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Estimating mean monthly incident solar radiation on horizontal and inclined slopes from mean monthly temperatures extremes

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Abstract Although satellite-borne sensors are now available to estimate cloud cover and incoming short-wave radiation across the Earth's surface, the study of climatic variation and its impact on terrestrial and marine ecosystems involves historical analyses of data from networks of weather stations that only record extremes in temperatures and precipitation on a daily basis. Similarly, when projections are made with global atmospheric circulation models, the spatial resolution of predicted radiation is too coarse to incorporate the effects of heterogeneous topography. In this paper, we review the development and set forth a set of general equations that allow both diffuse and direct solar radiation to be estimated for each month on the basis of mean daily maximum and minimum temperatures, latitude, elevation, slope, and aspect. Adjustments for differences in slope, aspect, and elevation are made by varying the fraction of diffuse and direct solar beam radiation. To test the equations on various slopes and under different climatic conditions, we drew on high-quality radiation data recorded at a number of sites on three continents. On horizontal surfaces the set of equations predicted both direct and diffuse components of solar radiation within 1%–7% of recorded values. On slopes, estimates of monthly mean solar radiation were with 13% of observed values with a mean error of less than 2 MJ $m^{-2}day^{-1}$ over any given month.

Keywords Radiation · Prediction · Minimum and maximum temperature · Slope correction

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Introduction

Although satellite-borne sensors are now available to estimate cloud cover and incoming short-wave radiation across the Earth's surface (Dubayah 1994), the study of climatic variation and its impact on terrestrial and marine ecosystems involves historical analyses that often depend on networks of weather stations that record only extremes in temperatures and precipitation on a daily basis. Similarly, when future projections are made using global atmospheric circulation models, the spatial resolution of predicted radiation layers is too coarse to incorporate the effects of heterogeneous topography.

In our own research, we have found a need to extrapolate limited years of calibrated radiation data back decades, to interpret the growth patterns of forests scattered across mountainous topography in Australia, western North America, and the United Kingdom (Coops et al. 1998; Runyon et al. 1994; Waring 2000).

Incoming solar radiation is a primary energy source for photosynthetic activity and the hydrological cycle (Woodwell 1967). Radiation from the sun passes through space practically undiminished until it reaches the top of the Earth's atmosphere (Brooks 1959). Even under clear sky conditions, the actual amount of solar radiation reaching the Earth's surface, compared to the potential, varies greatly over the year owing to many factors including the solar path length, aerosol, water vapor, dust and smoke content of the atmosphere. Topographical effects can also be highly significant, depending on the sun's position and the extent of cloud cover, which can both scatter and reduce the amount of solar radiation. For instance, in the Northern Hemisphere south-facing slopes on clear winter days may receive up to three times as much direct solar radiation as northern aspects with equivalent slopes (Klein 1977). By contrast the two aspects may receive nearly the same amount of solar energy on an overcast day, with a preponderance of diffuse radiation.

Economics limits the establishment of a network of radiation-monitoring stations even though a wide range of disciplines would profit by these data (Tovar et al. 1995). In contrast, there are many networks of stations that record temperature extremes and precipitation. These temperature data have the potential to be converted into estimates of incoming solar radiation (Thornton and Running 2000). A number of models now exist that predict solar radiation under a range of conditions but they differ in their demands for data describing the prevailing atmospheric conditions. Bristow and Campbell (1984) developed a model that related daily variation in air temperature to atmospheric transmittance. This approach has been coupled with potential radiation models that account for latitudinal, slope and aspect effects and then extended to separate diffuse from direct components of solar radiation (Garnier and Ohmura 1968; Buffo et al. 1972; Swift 1976; Hungerford et al. 1989). Recently, two critical constants required by the original Bristow and Campbell formulation have been determined more generally by Thornton and Running (2000).

In this paper, we demonstrate that both direct and diffuse components of monthly mean solar radiation can be predicted accurately using a combination of these methods. The combined technique is designed to provide good predictions of total, direct, and diffuse incoming solar radiation at various slopes and aspects on the basis of standard meteorological measurements. To test the equations on a variety of slopes and under different climatic conditions, we draw on high-quality radiation data recorded at a few sites on three continents.

Materials and methods

The modeling of incoming solar radiation began in the 1960s (Budyko 1956; Duguay 1993). Incoming solar radiation intersects the surface as either direct radiation, which arrives as a direct beam to the earth's surface, or diffuse radiation resulting from scattering from clouds and striking atmospheric gases, which may also include short-wave radiation that has been reflected by the earth's surface (Oke 1987).

