THE EFFECTS OF CLOUDS ON THE PERFORMANCE OF THE McMASTER SOLAR RADIATION MODEL

By

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ABSTRACT

The effect of clouds on the performance of the McMaster Solar Radiation Model was analyzed using global irradiance data from five Australian stations for the period 1978 to 1982. Ten cloud types were examined. Using values of RMSE and MBE, the model was found to perform well in 15 of the 24 years of analyzed data. The results, on average, parallel those found in previous Canadian studies. The dominance of low layer clouds coincided with all years displaying bad performance but also for some years displaying good performance. The analysis of specific cloud effects revealed that the model underestimates in the presence of low layer clouds, is not well represented with middle layer clouds and overestimates with high layer clouds. These cloud effects can be used to explain some of the error found in the model's performance. While these cloud effects reveal systematic error in the model's performance, much of the error present is random and cannot be explained by the effects of clouds.

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1. INTRODUCTION

This study assesses the performance of the McMaster Solar Radiation Model to determine the effects of different cloud types. Performance under ten different types ranging from optically thin cirrus to optically thick cumulus will be examined. Previous studies have only been concerned with performance under different total cloud amounts with no consideration of type. Performance assessment according to cloud type is important because cloud transmissivities for solar radiation vary greatly with type. The previous studies were also based upon Canadian data while in this study, data from 5 Australian stations will be used. These stations are located in climatic environments far different from those that are representative of Canada.

The model calculates values of global, direct beam and diffuse sky irradiance but for the purposes of this study, values of global irradiance will be used only. The assessment of the model's performance will firstly be based upon two error terms: the root mean square error and the mean bias error. These errors are the fundamental measures of accuracy used in the analysis of model performance. A total cloud type frequency distribution will then be analyzed for trends between years of good and bad performance. The total cloud type frequency distribution is the sum of every occurrence of each cloud type within a given year of data. The next step in the process is to assess the effect of each cloud type. For this, a new data set was created that selected records for those times when only one cloud type was present in the sky. This allows the effect of each cloud type to be isolated so that it can be determined if the model overestimates or underestimates the mean measured value of global irradiance in the presence of that cloud. The analysis performed in this manner will allow the effects of clouds on the performance of the McMaster Solar Radiation Model to be determined.

2. LITERATURE REVIEW

The McMaster Solar Radiation Model is a physically-based model that calculates hourly values of global, direct beam and diffuse sky irradiances under all sky conditions. Values of theoretical irradiance under cloudless skies are calculated first and then corrections are made for the effect of clouds. The model itself was developed using the work of many other researchers in the field of climatology. The theory and equations that are the foundation of the model will be outlined and, following this, the contributions of the previous workers will be assessed.

Under cloudless skies, direct beam irradiance (I_o) is calculated using:

$$I_o = I(o)\,\mu_o\,[T_o\,T_R - a_w]\,T_a \qquad (1)$$

where I(o) is the solar constant and μ_o is the cosine of the zenith angle. The variable a_w represents the water vapour absorption coefficient and T_o, T_R and T_A are the transmittances after absorption by ozone and carbon dioxide, Rayleigh scattering and attenuation by aerosols. The diffuse sky irradiance is the sum of three components:

1. Molecular (Rayleigh) Scattering

$$D_R = I(o)\,\mu_o\,T_o\,[1 - T_R]/2 \qquad (2)$$

2. Aerosol Scattering

$$D_A = I(o)\,\mu_o\,[T_o\,T_R - a_w][1 - T_a]\,w_o f \qquad (3)$$

where w_o is the single scattering albedo for aerosol and f is the ratio of forward to total scatter by aerosol.

3. Multiple Reflections

$$D_s = \alpha_b \alpha_s [I_o + D_R + D_A]/(1 - \alpha_b \alpha_s) \qquad (4)$$

where α_b is the atmospheric albedo of the surface reflected radiation and α_s is the surface albedo.

Therefore, the total diffuse irradiance (D_o) is given by:

$$D_o = D_R + D_A + D_s \qquad (5).$$

Global irradiance (G_o) is the sum of the direct beam (I_o) and diffuse sky (D_o) components:

$$G_o = I_o + D_o \qquad (6).$$

When cloud effects are incorporated into the model, other atmospheric properties are assumed to remain unchanged (Davies and Hay, 1980). Global irradiance is calculated from:

$$G = (I_o + D_R + D_A) \prod_{i=1}^{n} (1 - c_i + t_i c_i)/(1 - \alpha_b \alpha_s) \qquad (7)$$

where t_i is the total cloud transmittance and c_i is the cloud amount in the ith layer. Direct beam irradiance is given by:

$$I = I_o (1 - CO) \qquad (8)$$

where CO is the total cloud opacity and finally, the diffuse irradiance is calculated as a residual:

$$D = G - I \qquad (9).$$

The parameters and the equations used in the model have foundations in the work of other researchers. The values used for transmission after absorption by ozone and carbon dioxide and also for water vapour absorption, originate either from Houghton (1954) or Lacis and Hansen (1974). Davies et al. (1975) used Houghton's parameterizations for absorption and scattering when calculating cloudless sky irradiance.

Davies and Uboegbulam (1978) and subsequent studies have used those developed by Lacis and Hansen (1974). Lacis and Hansen's parameters were also used in this study. Transmittance after Rayleigh scattering was calculated by Davies using data and procedures from Elterman (1968). They are tabulated in Davies and Hay (1981).

