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Solar radiation and clear sky global turbidity on the north coast of New South Wales

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Measurements of global solar radiant exposure made over 17 years on the north coast of New South Wales were used to describe features of the radiation regime in a humid, subtropical, rural environment. Monthly means of daily solar radiant exposure varied from a high of 23.0 MJ m^{-2} in December to a low of 11.2 MJ m^{-2} in June. Whilst the monthly mean atmospheric transparency (τ_a) varied over a narrow range of 0.50–0.61 between months, daily values of τ_a varied widely. The frequency distributions of daily τ_a within a month were asymmetrical with a negative skew and modal values in the 0.6–0.8 range, which correspond to clear or nearly clear skies.

The upper bound of clear sky atmospheric transparency (UB-CSAT) was estimated by fitting an envelope curve through the high valued τ_a, expressed as a function of day number. A second analysis identified all clear days from the smoothness of the diurnal trend in radiant exposure. A comparison of the two sets of results showed that on clear days, global turbidity could reduce the τ_a below the UB-CSAT by 0.02–0.04 units in summer and 0.07–0.09 units in winter. The magnitude of clear sky global turbidity was broadly related to the amount and variation of atmospheric humidity, but other factors could also contribute to the turbidity.

Introduction

Rainfall, temperature and solar radiation are the main components of climate which affect agricultural production on the north coast of New South Wales (NSW). They are important in setting both the general level of productivity and for causing much of the variability in production on a weekly to annual scale. When sets of historical climate records are available, crop production models can be used to quantify the link between the variability in climate and crop production, and to describe the best management in an uncertain environment.

To avoid the need to estimate solar radiant exposure on the north coast by interpolation from other districts, routine measurements of global solar radiant exposure commenced at Wollongbar in March 1972. The general features of the resultant 17-year record are summarised in this paper. Special emphasis was placed on the clear sky radiant exposure since this, amongst the other factors, is associated with maximum agricultural productivity.

Data acquisition

The data were collected at the North Coast Agricultural Institute, Wollongbar, over the period March 1972 to June 1989. Wollongbar is located at 28°50′S, 153°25′E 160 m elevation, and is 19 km west of the Pacific Ocean. Mean annual rainfall is 1678 mm with 39 per cent falling in the three wettest months of January to March. It is located in a subtropical rural area, with negligible secondary industry which could pollute the atmosphere. However, primary industries cause some atmospheric pollution when sugar cane is burnt during the June to December harvesting season, and from limited burning in forests and grasslands during August to October.

Global solar radiant exposure was measured on Kipp and Zonen pyranometers (model CM-6), one instrument being used from March 1972 to 22 December 1979, and another from 27 December 1979 to June 1989. The recordings were based on the factory calibration of each instrument and because the first pyranometer was damaged by lightning, there was no opportunity to make comparative readings after the changeover. However, a broad check for a bias in one of the two instruments was made by comparing the mean daily recording over the full period of operation of each instrument.

From March 1972 to June 1986 the signal was measured continuously on an integrating millivolt meter (Fernsteuergeräte precision d.c. integrator model Z-V-KTf/7) and daily integrals (0000–2400 hours) were recorded. Thereafter, the instantaneous signal at 30-second intervals was measured on a digital data logging system (Hewlett Packard model 3421A) and hourly estimates of radiant exposure were recorded.

Monthly mean radiant exposure

Monthly means of daily global solar radiant exposure are shown in Table 1. The highest radiant exposure of 23.0 MJ m^{-2} occurred in December and the lowest of 11.2 MJ m^{-2} in June. Median values were typically 1–2 MJ m^{-2} higher.

The mean daily radiant exposure over the two periods when different pyranometers were used, March 1972 to 22 December 1979 and 27 December 1979 to June 1989, were 17.57 and 17.34 MJ m^{-2} respectively. This agreement suggests that neither of the two pyranometers had a serious bias in its signal.

A useful method of standardising radiant exposure for the daily trend in extraterrestrial factors such as distance between the earth and sun, and the sun's angle, is to express radiant exposure in terms of the atmospheric transparency (τ_a), where

$$\tau_a = H{\downarrow}/H{\downarrow}_e \qquad \ldots 1$$

and $H{\downarrow}$ and $H{\downarrow}_e$ are the daily radiant exposure (MJ m^{-2}) at the earth's surface and extraterrestrial radiant exposure respectively.