Calculating potential direct radiation

The equations used to calculate potential incoming solar radiation under different atmospheric conditions are based on Garnier and Ohmura (1968), Buffo et al. (1972), and Swift (1976). The basic equation calculates incoming solar radiation on a slope:

$$Q_s = I_s + D_s \quad (1)$$

where Q_s is the total incoming solar radiation on a slope at the Earth's surface, I_s is the direct-beam radiation on a slope at the Earth's surface, and D_s is the diffuse radiation at the surface. The direct-beam radiation I_s at the surface is calculated by

$$I_s = \cos\phi (R_o NT^M) \quad (2)$$

where ϕ is the latitude, R_o is the solar constant above the atmosphere, N is the time interval for calculation in seconds, T is the total atmospheric transmittance calculated using temperature extremes (see Eq. 7), and M is the optical air mass calculated by;

$$M = 1.0/\cos Z_s + 1.0\times10^{-7} \quad (3)$$

where Z_s is the zenith angle.

In sloping terrain, the zenith angle must be modified by the angle of incidence, i (also known as the beam slope angle), given by:

$$\cos i = \cos s \cos Z_s + \sin s \sin Z_s \cos(A_z + A_s) \quad (4)$$

where s is the slope of the surface, A_z is the solar azimuth, and A_s is the aspect.

Calculating potential diffuse radiation

The component of diffuse radiation depends primarily on the zenith angle via the optical depth of the atmosphere as well as the turbidity of the atmosphere, the wavelength of light, and the amount of sky visible at the observation point, i.e. the sky view factor. Diffuse radiation is often assumed to be distributed equally from all parts of the sky (isotropic) but, in reality, its intensity is greatest nearest the sun.

Short-wave radiation reflected to a point from surfaces in the surrounding terrain may also be important especially when the surrounding surfaces are highly reflective, such as snow, however, most radiation modeling techniques ignore terrain-reflected radiation in their calculations.

The diffuse radiation at the surface on a slope (s) is calculated from Hungerford et al. (1989) by:

$$D_s = D_f \cos(s/2)^2 \quad (5)$$

where D_f is the diffuse radiation on a flat surface, which is calculated by:

$$D_f = [(R_o N \cos Z_s)^2 T^M]^{0.5} (1 - R_o NT^M \cos Z_s)^{0.5} \quad (6)$$

where R_o, N, T, $\cos Z_s$ and M have been defined in Eqs. 2 and 3.

The daily sum of the direct and diffuse components is obtained by numerical integration using N generally at 20-min intervals (Garnier and Ohmura 1968). Monthly sums are often derived from daily totals using hourly intervals.

Estimating actual radiation

To predict the actual radiation reaching the earth's surface, potential incoming solar radiation must be attenuated as a function of the atmospheric transmissivity, which varies according to cloudiness and optical air mass parameters associated with elevation.

Frank and Lee (1966) were amongst the first to address the problem of estimating radiation on slopes. They produced tables of potential solar beam radiation for different slopes, latitudes and times of the year. Similar tables were produced by Buffo et al. (1972).

To predict the components of incoming solar radiation accurately, Bristow and Campbell (1984) developed a relationship between the diurnal temperature extremes recorded at weather stations and the daily total solar radiation incident at the surface. They tested the method using data from three stations in the northwestern United States (U.S.) and showed that it was in good agreement with measured values. The Bristow and Campbell method has been applied in a number of other research studies and applied to a wide variety of environments including the continental U.S. (Glassy and Running 1994; Running et al. 1987), Australia (Coops et al.1998) and Scotland (Waring 2000).

The technique allows the calculation of atmospheric transmissivity as:

$$T = A[1.0 - \exp(-B\Delta^C] \quad (7)$$

where T is the mean daily atmospheric transmittance, A is the maximum atmospheric transmittance expected at the elevation of the site, Δ is the daily range in temperature and B and C are empirical coefficients that determine when T reaches the maximum atmospheric transmittance (A) based on daily temperature range (Δ) (Bristow and Campbell 1984).