When incorporating cloud cover into the model, estimates of the fraction of the sky that is cloud covered for each level are required (Davies and McKay, 1982). Total transmittance of a cloud layer (γ_i) is calculated using:

$$\gamma_i = 1 - c_i + t_i c_i \qquad (10)$$

(Davies and McKay, 1982). This equation was used earlier by Monteith (1962) and in its multilayer form:

$$\gamma_i = \prod_{i=1}^{3} [1 - c_i + t_i c_i] \qquad (11)$$

by Manabe and Strickler (1964). Davies et al. (1975) proposed a method for correcting cloud amounts in layers that are obscured from the observer's sight by the presence of lower clouds. Observed cloud amounts for layers above the lowest level are corrected for the fraction of the sky that is obstructed from the observer's sight. For an observed middle cloud amount, c_m', in the presence of low cloud (c_i), a corrected middle cloud amount, c_m, can be calculated using:

$$c_m = c_m' (1 - c_i) \qquad (12).$$

For high cloud amounts:

$$c_h = c_h'/(1 - c_i - c_m') \qquad (13).$$

Following Haurwitz (1948), the transmissivity values, t_i, are calculated from:

$$t_i = A_i \exp(-B_i m_r) \qquad (14)$$

where m_r is the relative optical air mass. The values of A_i and B_i for cloud type i are taken from Haurwitz (1948). Haurwitz provided values for these constants for only 7 cloud types. These have been extended such that values for stratocumulus are used for cumulus and cumulonimbus and those for cirrostratus are used for cirrocumulus.

At this point, it seems appropriate to consider in more detail the work of Houghton (1954) and Monteith (1962). Houghton (1954), when calculating radiation for the northern hemisphere, suggested that the total transmission of the solar beam is a product of the transmission due to water vapour absorption (T_{wa}), aerosol absorption (T_{aa}), water vapour scattering (T_{ws}), Rayleigh scattering (T_R) and aerosol scattering (T_{as}). Ozone effects were not included. He assumed that absorption occurs before scattering. Thus:

$$I_o = I(o)\, \mu_o\, T_{wa}\, T_{aa}\, T_{ws}\, T_R\, T_{as} \qquad (15)$$

$$D_o = I(o)\, \mu_o\, T_{wa}\, T_{aa}\, (1 - T_{ws}\, T_R\, T_{as}) \qquad (16)$$

$$G_o = I(o)\, \mu_o\, T_{wa}\, T_{aa}\, (T_{ws}\, T_R\, T_{as} + 1) \qquad (17).$$

Modern work no longer recognizes water vapour scattering and following Paltridge and Platt (1976), equation (15) is usually written as:

$$I_o = I_o\, \mu_o\, T_o\, T_R\, (1 - a_w)\, T_{aa}\, T_{as} \qquad (18)$$

where a_w is water vapour absorption. This value is subtracted because water vapour absorbs at larger wavelengths than ozone.

Monteith (1962) applied Houghton's cloudless sky model for the northern hemisphere to calculate hourly cloudless sky radiation for a specific site at Rothamsted, England. He used a single layer model to incorporate cloud effects. Monteith included the effects of multiple reflections between the cloud base and the surface.

At the present time, there are 2 other models being used that are similar in form to the MAC model. The first was developed at the Center for Environment and Man (CEM) by Atwater (Atwater and Brown, 1974; Atwater and Ball, 1978). The second was by Suckling and Hay (1976, 1977) at the University of British Columbia (CLS). These models take the same approach for calculating global and direct beam irradiance, but the MAC and CEM models calculate diffuse radiation as a residual, while CLS calculates it independently.

The McMaster Solar Radiation model has evolved over the last 15 years. In the early 1970's, it was used at a specific Lake Ontario site with a restricted data set to calculate the solar radiation balance (Nunez et al., 1971). Model performance was later analyzed using data collected during the International Field YEAR on the Great Lakes (IFGL) from sites bordering Lake Ontario (Schertzer, 1975; Davies et al., 1975). The model was then used to calculate solar radiation in the Tropical Atlantic during the GARP Atlantic Tropical Experiment (Uboegbulam, 1977; Davies and Uboegbulam, 1977). It was also successfully applied to a study which related crop productivity to climate (Davis and Davies, 1981). In the late 1970's following the energy crisis, the model was tested along with several others and used to provide a solar radiation base for solar energy purposes in Canada (Davies and McKay, 1982; McKay and Morris, 1985). This study involved 6 stations representing a range of climatic conditions. The model's performance is being assessed at the present time using meteorological data from member countries of the International Energy Association (IEA). The data represent North America, Western Europe and Australia.

3. METHODOLOGY

The assessment of the model's performance utilized data from five Australian stations. These stations include Albany, Alice Springs, Laverton, Mildura and Rockhampton, which represent a range of climatic environments (Figure 1). The original data set offered 10 stations in total. The 5 stations were selected such that each site did not lie too closely to the boundary separating 2 climatic regions. This ensures that each station is only representative of one climatic region.

The individual records from the Australian data set are identified by the year, month, day and hour of the observation. The variables included in the data set are listed in Table 1.

Cloud type observations recorded according to the WMO "long" code were converted to the "short" code which is more compatible with most recording procedures. Clouds can exist at 3 levels in the sky (high, medium and low) and within each layer, there are nine various forms and combinations of cloud types. This represents the World Meteorological Organization's (WMO) long code for cloud classification (MANOBS, 1970). This was converted into a short code which is represented by ten cloud types for the three layers in total. The method of conversion is shown in Table 2. The Australian data set uses four cloud layers. Layers one and two were combined to represent low layer clouds. Table 3 gives a summary of the short code classification of cloud types. Cloud type 10 (Table 2) represents fog, but this was not present in the original data set and, as a result, was not included in the analysis. This short code was used for analyzing the performance of the model with respect to cloud effects.

