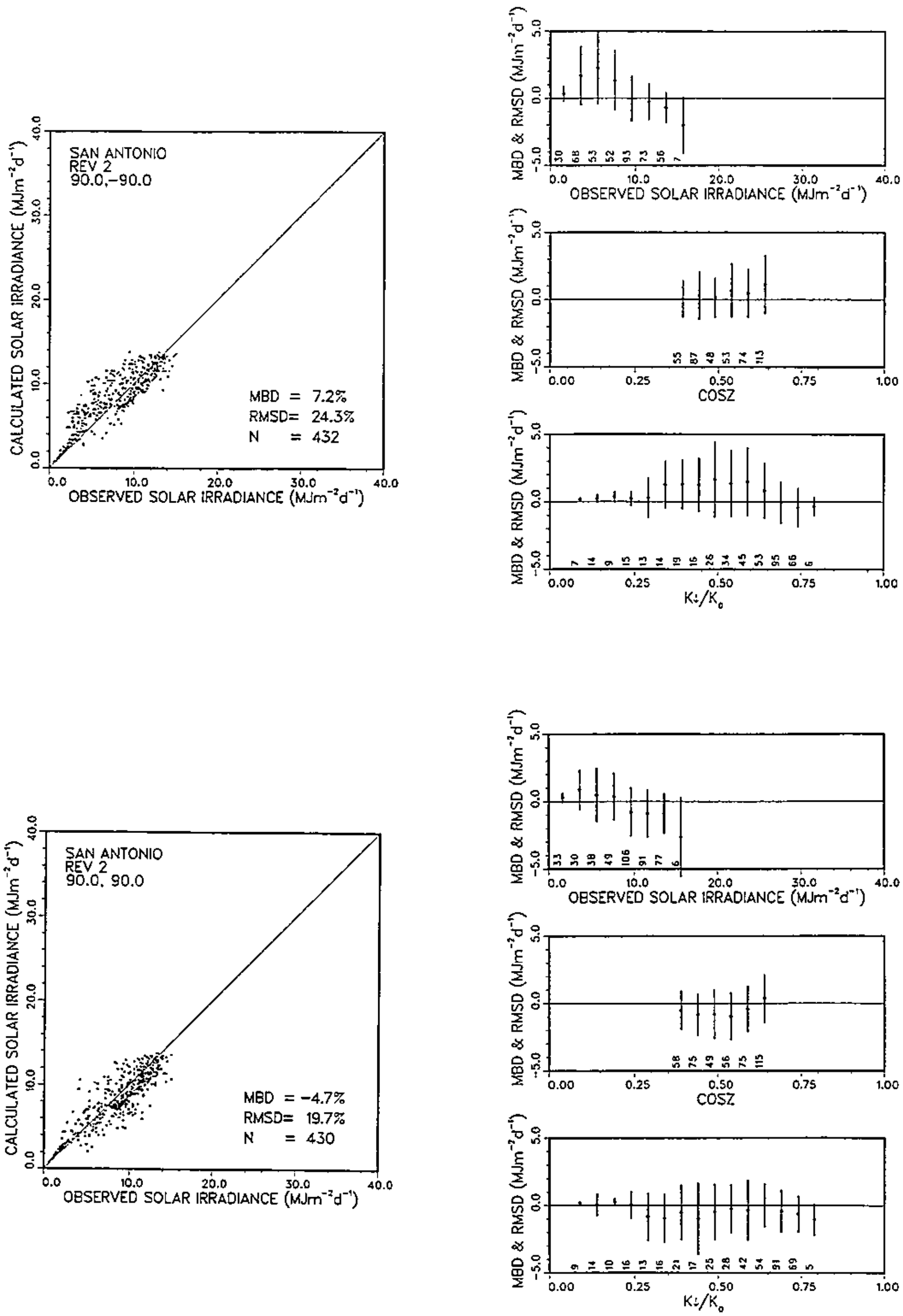


Figure 9f. As for Fig. 9b but for San Antonio.

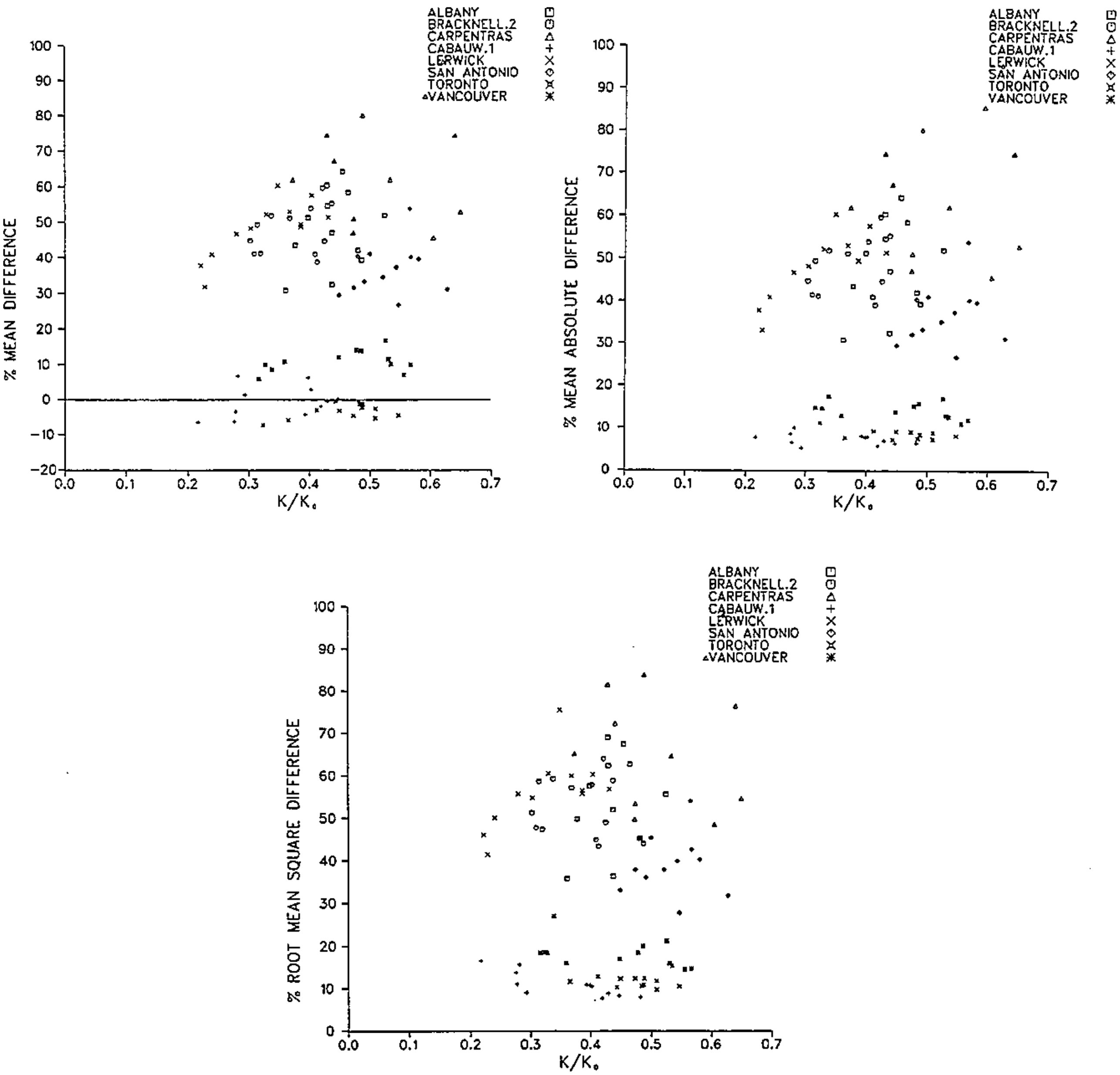


Figure 10a. The association between the overall monthly validation statistics and the clearness index ($K\downarrow/K_O$) for eight selected locations. Values are based on daily calculations of total solar irradiance using the Guey 2. R/ Rev 2 model and are presented for a vertical surface facing north.