Table 1 Values for coefficients (B and C) to calculate atmospheric transmissivity as a function of elevation (A) and temperature extremes Δ

Reference	A	B	C
Bristow and Campbell (1984)	0.70	0.036exp(−0.154Δ)	2.4
Thornton and Running (2000)	f (humidity, elevation)	0.031+0.201exp(−0.185Δ)	1.5
This paper	0.65+0.008 × elevation ×10^{-2}	0.031+0.201exp(−0.185Δ)	1.5

Replace (Elv.* 0.0001 +1.0143)*0.65

Table 2 Location of test sites and description of available data

Station name	Latitude (°)	Longitude (°)	Elevation (m)	Data available	Time step	Recording period	Aspect (°)	Slopes	Source
Eugene	123.07 W	44.05 N	150	Direct/diffuse	Daily/monthly	1997	–	0	University of Oregon Solar Laboratory (1983)
Corvallis	123.3 W	44.38 N	80	Direct/diffuse	Monthly	8 year averages	180	0, 15, 30, 45, 70, 90	Baker and Reynolds (1975)
Spokane	117.5 W	47.37 N	730	Direct/diffuse	Monthly	19 year averages	180	0, 15, 30, 45, 70, 90	Baker and Reynolds (1975)
Glasgow	4.2 W	55.5 N	10	Total	Monthly	50 years	–	0	Lebens 1986
Canberra	149.4 E	35.3 S	850	Total	Monthly	30 years	–	0	McMurtrie et al. (1994)

Thornton and Running (2000) undertook a sensitivity analysis of the estimation of coefficients A, B and C using a large selection of sites in North America for which both daily temperature extremes and solar radiation data were available. As a result of their analysis a number of adjustments were made in the estimation of A, B and C in the Bristow and Campbell method. These adjustments improved estimates of daily solar radiation to within ±2.4 MJ m^{-2} day^{-1} at 40 stations in the U.S. covering a range of climates and elevations.

Estimating monthly mean incoming solar radiation

Both the original Bristow and Campbell method and further work of Glassy and Running (1984) and Thornton et al. (1997) utilized daily temperature extremes to predict daily total solar incoming radiation. The original Bristow and Campbell method utilized 2-day averaging of daily temperature differences to provide a more stable estimate of the empirical coefficients. In the later work of Thornton and Running (2000) this type of averaging produced poorer results than simply taking actual daily temperature extremes. More accurate estimates of A, however, were obtained by recognizing regional differences in maximum atmospheric transmissivity as well as those associated with latitude, elevation and water vapor content of the atmosphere. Improvements were also made by including daily or 7-day mean adjustments of solar declination angles and day length.

In a detailed analysis Erbs et al. (1982) concluded that a number of variables affecting atmospheric stability were critical when predicting diffuse and direct radiation at hourly time scales. Their importance, however, diminished significantly when predicting mean incoming solar radiation per month. They concluded that estimates of monthly incoming solar radiation were generally more accurate than hourly or daily values.

Final monthly modeling formulation

Whilst it is possible to predict monthly mean direct and diffuse radiation accurately from monthly mean temperature averages, variation in solar declination angles and day length throughout the month need to be taken into account. The modeling procedure applied in this paper to predict monthly solar radiation includes the following six steps:

1. Monthly means of daily minimum and maximum air temperature estimates provided a basis for generating a set of daily temperature estimates necessary to account for daily shifts in solar radiation, solar declination, day length and zenith angle. To do this, a synthetic set of daily minimum and maximum temperature data were generated by replacing daily temperature estimates with the mean minimum and maximum temperatures for each respective month.
2. Site elevations and latitude are specified to estimate maximum clear sky transmissivity (A) with the assumption that A is 0.65 at mean sea level and increases by 0.008 per meter of elevation.
3. Final atmospheric transmittance is calculated as an exponential function of the diurnal temperature amplitude at the site (Bristow and Campbell 1984) using the revised estimates of empirical coefficients B and C (Thornton and Running 2000) (see Table 1).
4. Potential direct and diffuse radiation was calculated using a model adapted from Garnier and Ohmura (1968) and Swift (1976), which allows for adjustments for slope and aspect (see Running et al. 1987 for more details). The Garnier and Ohmura (1968) geometry also allows for the direct-beam solar irradiance to be truncated by the east and west horizon of the site if information is available about the local terrain. This latter step was not included in the current study.
5. The final estimate of incoming solar radiation to the site was then computed as the above-atmosphere radiation reduced by the atmospheric transmittance (Garnier and Ohmura 1968; Buffo et al. 1972; Swift 1976; Hungerford et al. 1989).
6. Monthly incoming solar radiation was then derived by summing daily estimates of solar radiation throughout the month.