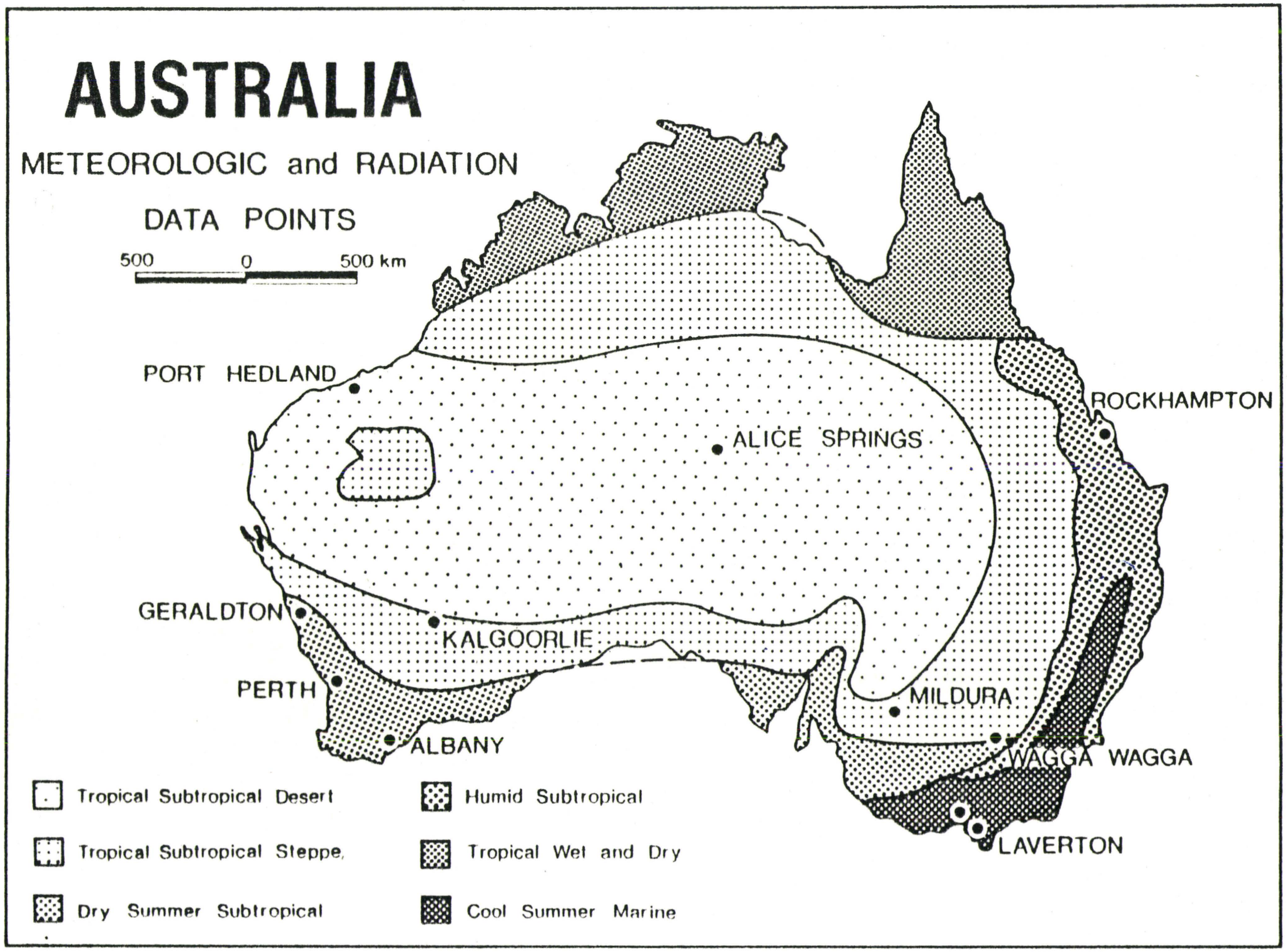
AUSTRALIA
METEOROLOGIC and RADIATION
DATA POINTS
500
0
500 km
PORT HEDLAND
ALICE SPRINGS
ROCKHAMPTON
GERALDTON
KALGOORLIE
PERTH
ALBANY
MILDURA
WAGGA WAGGA
LAVERTON
Tropical Subtropical Desert
Tropical Subtropical Steppe
Dry Summer Subtropical
Humid Subtropical
Tropical Wet and Dry
Cool Summer Marine

Figure 1

Variable Description
Station #
Date: yr, month, day
Time: hours + 10's of minutes
Station level pressure
Dry Bulb Temperature
Dew Point Temperature
Total Cloud Amount
Amount of first low cloud
Type of first low cloud
Amount of second low cloud
Type of second low cloud
Amount of sky obscured by low cloud
Amount of middle cloud
Type of middle cloud
Amount of high cloud
Type of high cloud
Global irradiance
Direct beam irradiance
Diffuse sky irradiance

Table 1 **Australian Data Set Parameters**

WMO LONG CODE →

LAYER ↓	1	2	3	4	5	6	7	8	9	10
1	8	8	9	6	6	7	7	8	9	5
2	8	8	9	6	6	7	7	6	9	5
3	4	4	3	3	3	3	5	3	3	10
4	0	0	0	0	2	2	2	2	1	10

Table 2 **Conversion Table of 'Long' Code to the 'Short' Code of Cloud Classification**

