Modelling Solar Radiation in the Forests of Southeastern Australia

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Abstract A solar radiation surface for the Eden forest region in south-eastern NSW was required as a component of forest growth models. To model radiation across the landscape requires consideration of sun position, atmospheric transmittance, local slope orientation, shadowing by surrounding terrain and the effects of cloud. Sun position is readily computed given the latitude, date and time, and slope orientation and shadowing can be derived from a suitable digital elevation model. The effects of cloud and atmospheric transmittance are usually determined from solar radiation measurements, but in this case there are no solar radiation measurements available anywhere in the study area. Hutchinson's Australian rainfall-corrected radiation surface was used to parameterise cloud effects. The SRAD model was used to estimate the long term average daily radiation for each month, with modifications to permit spatially varying climatic parameters. The implications of this parameterisation and the need for a validation study are discussed.

1. INTRODUCTION

The Comprehensive Regional Assessment process for the Eden forest region of New South Wales required estimates of average monthly and annual solar radiation across the region for tree growth modelling. Solar radiation is highly variable both in time and space. Temporal variability at fine scales (hours and days) is important for evaporation, but for plant growth long term average radiation is more appropriate, although seasonal variations must also be considered.

The spatial variability of solar radiation can be considered at three different scales. At the broadest scale, latitude is the dominant control. At intermediate scales, cloud and atmospheric absorption modulate the amount of solar radiation received at the surface. Finally topography — through slope and aspect and shadowing — and surface vegetation cover further modify the radiation regime at fine scales. The variations at different scales interact in a complex manner with each other and with the temporal variations: seasonal effects are greatest at high latitudes, as are topographic effects, while the topographic effects are less significant during cloudy periods than under clear skies.

In the Eden CRA region, and indeed the entire south coast of New South Wales, there are marked changes in climate and topography as one moves from the coastal lowlands up the rugged escarpment to the ancient rolling plateau of the Southern Tablelands. The changes in cloudiness, topography and elevation over a distance of only 60 km induce corresponding changes in the radiation regime.

There are less than 20 long-term radiation monitoring stations across Australia and around a hundred stations that record sunshine hours, from which radiation can be estimated. In the Eden CRA region there are no measurements of either type, so there is no radiation data available for the region. The only radiation estimates for this area are Hutchinson's monthly mean surfaces (Hutchinson et al., 1984), which were not considered sufficiently sensitive to the topographic complexity of the area. An explicit modelling approach was therefore required.

2. MODELLING SOLAR RADIATION

Figure 1 shows the conceptual model for short-wave solar radiation and its progression through the atmosphere. Radiation arriving at the top of the atmosphere is attenuated and scattered by its passage through the atmosphere. A proportion remains as direct radiation, while the scattered radiation gives rise to diffuse radiation from the whole sky. The radiation received at a site is the sum of the direct

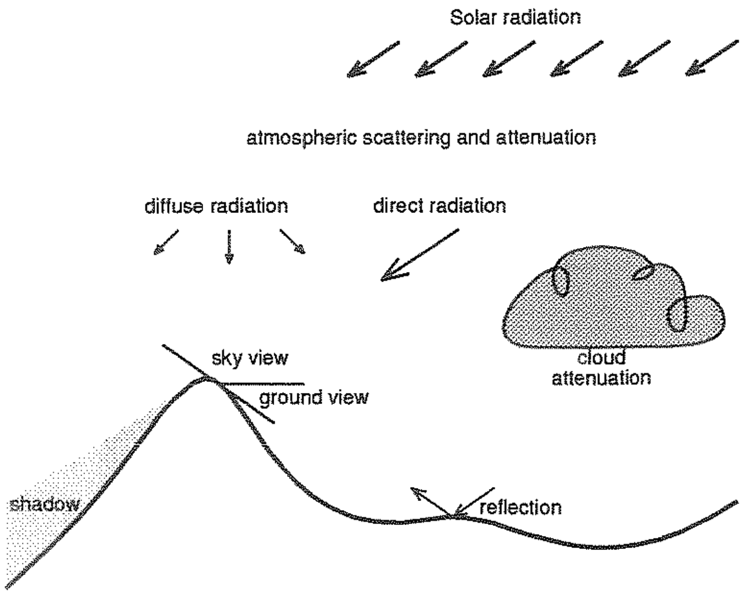


Figure 1: The conceptual model for shortwave solar radiation.

radiation (taking account of shadowing and the orientation of the surface), diffuse radiation (modified by sky view) and reflected radiation (controlled by the ground view).