Selection of test sites

The number of meteorological stations that routinely record daily or monthly measurements of total incoming solar radiation is limited (Nunez 1980). This number is further reduced if a breakdown is required of total incoming solar radiation into its direct and diffuse components and for a range of slopes and aspects. Fortunately, some limited sets of data have been compiled by architectural designers (Baker and Reynolds 1975).

We selected a number of data sources to test the modeling approach; some of these are listed below.

1. Direct and diffuse components of total incoming solar radiation were available at daily time steps for Eugene, Oregon (123.07°W, 44.05°N), USA, by the University of Oregon Solar Radiation Monitoring Network (University of Oregon Solar Radiation Laboratory 1983). The Eugene station is a designated first-class radiation station.
2. Baker and Reynolds (1975) compiled a dataset of global incoming direct and diffuse solar radiation at monthly time scales at 22 stations in the Pacific Northwest of the United States. In addition to the component breakdown, the dataset was compiled for architectural design applications and thus provided information for a number of different slopes ranging from horizontal to vertical at 15° slope increments. All of these data were collected at a single aspect (due south). In this study a subset of 2 stations was selected at two slopes: 15° and 45°.
3. Finally, to test the applicability of the model at a range of climatic extremes, standard meteorological station data on total incoming monthly radiation were obtained. Two meteorological stations were selected: Glasgow, Scotland, and Canberra, Australia. The data available at these sites, however, were limited to total incoming solar radiation measured on a standard horizontal plane.

Specific data on station locations and attributes, and the type and amount of data collected can be seen in Table 2.

Results

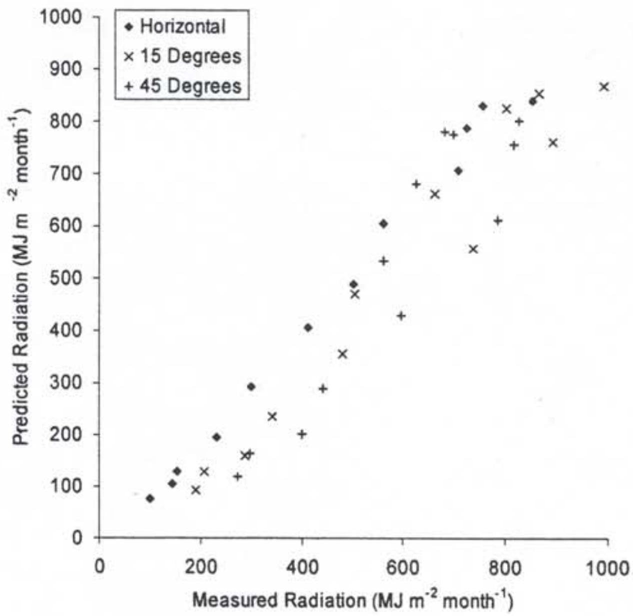
Figure 1a, b shows the relationships between measured and predicted total incoming monthly solar radiation at Spokane, Washington, and Corvallis, Oregon. At both sites, incoming solar radiation data were obtained from Baker and Reynolds (1975) who measured radiation at a number of slope angles. In this comparison, we selected horizontal, 15° and 45° slopes. In all cases, the slope aspect was 180°. At the Corvallis site, radiation data were averaged over a 9-year period, whereas 19 years of data were available at Spokane. In both cases, temperature data were extracted from the nearest long-term meteorological climate station and used as inputs for the predictions.

Linear regressions between the predicted components of incoming solar radiation at the different slope angles and the measured diffuse and direct components for the datasets are presented in Table 3. Table 3 also presents the number of points in the analysis (n), the coefficient of determination (R^2), the regression coefficients (m and c to provide the equation $y=mx+c$) and the standard error of the prediction (SE) in MJ m^{-2} $month^{-1}$.

Figure 2 shows the relationship between the predicted and observed total and diffuse incoming solar radiation at Eugene, Oregon, for a standard horizontal surface. These data were obtained from the University of Oregon and contained monthly radiation measurements for 1997 and mean monthly minimum and maximum temperature estimates for the same period. As a result, the predictions are for each month in 1997.