CODE #	CLOUD TYPE	ABBREVIATION	CLOUD LAYER
0	Cirrus	Ci	high
1	Cirrocumulus	Cc	
2	Cirrostratus	Cs	
3	Altocumulus	Ac	medium
4	Altostratus	As	
5	Nimbostratus	Ns	
6	Stratocumulus	Sc	low
7	Stratus	St	
8	Cumulus	Cu	
9	Cumulonimbus	Cb	

Table 3 **Short Code of Cloud Classification**

All computations were performed using a series of computer algorithms on a Compaq personal computer using WATFOR FORTRAN. The first algorithm computed radiation for the model using the parameter values from Table 1. The cloud data were recorded at time increments of three hours. The model requires hourly data values for operation and, as a result, hourly values were linearly interpolated between the three-hour data records. Air mass was calculated using the hour of observation and was then corrected for temperature and pressure. Precipitable water vapour was computed from surface dewpoint temperature using an equation from Monteith (1961). The values of A_i and B_i for use in equation (10) are given in Table 4. Measured radiation data were recorded in half hourly intervals. Hourly values were obtained as the sum of the value for the half hour before and the half hour after the hour.

The first algorithm applied to the data therefore calculated the global irradiance values for the MAC model using the Australian data and the parameter values. Based upon the calculated and measured values, two error terms were calculated. The root mean square error (RMSE) is a measure of non-systematic error and is calculated using:

$$\mathrm{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \varepsilon_i^{\,2}} \qquad (19)$$

where N is the sample number and ε is the difference between the calculated radiation value (W_m^{-2}) and the measured radiation value (W_m^{-2}). The mean bias error (MBE), a measure of systematic error or bias, is defined by:

$$\mathrm{MBE} = \frac{1}{N} \sum_{i=1}^{N} \varepsilon_i \qquad (20).$$

These errors are expressed as a percentage of the mean hourly or mean

CLOUD TYPE	A_i	B_i
Cirrus	0.871	0.020
Cirrostratus	0.923	0.089
Cirrocumulus	0.923	0.089
Altocumulus	0.556	0.053
Altostratus	0.413	0.004
Nimbostratus	0.368	0.045
Stratocumulus	0.368	0.045
Stratus	0.252	0.100
Cumulus	0.368	0.045
Cumulonimbus	0.368	0.045

Table 4 Transmissivity Parameters for Each Cloud Type

daily irradiance for the year. These error terms are the fundamental measures of accuracy used to analyze model performance (Davies et al., 1985; Davies and McKay, 1982). These error values were used to assess the overall performance of the model.

The second computer program that was utilized, grouped the results according to total cloud amount. This program calculated cloud type frequencies within each year for every occurrence of a particular cloud type. This cloud type frequency distribution is required within the data analysis.

The final algorithm used was the cloud distribution program. It selected from the results of the first program those records where only one cloud type was present. If multiple cloud types were present, then the record was considered invalid and it was not admitted to the new data file being created. The new file therefore accumulated values of global irradiance classified according to cloud type. By selecting the data in this manner, the effect of a specific cloud type on model performance could be isolated.

The results of this program yielded mean hourly values of global radiation for each cloud type over the span of 1 year. Cloud type frequencies were counted for that given year. The relative frequency of radiation for each cloud type was also calculated. These data reveal what percentage of the total radiation for the year was received when a given cloud was present in the sky. These three forms of output are available for both measured and calculated data of global irradiance. The relative frequency of cloud amount in octas for each cloud type was also available as well as the number of occurrences of a particular cloud type for each cloud amount.

All of the above output was available for the five Australian stations. Five years of data ranging from 1978 to 1982 were used for each station. The exception was Rockhampton, where only four years of data were available.

4. ANALYSIS OF RESULTS

Model performance was first assessed according to the root mean square error (RMSE) and mean bias error (MBE) results. A comparison of these values was made with the results from other Canadian studies to see if performance variations occurred. The second aspect of the assessment of model performance was to consider the effects of clouds using a short code of 10 cloud types. Two different data bases for cloud type frequencies were used. The first yielded frequency values for every occurrence of a cloud type, while the second yields values for the times when that cloud type occurred on its own in the sky. Using this data, the performance of the model will be assessed and analyzed for the occurrence of any trends.

4.1 The root mean square error (RMSE) values for the twenty-four analyzed years of daily statistics appear in Table 5. The error terms range from 7.9% to 19.8%. More specifically, Alice Springs reveals the lowest RMSE range (7.9% to 11.7%). Mildura is the next smallest (10.6% to 13.3%), while the other three stations fall into the range of 10.7% to 19.8%. These measure the non-systematic or random error in the data.