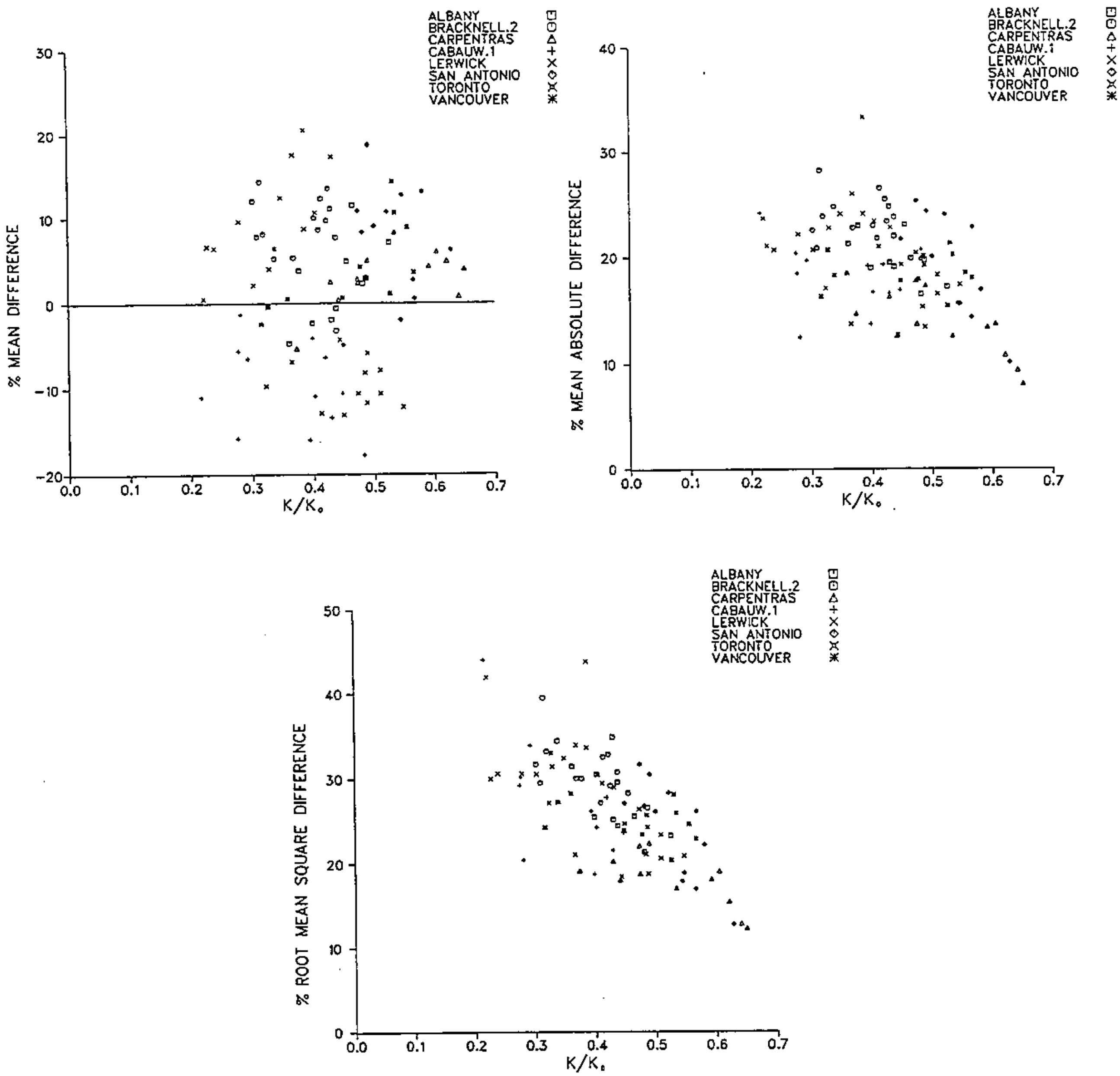


Figure 10b. As for Fig. 10a but for a vertical surface facing south.