In addition to the incoming shortwave radiation, both incoming and outgoing longwave radiation must be accounted for to arrive at an estimate of net radiation. The calculation of longwave radiation balance is largely independent of the shortwave component apart from the effect of shortwave radiation on surface temperature.

The factors that need to be accounted for to estimate shortwave solar radiation are:

- sun-earth geometry, dependent on location and time of year;
- atmospheric transmittance;
- the intensity and directional properties of diffuse radiation;
- the occurrence and transmittance of clouds;
- cast shadows and the orientation of the surface;
- radiation reflected from foreground terrain.

The precision with which these factors can be modelled varies greatly. Sun-earth geometry and the effects of slope, aspect and shadowing on direct radiation can be calculated very accurately. Atmospheric transmittance and scattering can be modelled less accurately, while cloud transmittance and occurrence are quite difficult to model largely because of spatial and temporal variability. The reflection of radiation from foreground terrain is also difficult to model accurately because of complex interactions between incident angle and apparent reflectance. The more complex phenomena require simplified models with parameters estimated from measurements.

3. THE SRAD MODEL

The SRAD model (Wilson and Gallant, 1997) was developed by the late Ian Moore (Moore et al., 1993) based largely on two existing programs: CLOUDY (Fleming, 1987) which calculates solar position, atmospheric and cloud effects and slope-aspect effects; and the fast horizon algorithm of Dozier et al. (1981). SRAD computes at every location in a DEM the incoming short-wave radiation accounting for direct, diffuse and reflected components, incoming and outgoing long-wave radiation, net radiation and minimum, maximum and surface temperatures. An overview of the model is given here; further details can be found in Moore et al. (1993), Wilson and Gallant (1997) and Iqbal (1983).

3.1 Sun-Earth Geometry

There are a number of factors to be accounted for in calculating extra-terrestrial radiation Q_A, the radiation received on a horizontal surface in the absence of an atmosphere. The earth's slightly elliptical orbit causes variations in the apparent solar intensity amounting to about +/- 3.5%. Solar declination also varies on a yearly cycle. The angle between the sun and the local zenith can be calculated from trigonometry given the declination, latitude, and time. From this relationship, the time of sunrise and sunset can be calculated (ignoring atmospheric refraction) and thus the number of hours in the day N. Equations for each of these can be found in Iqbal (1983).

The effects of slope and aspect are introduced after atmospheric and cloud effects have been included.

3.2 Atmospheric Absorption and Scattering

SRAD provides two options for computing atmospheric absorption and scattering: a component model based on water and dust concentrations, or a lumped model specifying only a single transmittance value. The latter option was chosen for this study because of the lack of information on the components.

The direct radiation component Q_{dir} is the radiation remaining after absorption and scattering, accounting for the relative optical path length due to sun elevation:

$$Q_{dir} = Q_0 T^{L_{opt}} \tag{1}$$

where Q_0 is the solar constant (radiation arriving at the top of the atmosphere), T is the atmospheric transmittance for a vertical path and L_{opt} is the relative optical path length (1 for a vertical path to sea level). L_{opt} is computed using trigonometry for solar elevations above 30° but atmospheric curvature and refraction makes this inaccurate at lower elevations so an interpolation table is used (Fleming, 1987).

Diffuse radiation Q_{dif} is equal to half the scattered radiation after absorption has been accounted for, based on the assumption of isotropic scattering with half directed downwards and the other half directed upwards back into space. In SRAD's lumped transmittance model diffuse radiation is modelled by a simple empirical formula:

$$Q_{dif} = 0.271 - 0.294\frac{Q_{dir}}{Q_0} \tag{2}$$

In practice it is apparent that the diffuse radiation is not isotropic even on perfectly clear days and a substantial proportion of the diffuse radiation arises from a region of the sky around the solar disk. This fraction is called the circumsolar diffuse component, and this portion of the diffuse radiation is considered together with direct radiation so it is affected by slope-aspect effects and shadowing.