Following Thompson, Barrie and Ayles (1981), $H{\downarrow}_e$ was estimated using

$$H{\downarrow}_e = 3600S[n \sin\delta \sin\phi + (12/\pi)\cos\delta \cos\phi\{\sin(\pi t_1/12) - \sin(\pi t_2/12)\}] \qquad \ldots 2$$

where S is the solar irradiance at the top of the atmosphere (Wm^{-2}), t_1 the local time of sunrise, t_2 the local time of sunset, n the number of hours between t_1 and t_2, δ the solar declination, ϕ the latitude (−0.503 radians), and

$$S = 1360\,(1 + 0.035\cos D) \qquad \ldots 3$$

where $D = 2\pi d/365$ is the day number in radians, and d is the day number (1 is 1 January etc., and in leap years both 28 and 29 February are day 59).

$$t_1 = (12/\pi).\text{arc}\cos[\tan\delta \tan\phi + 0.0145/(\cos\delta \cos\phi)] \qquad \ldots 4$$

Equation 4 indicates that sunrise occurs when the sun's centre is 50′ below the horizon, to account for the joint effect of refraction (~34′) and the radius of the sun (~16′).

$$t_2 = 24 - t_1 \qquad \ldots 5$$

$$\delta = 0.41\cos(D - 2.961) \qquad \ldots 6$$

The monthly mean τ_a, shown in Table 1, ranged from a high of 0.61 in August to a low of 0.50 in February. As expected, the τ_a was least during the wet season of January to March.

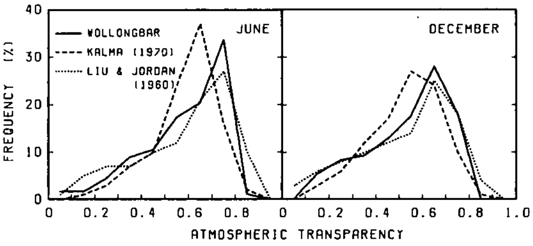
Table 1. Monthly summary of daily global solar radiant exposure ($H{\downarrow}$), atmospheric transparency (τ_a), clear sky global solar radiant exposure ($H{\downarrow}_c$), the upper and lower bounds of clear sky atmospheric transparency (UB-CSAT and LB-CSAT), and the range in τ_a with clear skies.

Month	*Mean* $H{\downarrow}$ *(MJ* m^{-2}*)*	*Median* $H{\downarrow}$ *(MJ* m^{-2}*)*	*Mean* τ_a	*Mid-month*			
				$H{\downarrow}_c$ *(MJ* m^{-2}*)*	*UB-CSAT*	*LB-CSAT*	*Clear sky range in* τ_a
January	22.5	24.1	0.53	31.4	0.73	0.69	0.04
February	19.7	21.0	0.50	29.0	0.73	0.71	0.02
March	17.3	18.5	0.51	25.6	0.74	0.71	0.03
April	14.7	15.8	0.53	21.2	0.77	0.70	0.07
May	11.6	12.4	0.53	17.4	0.79	0.69	0.10
June	11.2	12.0	0.58	15.4	0.81	0.72	0.09
July	12.1	13.2	0.60	16.3	0.81	0.72	0.09
August	15.3	16.7	0.61	19.7	0.80	0.73	0.07
September	18.8	20.3	0.60	24.5	0.78	0.72	0.06
October	20.8	22.8	0.55	28.7	0.76	0.72	0.04
November	22.5	23.9	0.54	31.5	0.75	0.71	0.04
December	23.0	24.9	0.53	32.3	0.74	0.72	0.02

Frequency distribution

The frequency distribution of daily τ_a within a month was asymmetric with a negative skew, as illustrated in Fig. 1 for June and December, and no single transformation could be found which provided either a near-symmetrical or some standard distribution in all months. Faced with the same problem, Kalma (1970) developed a family of empirical distributions to describe the statistical distribution of daily τ_a within a specified month at any Australian locality. With this procedure, only the monthly mean τ_a is required to specify the distribution for a selected month and site. The method was originally devised in the USA by Liu and Jordan (1960), but Kalma found that Australian distributions differed from those of Liu and Jordan.

Fig. 1 **The frequency distribution of atmospheric transparency in June and December, as measured over 17 years at Wollongbar, and as estimated from the generalised distributions derived by Kalma (1970) and by Liu and Jordan (1960).**



When tested at the 5 per cent significance level, the Wollongbar frequency distributions never significantly agreed with the distributions of either Liu and Jordan, or Kalma, but were closer to those of Liu and Jordan. As illustrated for June and December in Fig. 1, the frequencies of high-valued (>0.8) τ_a were overestimated by the Liu and Jordan distributions whereas the modes of the Kalma distributions always underestimated the observed mode at Wollongbar by about 0.1 units of τ_a.