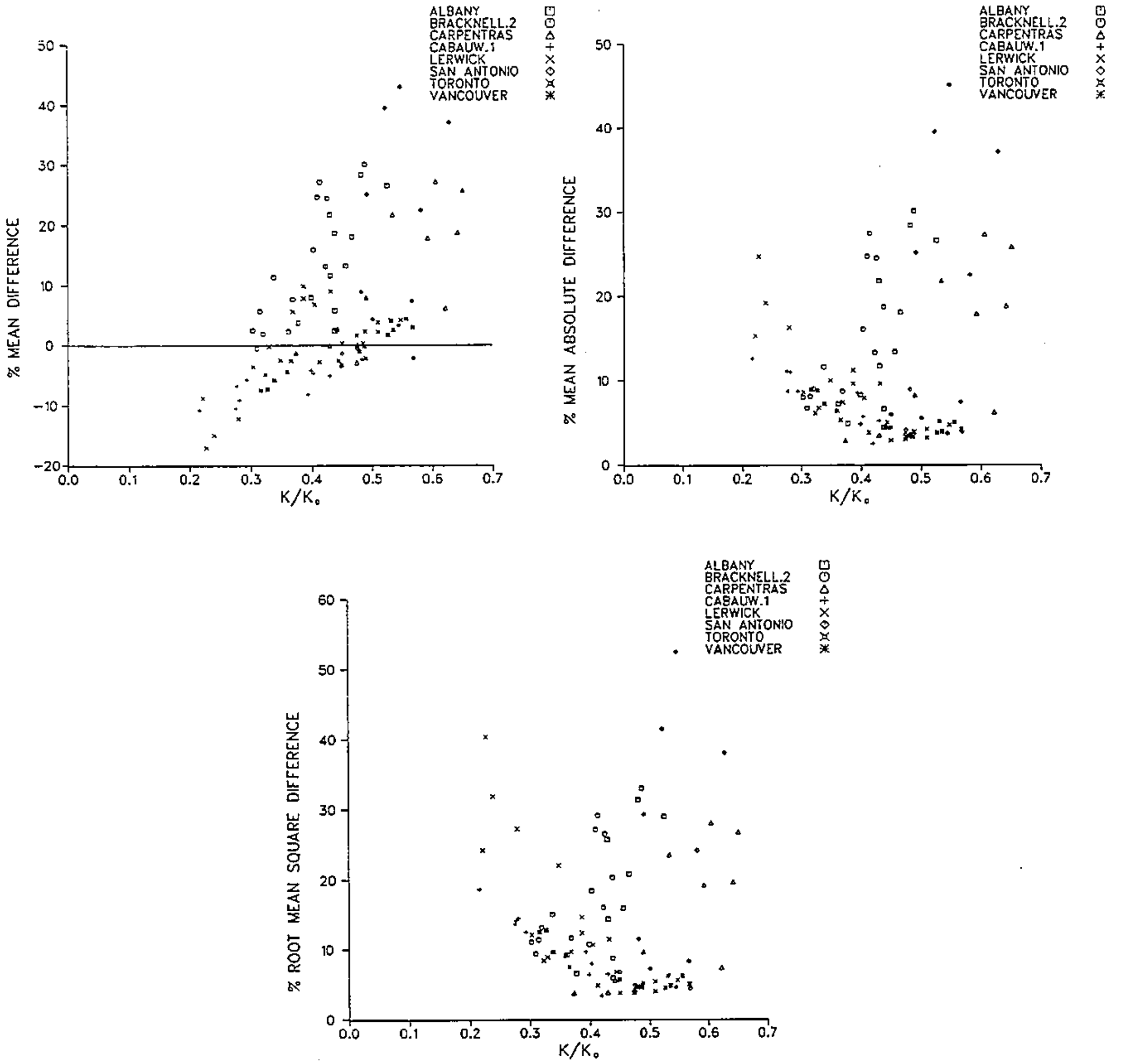


Figure 10c. As for Fig. 10a but for a vertical surface facing east.

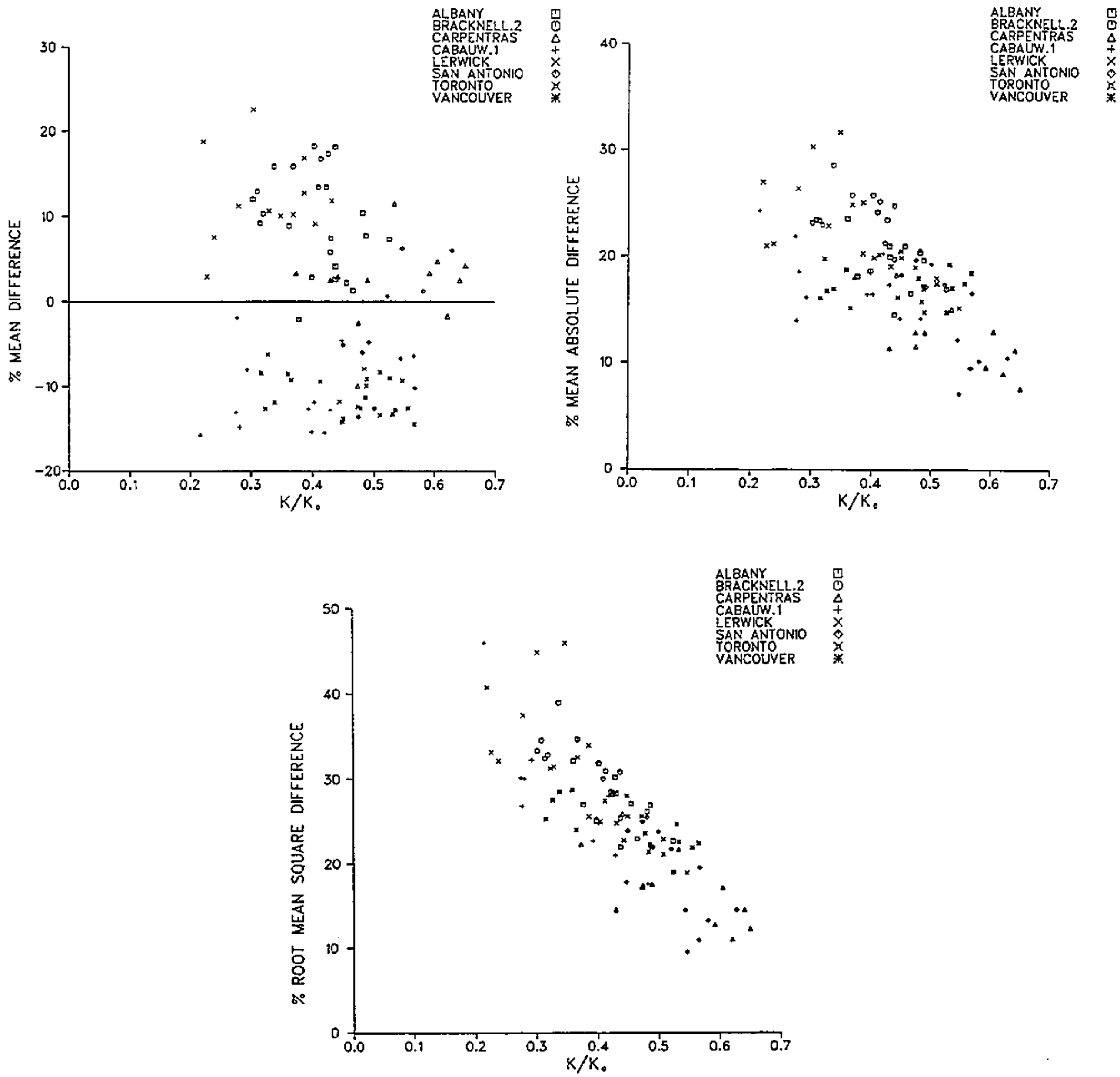


Figure 10d. As for Fig. 10a but for a vertical surface facing west.

9. COMPARISON OF HOURLY AND DAILY ALGORITHMS

Previous results have already alluded to the deterioration in the accuracy of slope irradiance estimates with the use of daily as opposed to hourly data together with the associated numerical procedures. This penalty is graphically illustrated in Figure 11 where the comparison is between the performance of an hourly model (Perez2) using hourly data and a daily model (Guey2.R/Rev2) using daily data. Since in both cases the estimates are compared to the observed daily global irradiance, the Perez2 estimates are combined with "exact" predictions of the direct irradiance and totalled to give daily values.

An important question relates to whether these significant differences decrease as a result of temporal averaging when longer-term estimates are required. This will be addressed in the following section.

10. TEMPORAL AVERAGING

The preceding analyses have shown that typically short-term estimates (single hours or days) of slope irradiance are subject to large errors even though the systematic error may be relatively small. In such cases temporal averaging results in a significant reduction in the error. It is important to assess both the rate at which this reduction occurs and whether approaches subject to smaller short-term errors (i.e. the hourly models) may lose their advantage when data are averaged over long time periods.

Both the hourly Perez2 (combined with "exact" direct irradiance calculations) and the daily Guey2.R/Rev2 models were used to estimate the global slope irradiances at three locations with long data records. Validation statistics were determined for the respective hourly and daily time scales and subsequently for longer time periods ranging from weeks to years. Thus, the original irradiance estimates were made on an hourly or daily basis as appropriate to the model. These estimates were then totalled for increasingly longer time periods and subsequently compared to measured irradiances also totalled for the corresponding time period.

The results (Figure 12) indicate that for time intervals of a week to a month the short-term errors are similar for both the hourly and daily approaches if the systematic errors (which are of course independent of averaging time) are ignored. At time intervals longer than a month the bias is the only discriminator between the two approaches.

For the daily model, monthly mean daily data or even long-term monthly mean daily data produce estimates of the monthly mean irradiance that are as reliable as those obtained by totalling the estimates for individual days in the month. However, the same is not true for the hourly model. In many cases estimates based on monthly mean hourly data or long-term monthly mean hourly data result in substantially higher values of both the RMSD and MBD indicating that in some cases the mean data do not adequately represent the relevant radiation conditions and hence do not modulate the hourly model in an appropriate manner.