3.3 Cloud Effects

Cloud is modelled in SRAD by dividing the daytime into clear and cloudy fractions. During the cloudy fraction the total radiation is reduced by a factor β representing average cloud transmittance:

$$Q_{cloudy} = Q_{clear}\beta \tag{3}$$

where Q_{clear} is the total clear-sky radiation on a horizontal surface. Q_{cloudy} is considered to be isotropic diffuse radiation so is affected by sky view but not slope-aspect and shadowing effects.

If the number of hours of clear-sky conditions is n, the cloud-free fraction of the day (the sunshine fraction) is n/N and the cloudy fraction is $1 - n/N$. The average radiation received is then:

$$Q = Q_{clear}(n/N + \beta(1 - n/N)) \tag{4}$$

Note that this equation does not allow for systematic variations in cloud throughout the day; this might be important in summer when clear mornings and cloudy afternoons are more common than the opposite.

This equation is not used directly because the direct and diffuse components of Q_{clear} are modified differently by topographic effects as shown in Equation 5.

3.4 Topographic Effects

The horizon is calculated as the angle above horizontal at 16 steps around the horizon. The algorithm used to perform this calculation is optimised and computes forward and backward horizon angles along a profile (Dozier et al., 1981). The profiles are constructed from the DEM at the 8 angles 0, 22.5, 45, 67.5, 90, 112.5, 135 and 157.5 degrees. These computations are performed once and the results stored for the duration of the run.

Sky view ν is the proportion of the sky hemisphere visible from a point on the surface, and is computed from the horizon angles. Ground view is $1 - \nu$.

Slope and aspect of each surface point are calculated from finite difference approximations (Gallant and Wilson, 1996) and are used to determine the direction of the normal to the surface. At a particular time the angle of incidence θ_I of the direct radiation component is the angle between the surface normal and the direction to the sun (Iqbal, 1983).

3.5 Reflected Radiation

The reflected radiation is modelled as the horizontal radiation multiplied by albedo α. Spatial variation in albedo is not accounted for; in eucalypt forests this is of little importance as albedo tends to be fairly uniform and low, usually less than 0.2. Variations of reflectance with the incident and reflected angles are ignored.

3.6 Total Shortwave Radiation

The total incoming shortwave radiation is the sum of radiation during clear periods and radiation during cloudy periods. Radiation in clear periods is comprised of direct and circumsolar diffuse radiation modified by slope, aspect and shadowing; diffuse radiation modified by sky view; and reflected clear-sky radiation on a horizontal surface, modified by ground view. Radiation in cloudy periods is comprised of the cloudy-sky radiation modified by sky view and reflected cloudy-sky radiation modified by ground view.

$$\begin{aligned} Q &= (Q_{dir}\cos\theta_I + Q_{dif}\nu + Q_{clear}\alpha(1-\nu))n/N \\ &+ (Q_{cloudy}\nu + Q_{cloudy}\alpha(1-\nu))(1-n/N) \end{aligned} \quad (5)$$

This equation is evaluated at 12 minute intervals from sunrise to sunset to give total daily shortwave radiation; the equivalent quantity for a horizontal surface without shadowing Q_{hor} is also computed. A further quantity, the shortwave radiation ratio $S = Q/Q_{hor}$ is also computed for use in temperature modelling.

3.7 Temperatures

SRAD requires surface and air temperatures to compute longwave radiation. Temperatures are modified by the shortwave radiation ratio to account for higher temperatures on surfaces facing the sun:

$$T = T_{hor} + C\left(S - \frac{1}{S}\right)\left(1 - \frac{LAI}{LAI_{max}}\right) \quad (6)$$

where T_{hor} is the temperature measured at a site in horizontal terrain, LAI is leaf area index and LAI_{max} is the maximum leaf area index — higher leaf area index moderates the effect of the shortwave radiation ratio S on temperature. This equation is a corrected version of the equation originally used in the program. Surface and maximum air temperatures are modified according to this equation, but minimum temperature is not since it occurs at night when there is no solar radiation.