Clear sky atmospheric transparency

Values of the upper bound of clear sky atmospheric transparency (UB-CSAT) were obtained by fitting an envelope curve through the high valued τ_a when expressed as a function of the day number (Heermann, Harrington and Stahl 1985; Dobson and Smith 1988). Recognising that measurements of solar radiant exposure can only be expected to be accurate to 5 per cent (Dobson and Smith 1988), a Fourier function of the day number was fitted to those τ_a which were within 5 per cent of peak values of τ_a (total of 204 days).

$$\text{UB-CSAT} = 0.769 - 0.0386\sin(D + 1.391) - 0.00713\sin(2D - 0.828) \qquad \ldots 7$$

Equation 7 had a standard error (se) of 0.013 and a coefficient of determination (R^2) of 0.79.

The observed radiant exposure on the same 204 days was used to express clear sky radiant exposure ($H{\downarrow}_c$) as a function of day number.

$$H{\downarrow}_c = 24.39 - 8.469\sin(D - 1.355) + 0.594\sin(2D - 1.489) \qquad \ldots 8$$

with a se of 0.48 and R^2 of 0.99.

Mid-monthly (15th day) values of UB-CSAT, which are shown in Table 1, ranged between 0.73 in January–February to 0.81 in June–July, and fell within the normal range of clear sky τ_a measured elsewhere. Paltridge and Platt (1976) considered that 0.7 was a typical clear sky value in industrial or moist tropical atmospheres, whilst 0.8 applied to fairly clear atmospheres. When only perfectly clear days were considered, Gentilli (1977) concluded that the τ_a in Australia varied between 0.7 and 0.8, with the lower values tending to occur in wet seasons and in cities. In the USA, Heermann et al. (1985) obtained τ_a values between 0.69 and 0.81 across a range of locations and the four seasons of the year.

Given the possibility that the UB-CSAT represented exceptionally clear conditions, a test was devised to examine whether clear skies were also present on days with a lower τ_a. The basis for the test was that global turbidity without cloud would reduce the τ_a without distorting the smooth diurnal trend of irradiance which occurs on clear days. On the other hand, intermittent cloudiness would cause a departure from the smooth trend. In the present context, cloud refers to a visible suspension in air of water droplets or ice. Rosenberg, Blad and Verma (1983) defined turbidity as any condition in the cloud-free portion of the atmosphere which reduces its transparency to radiative transfer. By analogy with the definition of global solar radiant exposure (World Meteorological Organization 1971), global turbidity refers to those non-cloud conditions which reduce the receipt of solar radiant exposure on a horizontal surface from a solid angle of 2π.

A simple sinusoidal function of time of day, taken from Monteith (1981), was used to approximate the shape of the diurnal trend in solar irradiance with clear skies and a total daily radiant exposure $H{\downarrow}$.

$$E{\downarrow}(t) = [\pi H{\downarrow}/(2n)] \sin(\pi t/n) \qquad \ldots 9$$

where t is the time in hours after sunrise and $E{\downarrow}(t)$

the irradiance at time t. The test was done on data collected between July 1986 and June 1989, when hourly radiant exposure was recorded. Each day's measurements provided a set of N observed hourly values (O), and integrals of Eqn 9 for the corresponding times gave the model values (M). The root mean square difference (rmsd) was used to quantify the level of agreement between the measured and smooth trend data within each day.

$$\mathrm{rmsd} = [(1/N)\Sigma\{(O-M)/M\}^2]^{0.5} \qquad \ldots 10$$

Radiant exposures, calculated from hourly integration of solar irradiance, were used to calculate the rmsd except for those periods which commenced at sunrise or finished at sunset. These were lengthened so that they always exceeded 1.5 hours, thus avoiding very small values of radiant exposure when calculating the rmsd.

The reduction in solar radiant exposure below the exceptionally clear sky value, expressed in atmospheric transparency equivalents, is termed the interception index (II).

$$\mathrm{II} = H{\downarrow}_c/H{\downarrow}_e - H{\downarrow}/H{\downarrow}_e \qquad \ldots 11$$

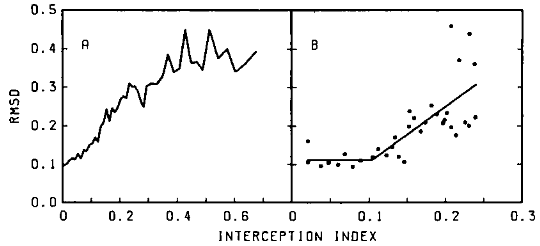
It has values ranging from zero with exceptionally clear skies, to near those of the UB-CSAT under a heavily overcast sky.

When all data used in the diurnal tests were grouped into sub-classes of the interception index, the rmsd increased with increases in the index as shown in Fig. 2(a), but the rate of increase declined when the index exceeded 0.24. Thus, on average, increases in the total attenuation of solar radiant exposure during a day were accompanied by a corresponding increase in the diurnal variability of the attenuation.