Linear regressions between the predicted components of the incoming solar radiation at Eugene and measured diffuse and direct components are also shown in Table 3. This analysis is for each day in 1997 using the measured daily minimum and maximum temperature values and the measured daily total, direct and diffuse components.

a



b

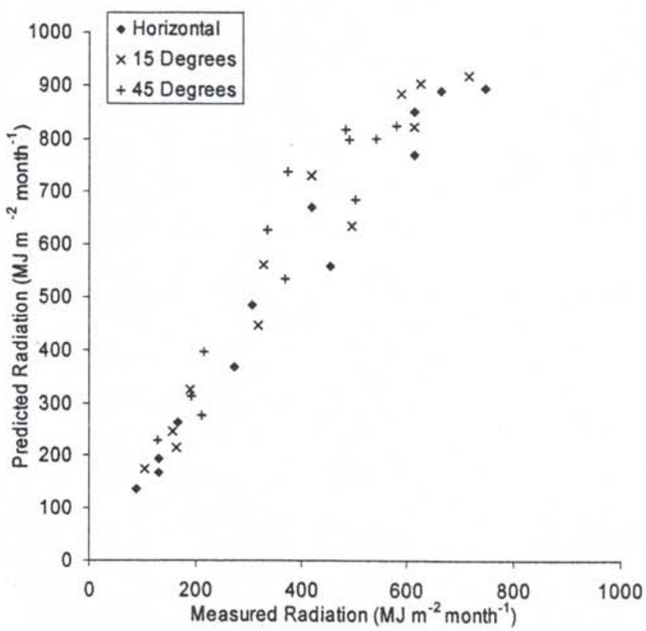


Fig. 1a, b Relationship between measured and predicted total monthly radiation for 3 slopes at (**a**) Spokane, Washington, and (**b**) Corvallis, Oregon

Again the R^2, regression coefficients, and the standard error of these linear regressions are presented in Table 3.

Figure 3 shows the technique applied to standard monthly long-term minimum and maximum temperature measurements to predict mean monthly total radiation at two sites representing diverse environments around the globe: Canberra, Australia, and Glasgow, Scotland. These examples demonstrate the generality of the modeling ap-

Table 3 Statistical comparison of observed with predicted solar radiation at several sites

Site	Radiation type	Slope (°)	Aspect (°)	Linear regression analysis				
				n	R^2	Slope (m)	Intercept (c)	SE (MJ m^{-2} $month^{-1}$
				Based on mean monthly statistics				
Spokane	Diffuse	0	–	12	0.98	1.18	1.0	9.06
	Direct	0	–	12	0.98	1.05	–42.2	36.08
	Total	0	–	12	0.99	1.09	–42.9	30.18
	Diffuse	15	180	12	0.97	1.16	–1.6	12.15
	Direct	15	180	12	0.93	0.97	–91.1	61.89
	Total	15	180	12	0.95	1.03	–100.5	65.42
	Diffuse	45	180	12	0.97	1.55	–1.9	11.98
	Direct	45	180	12	0.97	1.10	–175.9	88.55
	Total	45	180	12	0.87	1.26	–226.2	98.31
Corvallis	Diffuse	0	–	12	0.99	1.01	31.6	5.59
	Direct	0	–	12	0.93	1.34	43.2	61.21
	Total	0	–	12	0.96	1.23	47.0	54.43
	Diffuse	15	180	12	0.99	1.01	31.6	5.60
	Direct	15	180	12	0.95	1.37	46.2	70.80
	Total	15	180	12	0.97	1.30	56.1	65.54
	Diffuse	45	180	12	0.99	1.34	31.2	5.39
	Direct	45	180	12	0.90	1.34	59.8	76.70
	Total	45	180	12	0.94	1.41	65.2	77.10
Eugene	Diffuse	0	–	12	0.83	0.92	20.1	28.03
	Direct	0	–	12	0.89	1.01	63.0	73.25
	Total	0	–	12	0.97	1.12	20.8	49.30
Canberra	Total	0	–	12	0.95	1.2	–51.0	61.54
Glasgow	Total	0	–	12	0.93	1.2	39.8	78.30
				Based on daily values				
Eugene	Diffuse	0	–	365	0.37	0.39	3.6	1.61
	Direct	0	–	365	0.55	0.57	5.9	4.53
	Total	0	–	365	0.77	0.86	4.3	4.31