3.8 Longwave Radiation

Outgoing longwave radiation is calculated directly from surface temperature. Incoming longwave radiation arrives from both sky and ground, with the sky component controlled by atmospheric temperature:

$$L_{out} = \epsilon_s \sigma T_s^4 \quad (7)$$

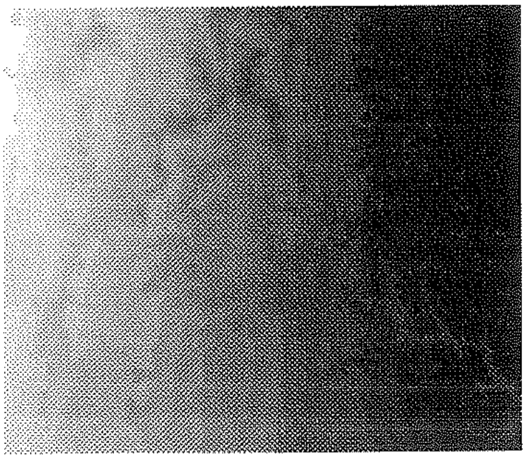
$$L_{in} = \epsilon_a \sigma T_a^4 \nu + L_{out}(1-\nu) \quad (8)$$

where ϵ_s and ϵ_a are the surface and atmospheric emissivity, σ is the Stefan-Boltzmann constans, T_s and T_a are the surface and air temperatures and ν is the sky view factor.

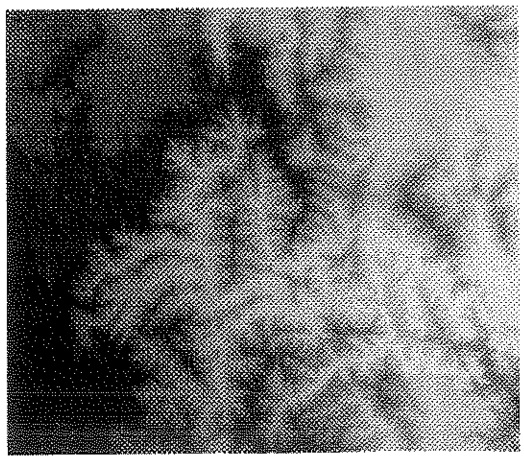
4. PARAMETERS

A number of parameters are required by the SRAD model, describing the properties of the atmosphere, cloud and surface. As originally developed, the model requires a single value of each parameter for each month. This permits seasonal variation of cloudiness and atmospheric properties but does not permit any spatial variation. The program was modified to allow some of the parameters to vary spatially by providing a parameter surface grid for each month, rather than a single value for each month. The parameter grids do not have to be at the same resolution as the DEM. In this study the DEM resolution was 20 m while the parameter surfaces were developed at 100 m resolution. The parameter values at each DEM grid point are derived from the nearest parameter grid points using bilinear interpolation.

With no radiation records within or near the study area, many of the parameters could not be calculated from measured data. Two parameters were set to "generic" values that are considered reasonable when there is no measured data available. Circumsolar coefficient was set to 0.25, as suggested by Wilson and Gallant (1997): 25% of all diffuse radiation comes from a region around the solar disk. For albedo, a typical value for eucalypts of 0.15 was chosen, and it was assumed that there is no variation from month to month.



(a)



(b)

Figure 2: Sunshine fraction surfaces for a segment of the Eden area. Lighter shades represent higher radiation values. (a) January; range is 0.59 to 0.63. (b) July; range is 0.61 to 0.66.