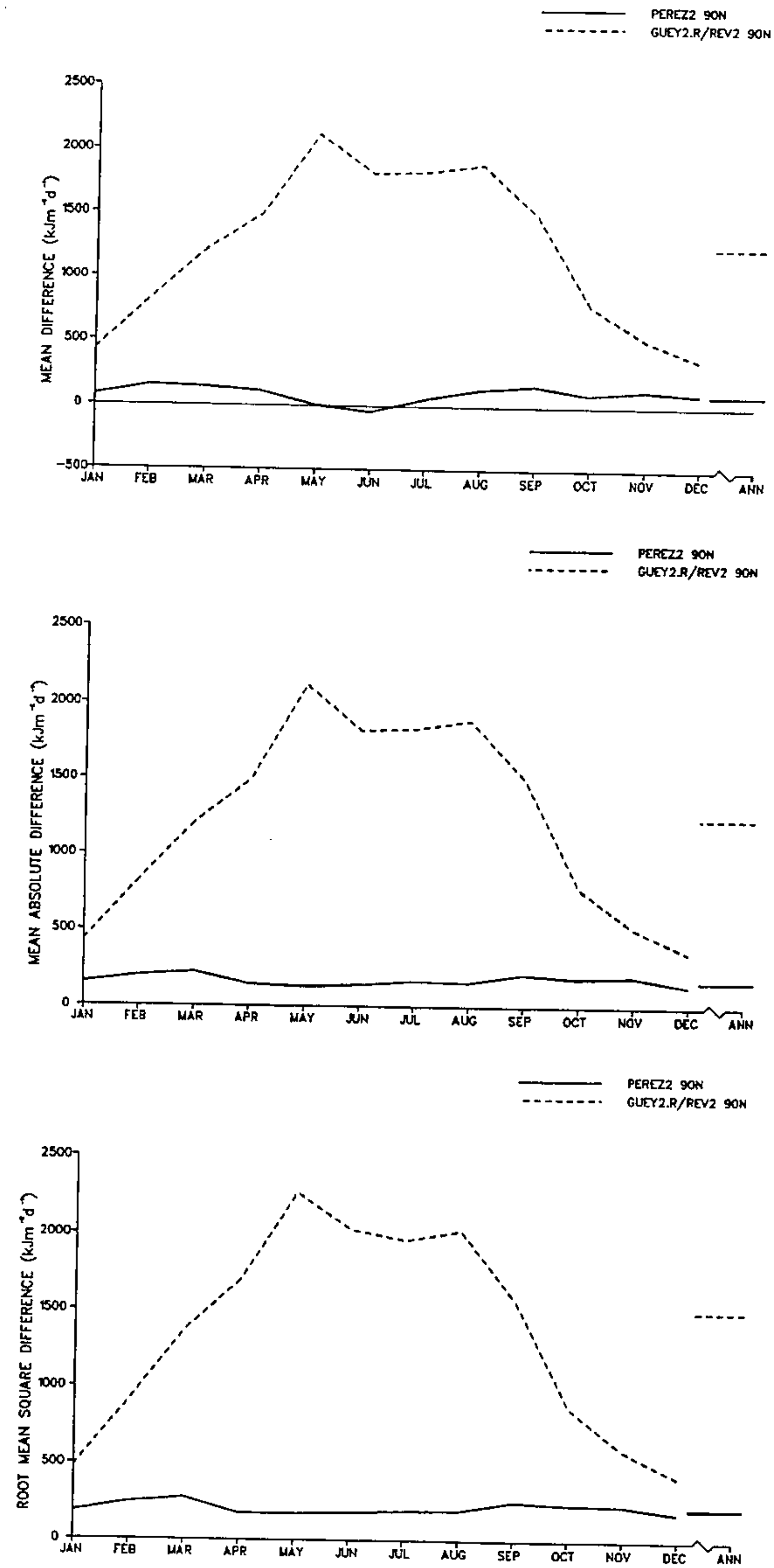


Figure 11a. Monthly and total period values of the validation statistics for a vertical north-facing surface at Albany. Data are presented for both the Perez 2 hourly model and the Guey 2.R/Rev 2 daily model.

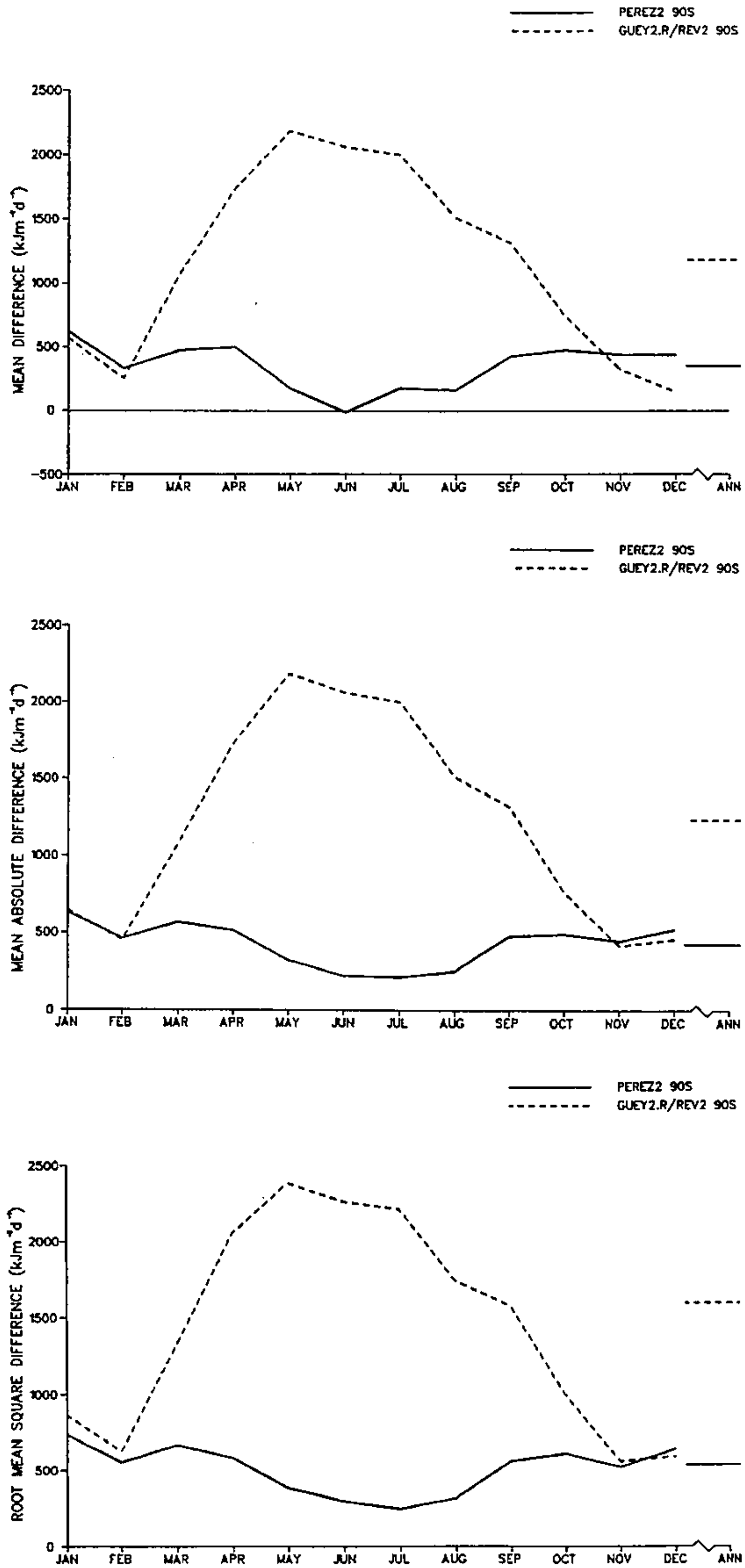


Figure 11b. As for Fig. 11a but for a vertical south-facing surface.