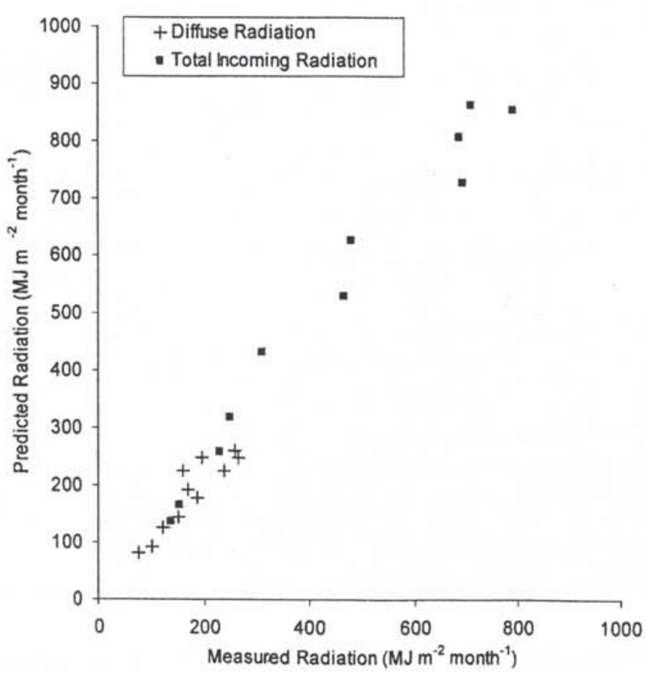


Fig. 2 Relationship between predicted and observed total and diffuse monthly radiation at Eugene, Oregon