Sunshine fraction, atmospheric transmittance and cloud transmittance were calculated using the modified Angstrom equation and the parameters derived by Hutchinson et al. (1984). The modified Angstrom equation describes the relationship between the total radiation received at the earth's surface Q, extraterrestrial radiation Q_A and the sunshine fraction n/N:

$$\frac{Q}{Q_A} = a + b\,n/N \qquad (9)$$

(Prescott, 1940; Iqbal, 1983). Hutchinson et al. (1984) used radiation and sunshine hours data from the 11 Australian radiation stations available at the time to determine the parameters a and b for each month. From these parameters the atmospheric transmittance T and average cloud transmittance β parameters can be calculated by re-arranging Equation (4) to the form of (9) and noting that $Q_{clear} = TQ_A$:

$$\begin{aligned} \frac{Q}{TQ_A} &= n/N + \beta(1 - n/N) \\ \frac{Q}{Q_A} &= T(\beta + (1-\beta)n/N) \qquad (10) \end{aligned}$$

from which it is clear that

$$\begin{aligned} a &= T\beta \\ b &= T(1-\beta) \end{aligned}$$

which can be re-arranged to give:

$$\begin{aligned} T &= a + b \qquad (11) \\ \beta &= \frac{a}{a+b} \qquad (12) \end{aligned}$$

Hutchinson's results and the derived T and β values are shown in Table 1.

Month	a	b	$T = a+b$	$\beta = a/(a+b)$
January	0.266	0.457	0.723	0.368
February	0.265	0.448	0.713	0.372
March	0.203	0.534	0.737	0.275
April	0.197	0.526	0.723	0.272
May	0.188	0.524	0.712	0.264
June	0.203	0.498	0.701	0.290
July	0.225	0.476	0.701	0.321
August	0.242	0.457	0.699	0.346
September	0.237	0.482	0.719	0.330
October	0.235	0.494	0.729	0.322
November	0.245	0.485	0.730	0.336
December	0.227	0.508	0.735	0.309

Table 1: The coefficients a and b of the modified Angstrom relationship as reported by Hutchinson et al. (1984), and the derived parameters atmospheric transmissivity T and cloud transmissivity β.

Hutchinson et al. (1984) also derived a radiation surface that accounted for spatial variations in cloudiness using a transformed rainfall surface as a third independent variable. From this rainfall-corrected radiation surface, a sunshine fraction (n/N) surface can be calculated by re-arranging Equation 9:

$$n/N = \frac{Q/Q_A - a}{b} \qquad (13)$$

Q_A can be calculated from solar geometry alone (Iqbal, 1983). It is likely that average cloud transmittance β varies spatially as well but there is no information from which this spatial variation can be determined.

Figure 2 shows the derived sunshine fraction surface for a section of the study area in both January and July.

Temperatures in the original model were extrapolated from a single reference station in the study area using lapse rates to account for changes due to elevation as well as Equation (6) to account for the effects of radiation relative to a horizontal surface. In a large study area this approach is too simplistic, so the program was modified to accept spatially varying temperature surfaces, obviating the need for lapse rates. The Australian climate surfaces (CRES, 1997) were used to derive minimum and maximum temperature and the average of these two was used for both average air temperature and surface temperature.

5. COMPUTATION

SRAD is written in Fortran 77 and requires about 80 bytes of memory per DEM grid cell. The Eden study area covered about 13 500 km^2 at 20 m resolution, comprising about 32 million grid cells. The memory requirements for the whole DEM were 2.6 Gbytes which exceed the limits of a 32-bit operating system, so the DEM had to be broken into 3 overlapping sections to perform the analysis.

On a Sparc Ultra computer with copious memory and disk capacity, the program required about 18 hours per section per month to execute. Outputs were obtained for mid-January, April, July and October and the results averaged to provide estimates of annual radiation.

6. RESULTS

Figure 3 shows the net radiation surfaces for January and July in a portion of the Eden area encompassing plateau, escarpment and flat lowlands. The plateau ranges from 1000 to 1200 m while the lowlands are at 100 to 200 m elevation.

In January the range of radiation values is from 11 to 18 MJ/m^2/day. Radiation increases with increasing elevation due to the reduced air mass; the plateau area also receives less rain and therefore (according to the assumptions used in the rainfall-corrected radiation surface) less cloud and higher sunshine fraction n/N. Radiation on the flat lowland areas is about 15.7 MJ/m^2/day and on the flat highland areas is about 17.4 MJ/m^2/day, an increase of about 10%. Approximately half of this difference is due to elevation alone and the other half to differences in cloudiness.