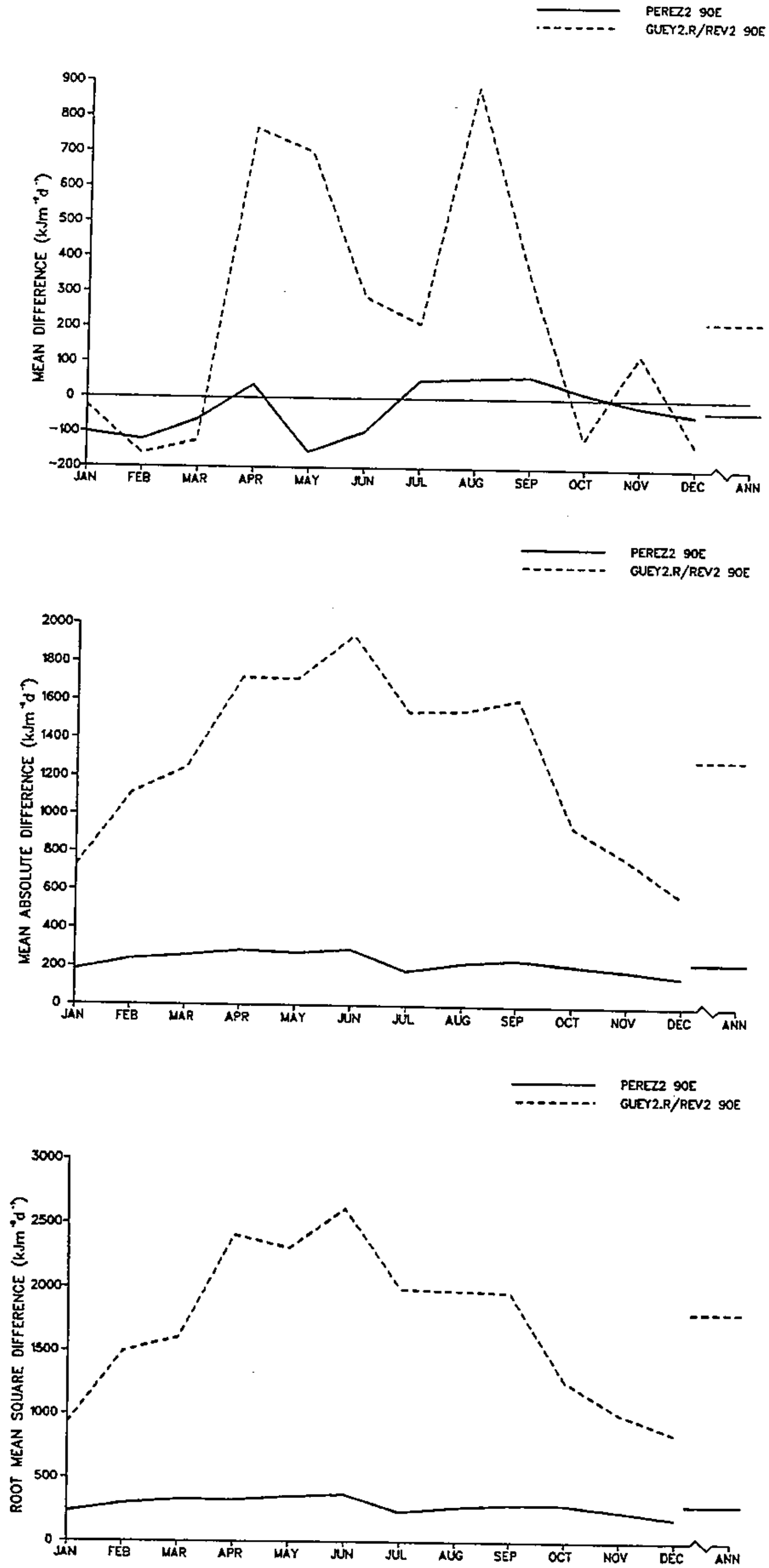


Figure 11c. As for Fig. 11a but for a vertical east-facing surface.