The mean bias errors (MBE) are found in Table 6. The values are both positive and negative, implying an overestimation (positive) and underestimation (negative) about the mean measured value of global irradiance. Performance of the model is deemed acceptable if the absolute value of the MBE is less than or equal to 3.0%. The data show that performance is good for 15 of the 24 years of data. Systematic error is present for Albany (1978, 1979, 1982), Laverton (1978, 1979) and Rockhampton (1978, 1979, 1981, 1982). Performance is good for all of

	ALBANY	ALICE SPRINGS	LAVERTON	MILDURA	ROCKHAMPTON
1978	17.7	10.4	19.8	13.4	12.9
1979	16.3	11.1	19.8	12.6	12.8
1980	17.8	7.9	17.4	10.6	--
1981	16.9	9.5	16.6	11.7	16.2
1982	18.4	11.6	16.3	11.2	14.0

Table 5 Root Mean Square Error - Year End Daily Statistics (%)

	ALBANY	ALICE SPRINGS	LAVERTON	MILDURA	ROCKHAMPTON
1978	-7.7	-1.7	-3.6	-0.6	-4.7
1979	-4.4	-1.8	-4.8	-0.5	-3.8
1980	-2.3	0.4	0.6	0.8	--
1981	-1.4	0.3	2.7	1.8	-6.8
1982	3.4	2.9	1.5	2.3	-3.8

Table 6 Mean Bias Error - Year End Daily Statistics (%)

Alice Springs and Mildura and the remaining years of Albany and Laverton. The MBE values are in the range of -7.7% to 3.4%, with the best performance occurring in Alice Springs 1981 (+0.3%) and the worst in Albany 1978 (-7.7%).

These RMSE and MBE results for Australia can be compared to Canadian performance results. Davies (1981) used 11 years of data (1968-1978) for six stations to assess model performance. RMSE values were found in the range of 11-15%, while MBE values were -5.1 to 3.8%. Davies et al. (1984) used 3 years of data (1974-1976) for four Canadian stations and found RMSE values of 13.3 to 18.9% and MBE values of -5.2 to 1.6%. The Australian results in general fall into the range established by the Canadian studies of model performance.

4.2 Using the data produced by program 2, which calculated cloud type frequencies for every occurrence of a particular cloud type, differences between total cloud type frequencies of good and bad performance years will be examined. To begin with, the values were first grouped into categories of high, medium and low clouds (Table 7). In this section of the analysis, 2 years of data (Alice Springs, 1978 and Rockhampton, 1978) have been omitted, since they were missing. The data shows that, in 20 of the 22 years of data, low level clouds are the dominant cloud type present. The two exceptions are from Alice Springs (1980, 1982), where middle layer clouds dominate over low clouds. Alice Springs 1980 yielded the second best performance overall and displays a fairly even distribution of total cloud occurrence for the three levels. However, this is not true for 1982, where an even distribution produced a MBE of 2.9%. For the years of bad performance, the low level clouds outnumber

	PERFORMANCE	MBE	LOW	MEDIUM	HIGH
ALICE SPRINGS 1982	$\lvert \mathrm{MBE} \rvert \leq 3.0\%$	2.9	588	620	536
LAVERTON 1981		2.7	1527	523	516
MILDURA 1982		2.3	583	346	484
MILDURA 1981		1.8	740	399	487
LAVERTON 1982		1.5	1378	472	412
MILDURA 1980		0.8	751	359	470
LAVERTON 1980		0.6	1447	530	514
ALICE SPRINGS 1980		0.4	606	635	463
ALICE SPRINGS 1981		0.3	748	682	541
MILDURA 1979		-0.5	823	465	447
MILDURA 1978		-0.6	885	393	436
ALBANY 1981		-1.4	1850	288	387
ALICE SPRINGS 1979		-1.8	769	646	484
ALBANY 1980		-2.3	1842	280	292
ALBANY 1978	$\lvert \mathrm{MBE} \rvert > 3.0\%$	-7.7	1782	352	499
ROCKHAMPTON 1981		-6.8	1631	596	466
LAVERTON 1979		-4.8	1541	531	462
ALBANY 1979		-4.4	1783	336	350
ROCKHAMPTON 1982		-3.8	1577	374	352
ROCKHAMPTON 1979		-3.8	1631	596	466
LAVERTON 1978		-3.6	1538	504	374
ALBANY 1982		3.4	1828	300	378

Table 7 Cloud Layer Frequency Distribution for Every Occurrence of a Cloud Type

the other two levels by a considerable amount.

Table 8 reveals the breakdown of the data from Table 7 into frequency distributions for specific cloud types. Two groupings of the cloud types were performed as As/Ns and Ci/Cc formed two categories. The data is also subdivided into years of good performance and years of bad performance. Several approaches will be taken to analyzing this data. The first considers cloud type frequencies for years of good and bad performance for 1 station using Albany 1978 (-7.7%) and Albany 1981 (-1.4%). A comparison of the cloud frequencies revealed that substantial differences existed only for St and Cu. Stratus in Albany 1981 exceeded that in 1981 by 124, while cumulus in 1981 exceeded 1978 by 149. This implies an influence of low level clouds.

A second comparison concerns good and bad performance years for different stations. Alice Springs 1981 and Albany 1978 were used. Considerable differences were found for Ci/Cc, Ac, St, Sc and Cu for these 2 years. Alice Springs has a greater abundance of high cloud, while Albany has more low cloud. Alice Springs also has more middle layer altocumulus. Once again low clouds appear to be prevalent in a year yielding bad model performance, especially for Cu and Sc which exhibit the largest frequency differences between the 2 years of data.

Alice Springs which yielded good performance for all 5 years showed only small differences in cloud type frequencies. The MBE values (Table 6) are negative for 1978 and 1979 and are positive for 1980, 1981 and 1982. No trend in the data can be found for cloud type frequencies but, as the magnitude of the values are less than 3%, the variations in the values (positive and negative) would appear to be inconsequential.