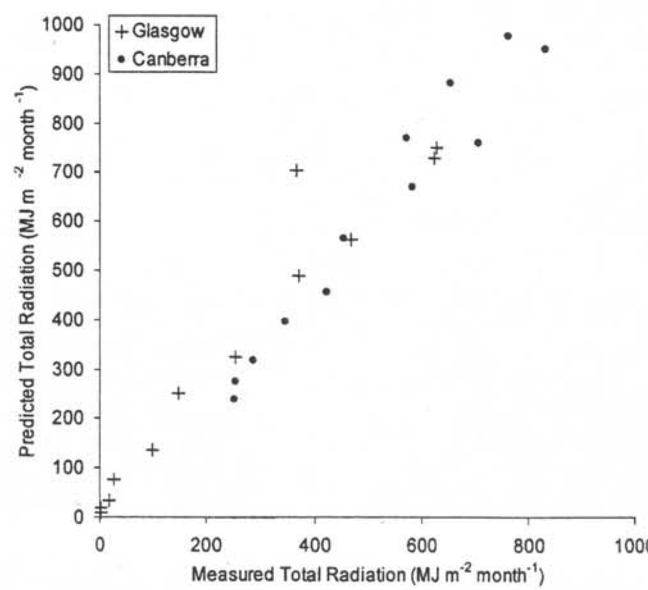
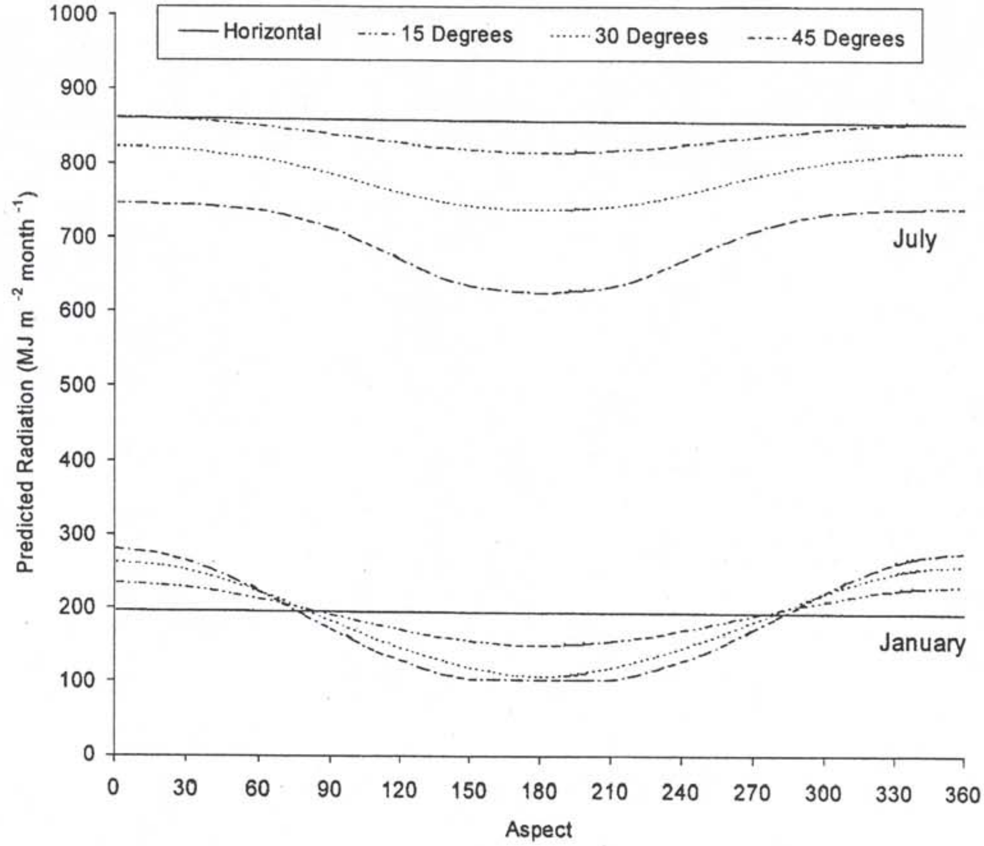
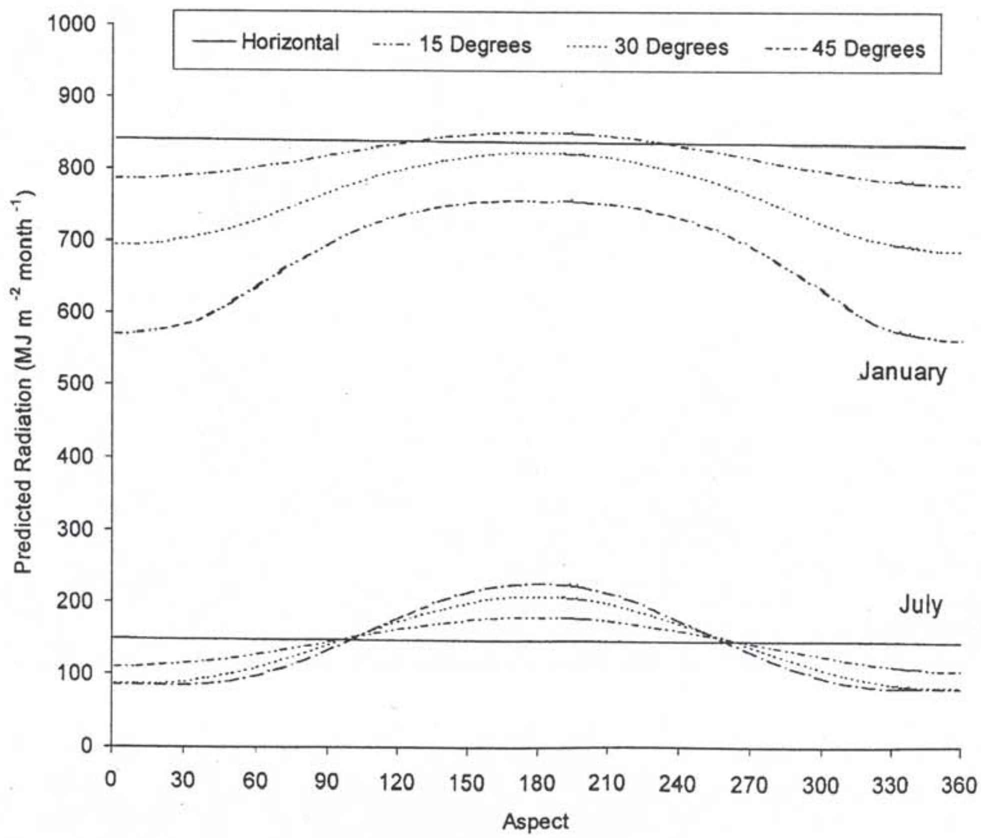


Fig. 3 Relationship between predicted and observed total monthly radiation at Glasgow, Scotland, and Canberra, Australia

Fig. 4a, b Predicted magnitude and radial distribution of total incoming solar radiation at (**a**) Eugene, Oregon, and (**b**) Canberra, Australia, for January and June at four different slopes. The magnitude of the total monthly solar radiation predicted at each site for four different slopes (horizontal, 15°, 30° and 45°) is displayed for two selected months, January and June





proach as it allows estimates of monthly mean solar radiation to be extended to locations where only mean monthly minimum and maximum temperature data are available. Table 3 also shows the linear regressions between observed and predicted estimates at these two sites.