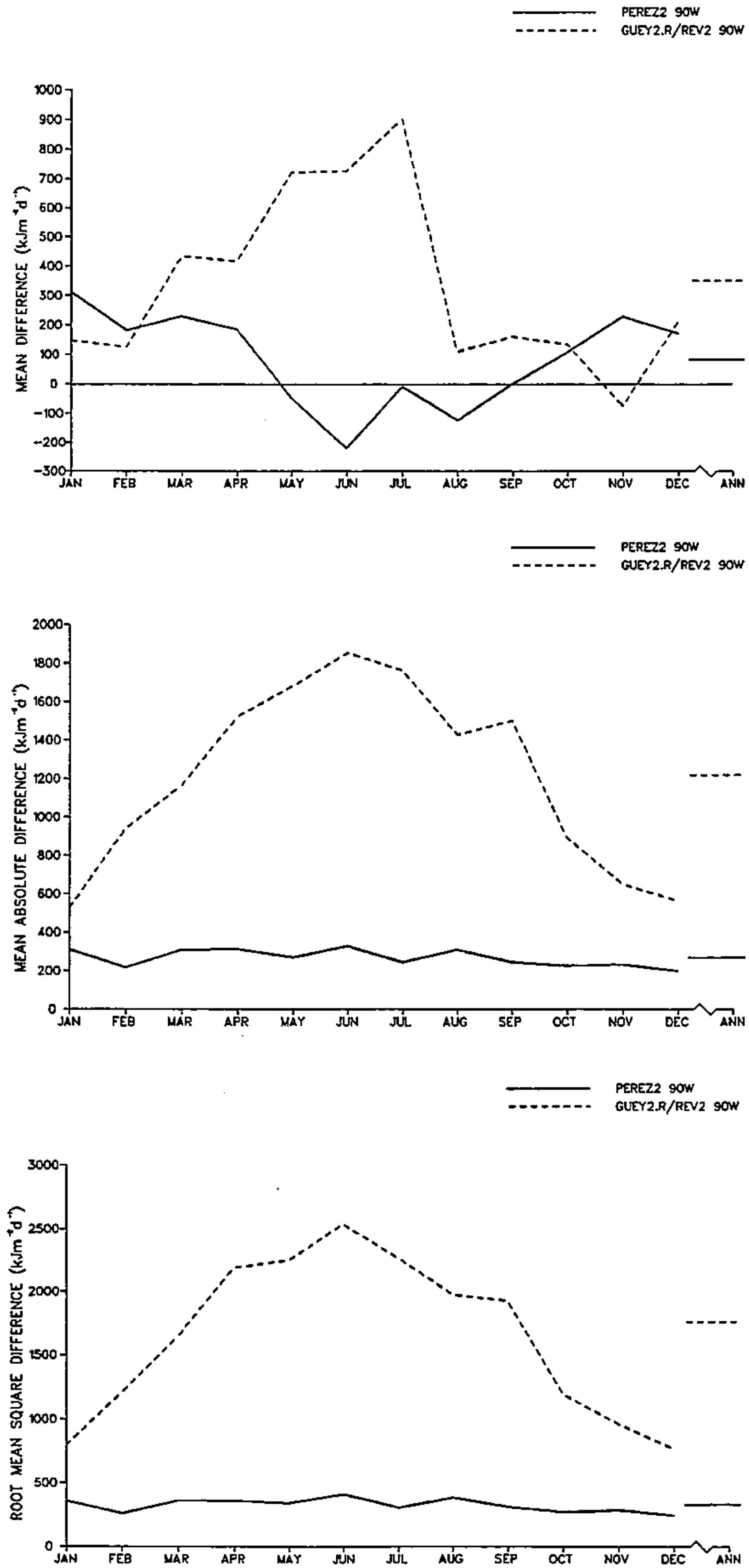
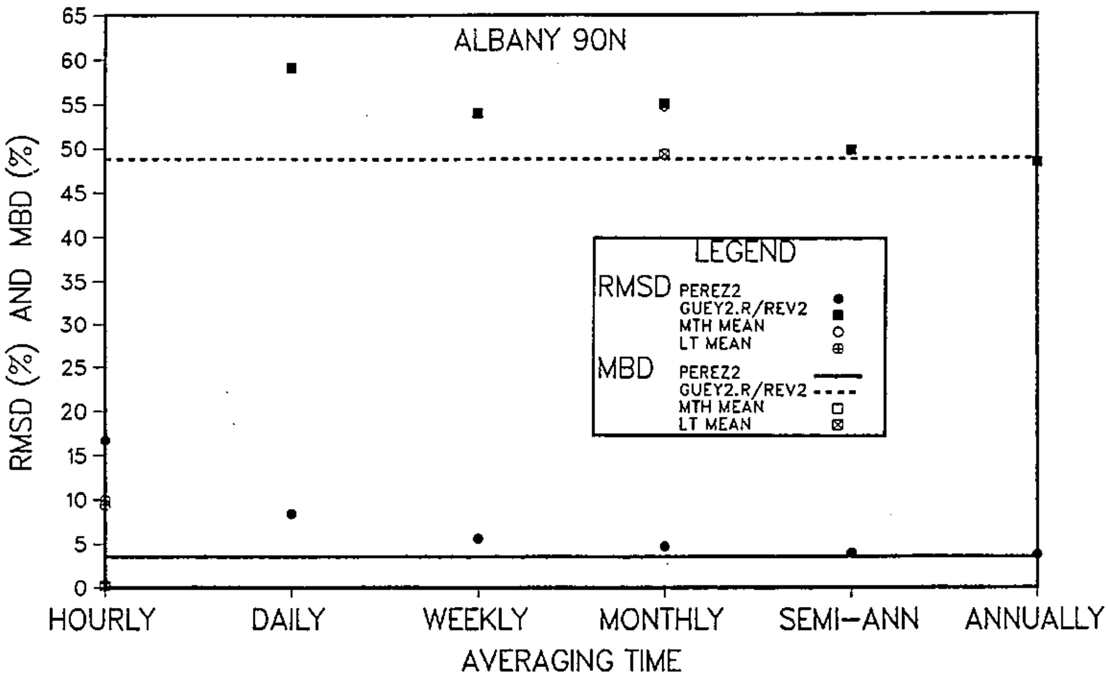


Figure 11d. As for Fig. 11a but for a vertical west-facing surface.



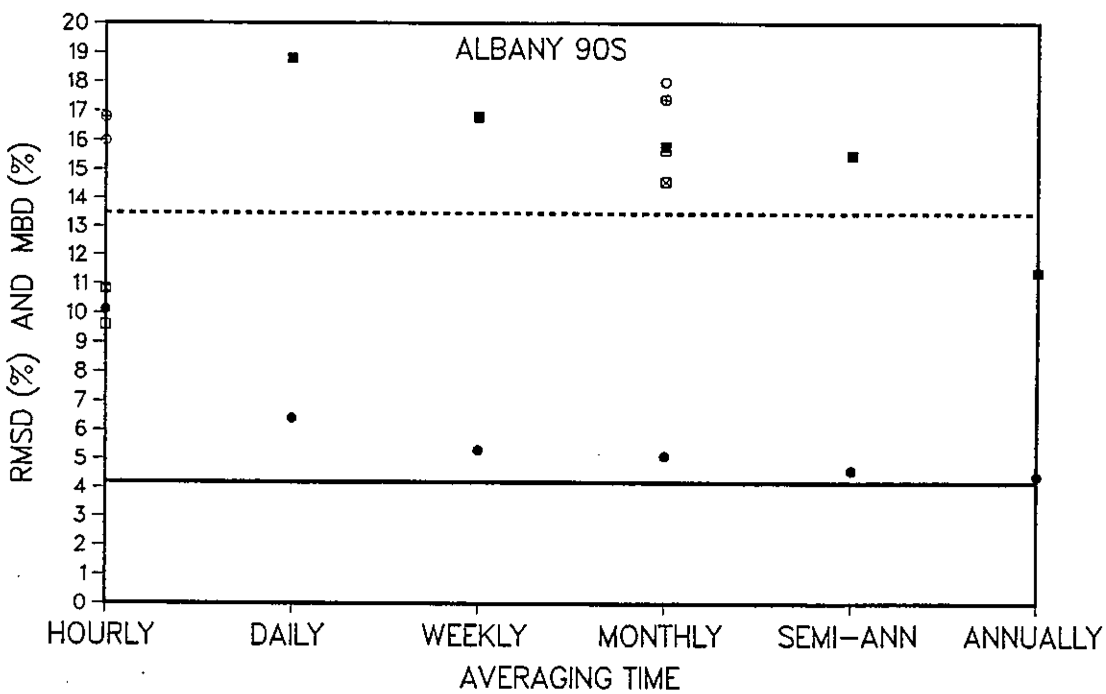
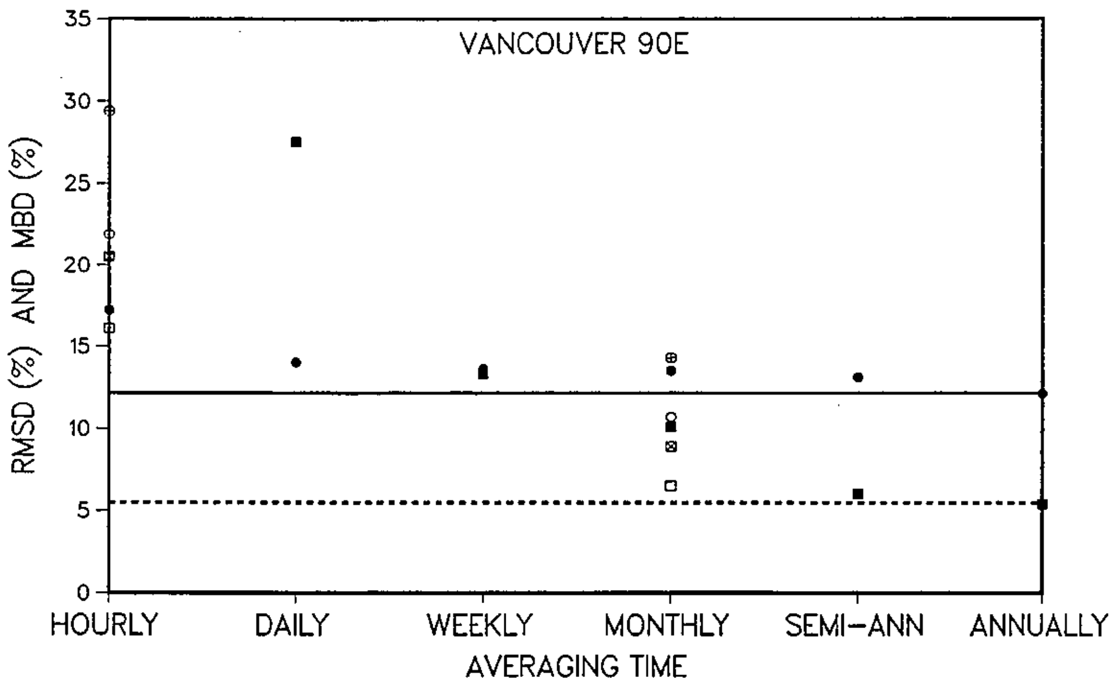