Because the sun is very high in summer the effect of slope and skyview (horizons) is stronger than that of aspect. Ridge lines show up as high radiation areas, with lower values on the slopes. South-facing slopes have somewhat lower radiation than north-facing slopes, but the lowest radiation areas are on steep east- and west-facing slopes that are shadowed for a substantial portion of the day. Some typical values from the rugged escarpment area are: ridge 17.1; north-facing slope 15.4; south-facing slope 14.1; and west-facing slope 11.0 MJ/m^2/day.

In winter the radiation is much less and the spatial patterns are very different. The difference between flat lowlands (2.0 MJ/m^2/day) and flat highlands (2.2 MJ/m^2/day) is still about 10%, but this difference is now overwhelmed by the effects of aspect because of the low sun angles. The north-facing slopes now receive substantially more radiation than the flat areas regardless of elevation, up to 4.3 MJ/m^2/day. South-facing slopes receive much less and some steep areas are permanently shadowed resulting in very little incoming shortwave radiation (diffuse only) and negative net radiation (-0.2 MJ/m^2/day) due to the long-wave radiation deficit.

6.1 Validation

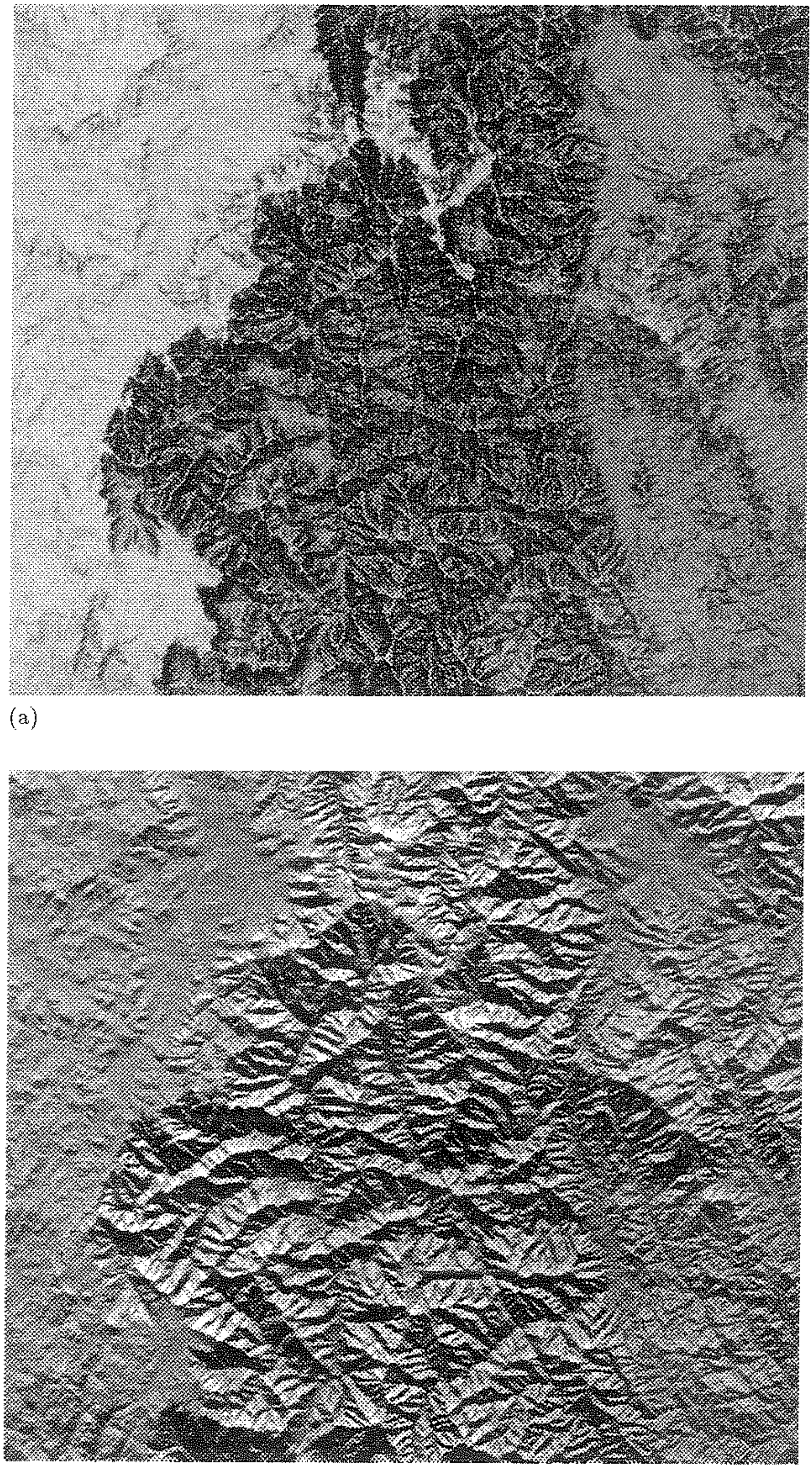
In the absence of any radiation measurements in the area, validation of this model application is not possible. Although much of the model is based on sound physical equations, some parts such as the cloud effects are entirely empirical and should be tested in a variety of environments.