Discussion

The results presented in Fig. 1a and Table 3 for Spokane demonstrate generally good agreement between predicted and observed total monthly incoming solar radiation, and the diffuse and direct-beam components. For a horizontal surface, the modeling approach explains 99% of the variation observed in total radiation with a bias in the slope of the comparison of less than 10%. This prediction has a mean error of 30 MJ m^{-2} $month^{-1}$, which corresponds to less than 1 MJ m^{-2} day^{-1}. The error in the diffuse component is significantly smaller (9.0 MJ m^{-2} $month^{-1}$) primarily because of its smaller magnitude. These results are similar to the Corvallis site, as shown in Fig. 1b, with a slightly lower R^2 value (0.96) and an increased standard error of 54 MJ m^{-2} $month^{-1}$.

The relation between predicted and observed monthly radiation measured at two different slopes (15° and 45°) remains strong with predictions explaining more than 87% of the observed variation at Spokane and 94% at Corvallis. The relationship becomes slightly weaker as the slope increases possibly because of the effect of reflected radiation, which is not accounted for in these predictions and has increasing importance on steep slopes. The modeling approach appears to over-estimate radiation slightly at both sites with the linear regression slope reaching 1.2 with a standard error of 98 MJ m^{-2} $month^{-1}$, which is still less than 3 MJ m^{-2} day^{-1} at Spokane. Again, the results are similar at Corvallis, as demonstrated in Fig. 1b, with the predictions achieving greater accuracy (an equivalent error of 2.5 MJ m^{-2} day^{-1}) with increasing slope gradient.

Predictions of actual monthly radiation estimates at Eugene, based on 1997 monthly temperature data, showed similar accuracy to the results observed at Spokane with a very high coefficient of determination for total incoming solar radiation over the 12 months. Prediction of diffuse radiation is slightly less accurate (R^2=0.83) although the overall error is still around 28 MJ m^{-2} $month^{-1}$. Daily predictions of solar radiation are also highly significant (Table 3 in the lower section) although less accurate than the monthly estimates. Error associated with these latter estimates is greater because of diurnal variation in temperature and seasonal variation in atmospheric conditions. In this aspect, these results are similar to those presented by Thornton and Running (2000) who obtained a standard error of estimate of daily total incoming solar radiation of 2.98 MJ m^{-2} day^{-1} over a 4-year period compared to 4.3 MJ m^{-2} day^{-1} for a 1-year period.

Figure 4 indicates the general utility of the modeling approach by displaying the results that can be expected when applying the observed relationships at a variety of locations over the globe. Usually the predictions have R^2 >90% with SE <2 MJ m^{-2} day^{-1} for mean monthly predictions. The approach appears applicable in either hemisphere and over a range of elevations.

One of the major benefits of the modeling approach is its capacity to be applied to any slope and aspect. This makes the approach useful at individual sites as well as across broad landscapes. An example of the generality of the approach is demonstrated in Fig. 4. which shows how the total solar radiation varies at Eugene, Oregon (44°N), and Canberra, Australia (35°S), on 0°, 15°, 30° and 45° slopes in the months of June and January. Besides the obvious seasonal differences in solar radiation at different latitudes, the diagram shows a general reduction in the total solar radiation at increasing slope gradient. This occurs except when the aspect is exposed to direct-beam slope radiation, which occurs at southern aspects in the Northern Hemisphere and at northern aspects in the Southern Hemisphere. By accounting for slope and aspect, the radiation is estimated to vary by more than 200 MJ m^{-2} $month^{-1}$ during the summer in both hemispheres. Clearly there are benefits in accounting for slope and aspect when predicting incident solar radiation.

This modeling approach illustrates the possibility of obtaining realistic radiation data for many types of model at selected geographical locations via extrapolation of temperature data across broad landscapes. Whilst detailed process-based models of radiation, at short time scales, may be appropriate for fine-scale modeling of incoming solar radiation at single-point locations, more general empirical models, such as the one presented here, are more appropriate for longer time frames and landscape-based model regimes. Likewise, whilst satellite-borne sensors are now available to estimate cloud cover and estimate incoming short-wave radiation across the earth's surface, there is still a strong requirement to compute total incoming solar radiation from existing meteorological datasets (Wang et al. 2000). This is both for generation of historical datasets based on existing climatic databases as well as for the prediction of incoming solar radiation from global atmospheric circulation models. This issue is particularly timely because of the increased usage of global circulation models in global change scenarios. Typically, radiation estimates are produced at spatial scales that do not allow incorporation of the effects of heterogeneous topography and may be predicted independently of changing precipitation regimes or atmospheric vapor pressure deficit. As a result, an independent method of predicting spatial coverages of incoming total solar radiation is widely beneficial.

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