Figure 12a. The influence of averaging time on validation statistics (RMSD and MBD) for the Perez 2 hourly model and the Guey 2.R/Rev 2 daily model based on hourly and daily data, respectively. Also shown (arbitrarily plotted for the monthly averaging time) for both models are results of calculations based on monthly mean ("Mth Mean") and long term mean ("LT Mean") data. Values are for a vertical north (top) and south facing surfaces at Albany.



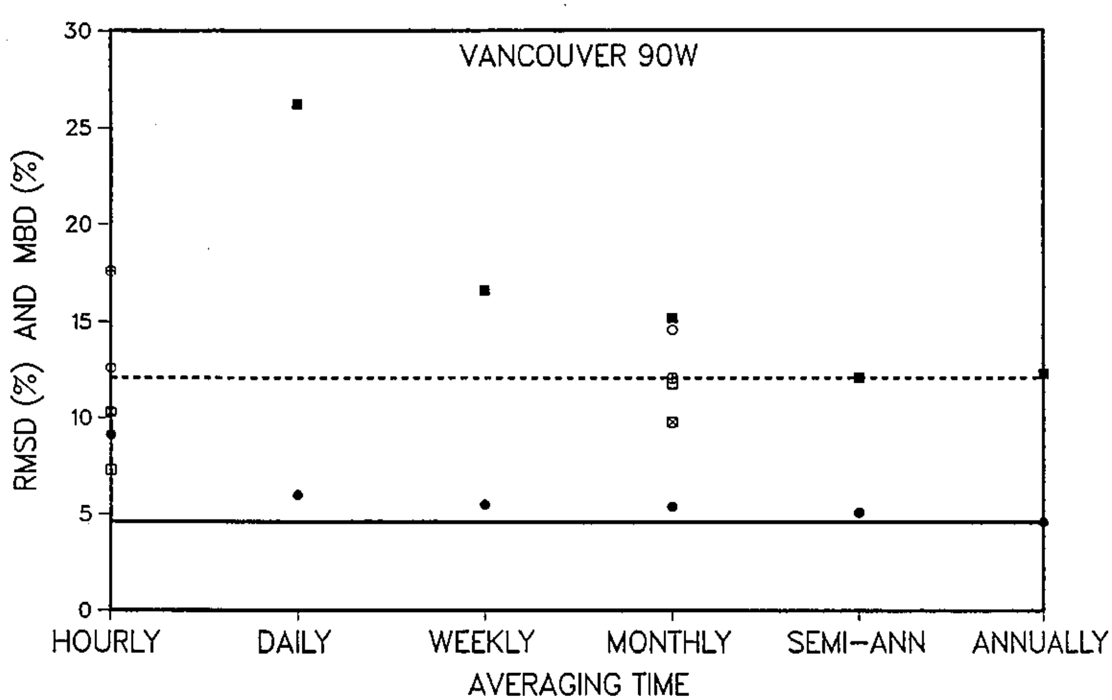
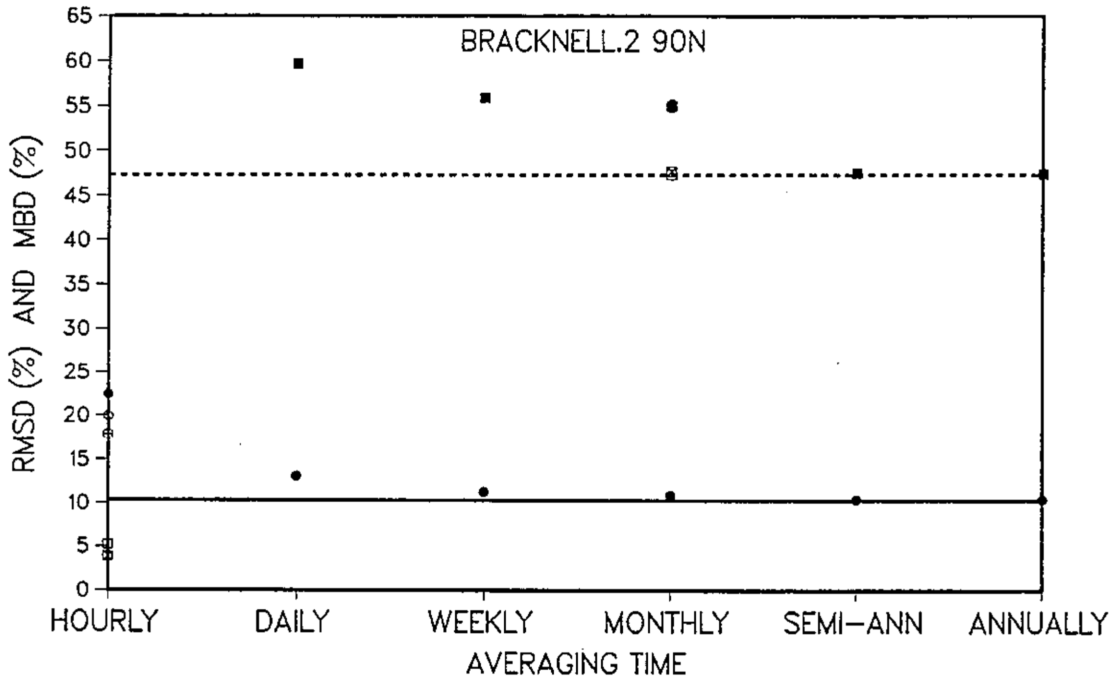


Figure 12d. As for Fig. 12b but for Vancouver. See Fig. 12a for legend.