	PERFORMANCE	MBE (%)	Ci/ Cc	Cs	Ac	As/ Ns	St	Sc	Cu	Cb
ALICE SPRINGS 1982	|MBE| ≤ 3.0%	2.9	456	80	475	145	89	74	387	38
LAVERTON 1981		2.7	375	141	334	204	188	649	665	28
MILDURA 1982		2.3	377	57	240	106	27	203	348	5
MILDURA 1981		1.8	417	70	257	142	70	261	404	5
LAVERTON 1982		1.5	315	97	296	176	136	580	640	22
MILDURA 1980		0.8	387	83	238	121	74	266	400	11
LAVERTON 1980		0.6	406	108	348	182	164	666	596	21
ALICE SPRINGS 1980		0.4	412	51	511	124	55	107	419	25
ALICE SPRINGS 1981		0.3	489	52	513	169	89	136	485	38
MILDURA 1979		-0.5	353	94	309	156	73	290	446	14
MILDURA 1978		-0.6	350	86	241	152	92	299	469	25
ALBANY 1981		-1.4	325	62	180	108	90	896	835	29
ALICE SPRINGS 1979		-1.8	411	73	529	117	97	167	447	58
ALBANY 1980		-2.3	242	50	182	98	128	846	847	21
ALBANY 1978	|MBE| > 3.0%	-7.7	305	98	194	148	214	848	686	34
ROCKHAMPTON 1981		-6.8	419	47	418	178	216	442	946	27
LAVERTON 1979		-4.8	351	111	307	224	148	732	637	24
ALBANY 1979		-4.4	292	58	211	125	214	827	728	14
ROCKHAMPTON 1982		-3.8	334	18	298	76	110	419	1030	18
ROCKHAMPTON 1979		-3.8	324	48	370	1138	121	528	976	13
LAVERTON 1978		-3.6	363	111	280	224	186	662	675	15
ALBANY 1982		3.4	261	117	118	119	135	928	763	24

Table 8 **Total Cloud Type Frequency Distribution for Every Occurrence of a Cloud Type**

Model performance was also good for all 5 years of Mildura data but, as with Alice Springs, positive (1980, 1981 and 1982) and negative (1978, 1979) MBE values were found. Between 1978 and 1979, no large differences were evident in the cloud type frequency distribution. For the other 3 years, the same trend was found. Overall though, a trend is seen in that the negative MBE's have a larger frequency of Cs, As/Ns, St, Sc, Cu and Cb with smaller values of Ci/Cc. Low and middle layer clouds appear to be influential on the error terms.

The MBE values for Albany produced negative numbers for 1978 to 1981 and a positive number for 1982. A comparison of 1982 with years of bad model performance, revealed that no extraneous cloud type frequencies were present that would explain the positive MBE value.

Rockhampton displayed bad performance for all four years. The frequency of occurrence of cumulus clouds is highest here than at any other station while for stratus it is lowest. The year 1981 (MBE = -6.7%) displayed the highest occurrence of Ci/Cc, Ac, As/Ns, St and Cb, 1979 had more Sc and 1982 had more Cu. Due to the breakdown of the cloud types between the years of data, it is not possible to establish a cloud type frequency pattern.

In summary, certain aspects of the analysis suggest that frequently, the presence of low level clouds, especially Cu and Sc affect the results. However, this is not universally true.

4.3 The next step is to consider the actual differences in values of global irradiance (W_m^{-2}) between the calculated and measured values. The data was collected by the third program which selected valid records for those records when only one cloud type was present in the sky at the time of observation. Tables 9 to 13 show the differences between the values of measured and calculated global irradiance (W_{m}^{-2}). A positive value implies overestimation, while a negative value implies underestimation. In general, from these tables, the model tends to overestimate for high clouds and to underestimate for low clouds. The model results with middle layer clouds are not well represented. It should be noted that there are several stations and years of data in which a particular cloud type did not occur on its own.

With the presence of cirrus clouds, the model tends to overestimate global irradiance in all cases. This is based upon a sample number of 25 to 224 which is statistically sound. Overestimation and underestimation by the model in the presence of cirrocumulus. It is not well represented in sample number with never more than 3 occurrences per year and there are several years where data is missing altogether. When cirrostratus is present, the model overestimates with the exception of Rockhampton 1978. Albany 1980 and 1981 show very high values (good performance years) and, hence, will not contribute to the systematic error that appears in the data.

With altocumulus, a middle layer cloud, the model both overestimates and underestimates global irradiance for Alice Springs, Mildura and Rockhampton, while only overestimation occurs for Albany and Laverton. The sample number ranges from 14 to 178 being most abundant in Alice Springs. In the presence of altostratus, the model overestimates with the exception of Alice Springs 1982. The sample number never exceeds 7 times per year and it is often absent altogether. For this reason, the results cannot be relied on too heavily. Overestimation by the model

	Ci	Cc	Cs	Ac	As	Ns	Sc	St	Cu	Cb
1978	+17.3 52	-45.6 1	+24.8 11	+35.3 18	–	+108.6 25	-39.3 271	-65.9 20	-29.7 94	–
1979	+77.2 56	+51.0 2	+114.3 10	+9.9 27	+87.5 1	+85.1 6	-4.3 256	+59.7 15	-25.3 98	–
1980	+37.5 54	–	+267.6 4	+15.0 17	–	+144.1 15	-34.3 251	-30.3 10	-30.7 122	–
1981	+58.5 58	–	+167.6 8	+30.0 23	–	+117.6 16	-32.7 221	-7.7 3	-4.3 96	–
1982	+62.6 58	–	+67.9 6	+41.0 25	–	+150.8 24	-11.7 292	-44.2 12	+9.3 56	–