The spatial patterns shown in Figure 3 appear reasonable and consistent with the concepts embedded in the model. The quantitative differences between summer and winter radiation values also appear reasonable.

7. DISCUSSION

7.1 Angstrom Parameters

The parameters a and b for the modified Angstrom equation were derived from radiation data across Australia. These two parameters define the atmospheric transmittance T and average cloud transmittance β. It is unlikely that both of these properties are uniform across the whole of Australia. Hutchinson et al. (1984) demonstrated that the parameters vary from month to month, but did not examine the variations from place to place.



(a)

(b)

Figure 3: Net radiation derived from SRAD for a segment of the Eden area. Lighter shades represent higher radiation values. (a) Net radiation in January, 11 to 18 $MJ/m^2/day$. (b) Net radiation in July, -0.2 to 4.3 $MJ/m^2/day$.

The conventional wisdom is that atmospheric transmittance is higher ("clearer" air) in winter than in summer, whereas Table 1 shows higher T in summer than in winter. The reasons for this are not clear.

7.2 Escarpment Climate

First-hand observations of climatic conditions and vegetation suggest that the escarpment area is considerably wetter and cloudier than either the adjacent plateau or the coastal lowlands. The rainfall surface does not show this but indicates a gentle gradient from the coast to the plateau, with local detail due to elevation. This may be because there are few rainfall stations in this wet escarpment area due to its rugged terrain and lack of population centres.

Because the rainfall surface is used (after transformation) as an independent variable in the rainfall-corrected radiation surface, it is likely that the cloudiness of the escarpment area has been significantly underestimated. This would result in an over-estimate of total radiation and an over-estimate in the strength of slope and aspect effects in this part of the landscape, since cloudy conditions reduce the effects of surface orientation.

7.3 Other Data Sources

Given the importance of radiation in environmental management in this region, and the complete lack of radiation measurements in the area, the establishment of a radiation monitoring network should be considered. The network should be designed to capture both the meso-scale climatic gradient across the escarpment and the topo-scale slope, aspect and horizon effects. Such a network would support refinement of the radiation surface and model validation data.

There are other possible sources of data which could be utilised to enhance the parameterisation of a radiation model. Satellite imagery archives could be used to determine spatial patterns of long-term average cloud conditions on a monthly basis (Dubayah, 1997), although ground-based radiation observations would still be needed to account for cloud transmittance.

8. CONCLUSIONS

The model appears to give satisfactory results in that it shows the expected patterns at meso- and topo-scales. Some aspects of the model such as the cloud and temperature models could be improved, but the most serious constraint on solar radiation estimation is the lack of data for parameterisation and validation. Radiation measurements within the study area are required to validate the results.

The SRAD program is part of the TAPES-G package of terrain analysis programs available free of charge through the CRES Web site http://cres.anu.edu.au/software.html.

9. ACKNOWLEDGEMENTS

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