The reduction in τ_a due to clear sky global turbidity was estimated from the relation between the interception index and rmsd for daily data within a month. The relation is illustrated in Fig. 2(b), using data from May when the range in clear sky global turbidity was greatest. It had an initial phase where the rmsd was relatively constant over a range in the interception index, corresponding to clear skies with varying amounts of clear sky global turbidity. Further increases in the interception index were accompanied by increases in the rmsd, indicating uneven diurnal attenuation which was attributed to cloud.

The threshold value at which the rmsd commenced to increase with an increasing interception index, defined the maximum reduction in τ_a caused by clear sky global turbidity alone. It was determined by fitting two intersecting straight lines to daily values. The two lines were fitted by an iterative procedure which varied the threshold value until that giving the minimum residual sum of squares was found. Only data with an interception index less than 0.24 were included in the analysis, to avoid the necessity of using a curvilinear relation to express the non-linear change in rmsd at even higher values of the interception index, as shown in Fig. 2(a).

Fig. 2 **Changes in the root mean square difference (rmsd) which was used to measure the diurnal departure of observed radiant exposure from the expected clear sky trend, with increasing values of the interception index. Data were measured over 1986–89. (a) shows the mean trend when data from all months were pooled, and (b) shows values for individual days in May when the interception index was less than 0.24.**



The lower bound of clear sky atmospheric transparency (LB-CSAT) was calculated by subtracting the maximum reduction in τ_a with clear skies from the UB-CSAT. The results, which are tabulated in Table 1, show that the LB-CSAT varied little between months and ranged from 0.69 to 0.73. The annual mean difference between the upper and lower bounds was 0.06 and indicates the average range in τ_a due to clear sky global turbidity. It is less than the yearly mean of 0.10 at Rothamsted (Monteith 1962) or 0.15 at Kew (Stagg 1950).

Some of the seasonal variation in clear sky τ_a can be related to the prevailing atmospheric humidity, which can markedly attenuate solar radiant exposure (Paltridge and Platt 1976). Summer is the wet season on the north coast of NSW and the humidity is usually high. In the wettest month of March, for instance, the mean water vapour pressure measured at a 1.3 m elevation is 2.1 kPa, with a low standard error of 0.27 kPa between daily values. The generally low and small range in clear sky τ_a during summer is consistent with these conditions.

A different situation prevails during winter when the atmospheric humidity is lower and more variable. In July, the mean water vapour pressure is 1.3 kPa with a standard error of 0.90 kPa. A low humidity provides the opportunity for exceptionally clear days, but other days have a similar global turbidity to that in summer.

Whilst changes in humidity can explain some of the variation in clear sky global turbidity, other relevant factors include changes in atmospheric dust levels associated with a change in wind direction or periodic storms, and local burning in sugar cane and forests. Seasonal changes in the optical air mass arising from changes in the atmospheric path length for direct solar radiant exposure would also cause some seasonal variation in τ_a, with the greatest reduction in winter. For instance Bernhardt and Phillips (1958), quoted by van Wijk and Scholte Ubing (1966), estimated that the τ_a of direct solar radiant exposure at 30°S latitude, after correcting for Rayleigh scattering, would change from 0.88 in January to 0.83 in July. The inclusion of diffuse radiant exposure in the global solar radiant exposure values presented in the present paper would dampen the impact of this effect, but a small seasonal trend which is the reverse of the observed seasonal trend in UB-CSAT would remain. In other words, seasonal changes in attenuating factors such as atmospheric humidity would be a little greater than that suggested by the UB-CSAT values.

The UB-CSAT was estimated from a subset of data taken from 17 years of records. Whilst the data set was extensive, the method of fitting an envelope curve introduces some empiricism (Heermann et al. 1985), which is difficult to validate other than by comparing the general magnitude of the peak τ_a with results obtained by others. In contrast, the LB-CSAT was estimated from records collected over only three years, when hourly records were kept. This record length is less than ideal, but the results were generally consistent between months.

Summary

The monthly mean daily global solar radiant exposure at Wollongbar ranged from a high of 23.0 MJ m^{-2} in December, to a low of 11.3 MJ m^{-2} in June. Corresponding mean values of atmospheric transparency (τ_a) were 0.53 and 0.59.

Reflecting the rural environment and sometimes low absolute humidity, the winter sky can be exceptionally clear, giving an τ_a of 0.81. However clear sky global turbidity can reduce this by up to 0.09 units. During the wettest months of January to March, when the atmosphere was consistently more humid, the clearest skies had an τ_a of 0.73–0.74 and clear sky global turbidity reduced this by a maximum of 0.04 units.

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