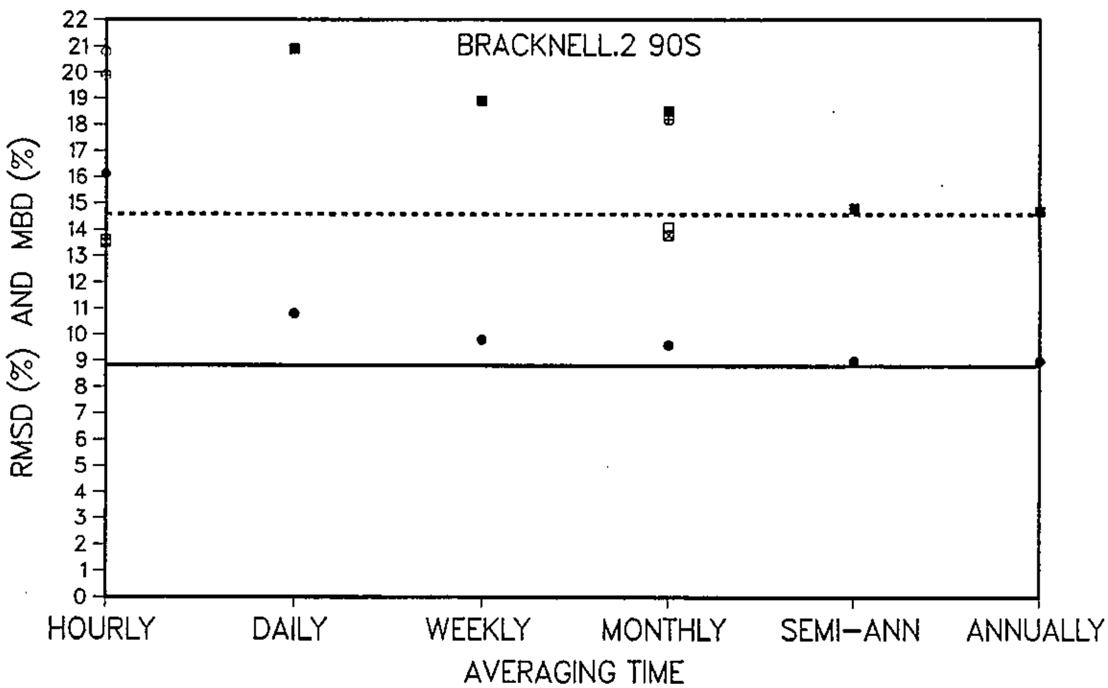
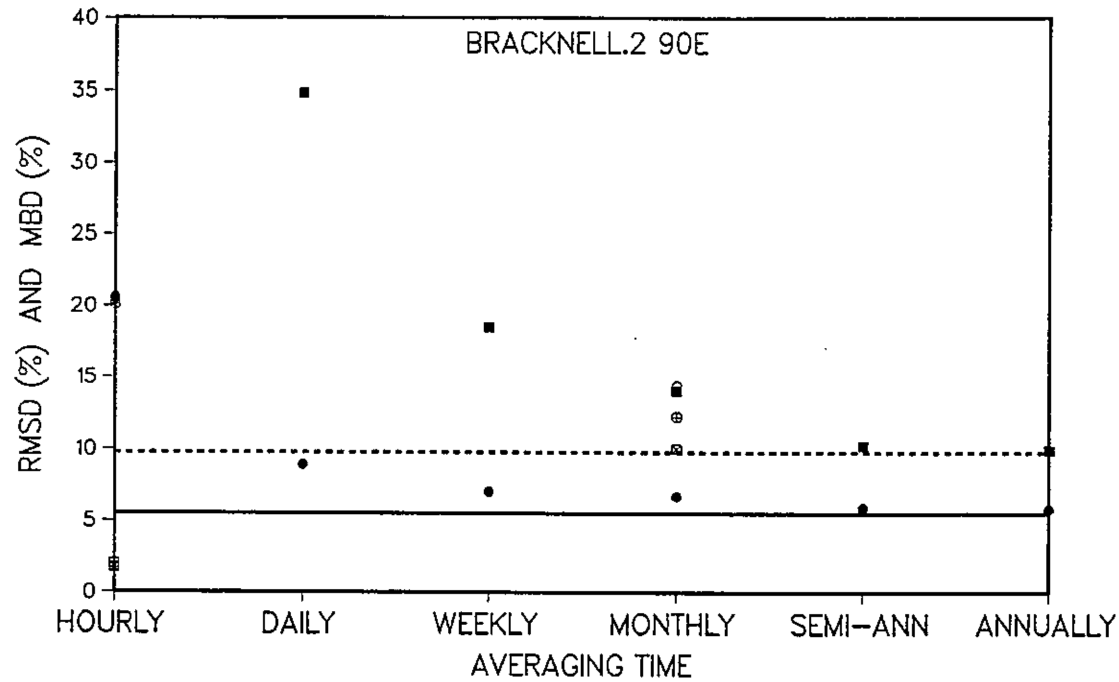


Figure 12e. As for Fig. 12a but for Bracknell. See Fig. 12a for legend.



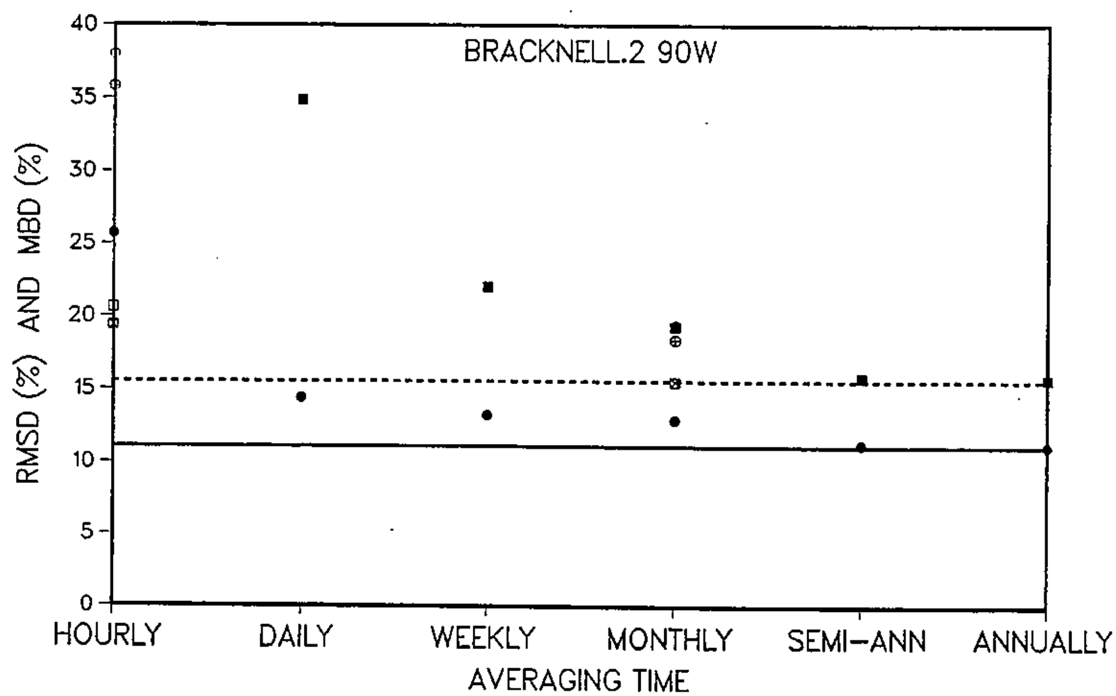


Figure 12f. As for Fig. 12b but for Bracknell. See Fig. 12a for legend.

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The project has benefited from the computing and other talents of Mark Roseberry and from the conscientious work of Arthur McClean. The authors of the various slope irradiance algorithms are thanked for their assistance with the implementation of the various models. The study would not have been possible if numerous individuals had not painstakingly collected the slope irradiance data. Their contributions are gratefully acknowledged, as are the efforts of those who provided the actual data tapes and documentation.

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