Table 9 Albany

	Ci	Cc	Cs	Ac	As	Ns	Sc	St	Cu	Cb
1978	+17.4 108	+1.11 3	+28.3 8	-21.3 168	–	+75.4 67	-45.2 84	-53.4 7	-41.6 112	–
1979	+13.9 95	–	+51.9 12	-8.8 178	–	+77.6 31	-66.9 61	-34.9 9	-67.0 129	–
1980	+20.7 147	–	+34.6 12	-6.6 168	–	+42.2 45	+0.8 31	-8.4 3	-14.6 106	–
1981	+25.4 189	+83.3 1	+19.1 11	-3.8 155	–	+31.9 48	-16.6 26	+39.3 7	-54.8 92	–
1982	+41.5 160	+26.9 2	+83.7 16	+8.9 152	-18.6 4	+66.4 47	-13.4 21	+36.5 2	-24.7 96	–

Table 10 Alice Springs

	Ci	Cc	Cs	Ac	As	Ns	Sc	St	Cu	Cb
1978	+13.7 70	-21.1 1	+111.4 7	+54.4 28	+51.8 4	+135.9 27	-41.8 155	-60.8 25	-52.3 142	–
1979	+23.1 65	+6.1 2	+11.9 15	+14.4 25	+101.7 5	+187.8 45	-60.2 174	-54.3 16	-25.2 100	+58.8 2
1980	+50.9 97	+102.8 2	+33.6 13	+3.4 37	+75.1 2	+111.9 36	-23.2 118	-69.9 17	-18.3 113	-34.4 2
1981	+45.5 59	+20.6 2	+48.2 17	+21.2 36	+33.4 3	163.7 35	-15.2 115	-3.5 18	-2.2 114	-10.6 1
1982	+55.2 73	-2.9 2	+88.0 17	+1.1 49	–	147.5 51	-15.6 146	-50.8 19	-28.0 124	+405.6 1

Table 11 Laverton

	Ci	Cc	Cs	Ac	As	Ns	Sc	St	Cu	Cb
1978	+25.7 160	+36.8 2	+49.1 33	-4.7 56	+53.6 4	+124.3 49	-45.0 101	-71.9 23	-60.2 168	+98.4 3
1979	+40.0 145	-22.8 1	+56.0 22	-6.3 83	+4.7 6	+88.5 66	-52.7 99	-74.3 25	-42.3 153	-36.7 1
1980	+23.5 197	+40.3 1	+104.2 22	-19.6 63	+22.2 1	+83.2 14	-61.5 87	-57.3 24	-53.2 149	–
1981	+35.3 224	+78.9 2	+79.9 26	+13.0 86	+66.8 4	+104.8 51	-35.0 94	-43.9 15	-54.0 155	–
1982	+48.5 210	+24.7 1	+56.1 24	+48.2 84	+27.5 3	+110.0 61	-24.7 124	-62.1 7	-36.1 170	+90.1 3

Table 12 Mildura

	Ci	Cc	Cs	Ac	As	Ns	Sc	St	Cu	Cb
1978	+5.9 36	–	-33.9 5	-7.5 42	–	+132.7 5	-36.4 59	+31.0 13	-59.4 366	+36.9 1
1979	+46.8 25	–	+51.8 2	-21.2 23	–	+134.7 4	-15.4 65	-39.8 9	-49.3 361	–
1981	+31.2 67	+200.6 1	+82.0 5	-2.5 54	–	+128.3 3	-29.8 45	-52.9 19	-74.5 283	–
1982	+76.5 49	–	–	+20.6 14	–	+141.9 4	-4.5 69	-68.7 5	-45.6 415	–

Table 13 Rockhampton

	Ci	Cc	Cs	Ac	As	Ns	Sc	St	Cu	Cb
ALBANY	+51.3 278	-18.6 3	+108.6 39	+26.1 110	+87.5 1	+126.6 86	-24.0 1291	-21.3 60	-19.1 466	–
ALICE SPRINGS	+25.3 699	+23.4 6	+47.7 59	-6.6 821	-18.6 4	+58.9 238	-38.4 223	-13.0 28	-41.6 535	–
LAVERTON	+38.8 364	+25.8 9	+53.8 69	+16.2 175	+69.0 14	+151.5 194	-33.5 708	-48.8 95	-26.5 593	+34.8 6
MILDURA	+34.7 936	+39.1 7	+67.8 126	+8.5 372	+34.2 18	+102.4 269	-42.5 505	-63.6 94	-49.8 795	+75.6 7
ROCKHAMPTON	+40.8 177	+200.6 1	+28.7 12	-4.9 133	–	+134.7 16	-20.2 238	-28.3 46	-55.8 1425	+36.9 1

Table 14 5 Year Means

always occurs in the presence of nimbostratus. The values are lowest for Alice Springs (+31 to +77 W_m^{-2}), while all other stations fall above that range. It is well represented in sample number.

The model underestimates global irradiance for all but 4 years (Albany, 1979; Rockhampton, 1978; Alice Springs, 1981 and 1982) in the presence of stratus. The first 2 years show negative MBE's (bad performance) while for Alice Springs, the values are positive with good performance. With stratocumulus, an underestimation of global irradiance occurs except for Alice Springs, 1980. The underestimation is in the range of -6 to -66 W_m^{-2} and it is well represented in number (21-292). An underestimation by the model also occurs in the presence of cumulus with the exception of Albany, 1982. The overestimation occurs for the smallest sample number and it is in a year where Albany has a positive MBE. With the final cloud type, cumulonimbus, the model both overestimates and underestimates global irradiance. This observation though is based upon a limited sample number which never exceeds more than three occurrences per year.

Analyses of the five year means (Table 14) improve upon the observations of model performance with respect to cloud type. Overestimation is associated with cirrocumulus, cirrostratus and cumulonimbus. The trends for the other cloud types remain unchanged.

In consideration of the performance of each cloud type at the individual stations, Alice Springs yields the best performance for Ci, Cs, Ns and St; Rockhampton for Cs and Sc; Albany for Cu and Laverton for Cb. Due to the values of Ac and As being both positive and negative, isolation of a station yielding the best performance is not possible.

5. DISCUSSION OF RESULTS

The discussion of the results will begin first by considering the limitations present in the data set and then the actual results will be assessed for the effect of clouds on model performance.

There are several restrictions present within the data set due to the methods of data selection by the computer programs as were outlined previously. To begin with, the maximum number of possible observations is 4380 hours per year (365 days/year x 12 hours/day). This is an idealized number, as there will always be missing hours of data. Tables 9-13 show the individual totals for each cloud type when the cloud was present alone. There are several cloud types that for some stations, do not appear alone, so the data set is curtailed. If the values from Tables 9 to 13 are compared with those from Table 8 (totals for every occurrence of a cloud type), there is a large difference in sample number present. Table 15 provides the values of total number of hourly observations summed from Tables 9-13. The values range from 400 to 687. This represents only 1/6 to 1/8 of the total number of possible observations. The data set became limited in sample number when the effects of cloud type on model performance were being isolated. This implies that greater uncertainty is present within the results, because a smaller data sample was used.

The overall performance of the MAC model is comparable with the results found in previous Canadian studies. This indicates that the model can be applied to a variety of study sites that are located in varying climatic environments.

The analysis of the cloud type frequency data with respect to

	MILDURA	ALBANY	ROCKHAMPTON	LAVERTON	ALICE SPRINGS
1978	599	492	527	459	557
1979	601	471	489	449	515
1980	558	473		437	512
1981	657	425	477	400	529
1982	687	473	556	482	500

Table 15 **Total Number of Hourly Observations in Which Only One Cloud Type is Present in the Sky**

model performance offered 2 lines of interpretation. The first suggestion that the presence of low clouds will affect model performance because they are the most frequent cloud types and as the results show the model tends to underestimate measured global irradiance in their presence. This implies systematic error. The second interpretation contradicts the first and suggests that the error is random and, as a result, the effects of clouds on model performance cannot be isolated. The data supports both of these observations.

Section 4.2 showed that good and bad performance within 1 station displayed varying cloud type frequency distributions for cumulus and stratocumulus. Albany 1978 exceeded 1981 for Sc, while the reverse occurred for Cu. Albany 1978 had the highest MBE value for all the years of data. This suggests the possible influence of low layer stratocumulus on the poor model performance. The dominance of these 2 low layer clouds offer an explanation as to why the negative MBE values occur in the observations from Section 4.3 are considered in that the model underestimates in the presence of these clouds. The results from Table 9 show that the underestimation is larger for Sc than for Cu.

It was also shown in Section 4.2, that Alice Springs 1981 had a greater frequency of high clouds, while Albany 1978 had a larger number of low clouds (almost double). Using the conclusions from Section 4.3, the bad performance of the model for Albany 1978 can be explained by suggesting that the large number of low level clouds whose presence indicate a tendency for model underestimation, will produce large negative numbers. In the case of Alice Springs 1981, a more even distribution of clouds is present. The observations from 4.3 would balance each other, thereby yielding a measure of good performance. This observation supports the first interpretation indicating the presence of systematic error. Further analysis of other years though, illustrate that this pattern is not applicable to all of the analyzed years of data.

From Section 4.3, the larger frequency of low and middle layer clouds for the negative values of MBE's in Mildura suggest that the influence of low layer clouds on model performance is important. Due to the fact that middle layer clouds are not well represented, their influence on model performance cannot be assessed.

One of the major observations that supports the second proposal is when the 4 years of bad performance for Rockhampton were considered. No pattern is evident among the data to explain the systematic error.

Based on this discussion, the observation that the presence of low clouds may affect model performance is valid. There is evidence present though that contradicts this observation. The possible effect of low clouds can be explained to some degree by considering that low clouds can exist at varying thicknesses. They may be towering or fairly thin. Only one transmissivity value though is available for each cloud type such that variations in the thickness of a cloud will affect the amount of radiation transmitted by the cloud. This can yield negative values. Another observation to explain the influence of low clouds is that overestimation of low cloud amounts will cause an overestimation of global irradiance. The overestimation of cloud amount can occur if the cloud sides are taken into consideration instead of only the cloud base.

6. CONCLUSIONS

The assessment of the performance of the McMaster Solar Radiation Model for the effects of clouds has revealed using values of RMSE and MBE, that the model performs well in 15 of the 24 years of analyzed data. This performance is comparable with the results from other Canadian studies such that the varying climatic regimes in Australia have caused no substantial variations in performance. The analysis of the total cloud type frequency distributions for years of good and bad performance indicate that systematic errors can be attributed to the presence of low clouds which are often the dominant cloud type. The analysis of the individual cloud type frequency distributions have shown that in the presence of low level clouds, the model tends to underestimate measured global irradiance values but overestimates radiation beneath high clouds. Middle layer clouds were not well represented.

Using the above conclusions, the systematic error in the model can be explained by the last conclusion, where the model underestimates with low clouds and overestimates with high clouds. These cloud effects can be applied in some cases as explanations for model performance being positive or negative. It is not universally true though. As a result, random error is also present. The effect of clouds therefore influences model performance to a degree, but they cannot be used as an explanation for all errors.

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