ESTIMATING NET RADIATION IN THE PEACE RIVER DISTRICT, BRITISH COLUMBIA

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by

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ABSTRACT

A simple model, expressed in terms of cloud amounts and heights, and air temperature (recorded hourly at Ft. St. John, B.C.) and daily radiosonde records (from St. Nelson, B.C.), is used in an attempt to approximate incoming solar and net radiation values at a nearby pasture site, where hourly measurements were recorded. Results from the model indicate that measured values on a daily basis were estimated within 20%, while five and ten day running means were calculated within 10% of the measured means.

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CHAPTER 1

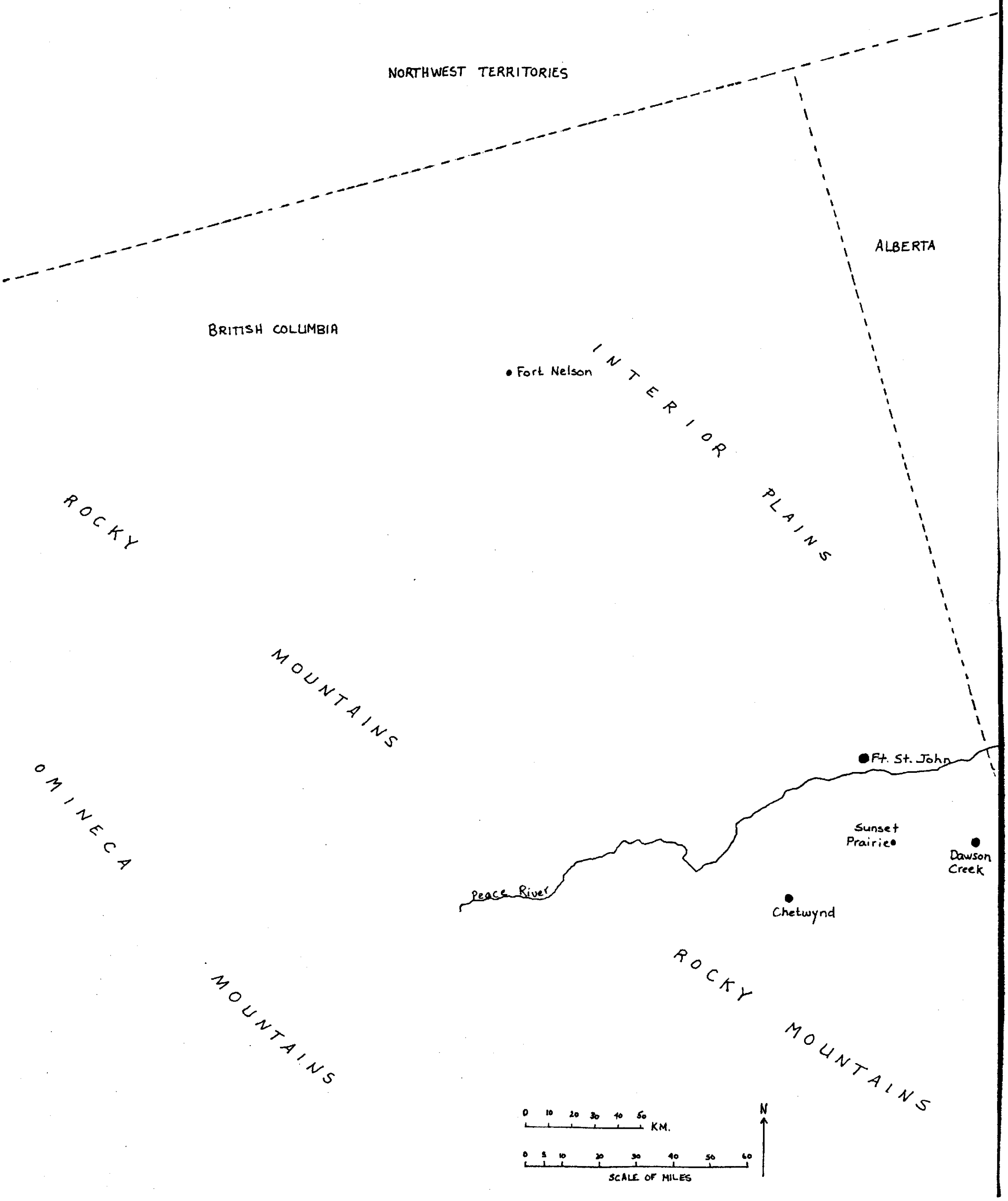
INTRODUCTION

There have been many attempts to model the radiation balance and its components. A model would eliminate much of the time and cost involved in measuring all components directly, and would allow estimates to be made in locations where direct measurements are not made. Models are still in an experimental stage and need to be tested. Studies such as this one use measured data to evaluate model performance.

The model used in this study is very simple, requiring daily radiosonde records, hourly cloud heights and amounts, and hourly air temperature measurements. It uses basic physical principles. The results from the model are compared with solar and net radiation measurements, recorded hourly from May to August, 1977 at a station situated 60 km south of Ft. St. John (56° 14'N, 120°55'W), Peace River district of B.C., in a foothills pastureland referred to as Sunset Prairie Pasture (55°20'N 120°20" W) (Figure 1). The radiosonde measurements made at Ft. Nelson, B.C., (58°N, 123°W) about 210 km north of the measurement site were used with cloud and temperature measurements from Ft. St. John airport.

It is unlikely that model calculations will be as accurate as measurements, and an accuracy of +15% is considered as a reasonable, attainable target in this investigation. If this can be reached, models could be used to estimate net and solar radiation in northern pastureland near stations collecting cloud data, and moderately close to radiosonde ascents (although precipitable water can be calculated from surface dewpoint temperature).

FIGURE 1 : STUDY REGION



CHAPTER II

NUMERICAL MODELS

This chapter describes the models used in this study. Hourly values of incoming solar, net and longwave radiation were calculated from two models. Model calculations should satisfy the following criteria (Atwater and Brown, 1974):

1. Accuracy in computing downward fluxes
2. Efficiency and economy of computing
3. Applicability of the model to the troposphere
4. Inclusion of most major factors influencing radiative transfer
5. Suitability for use with standard meteorological data

1. Solar Radiation

a. Cloudless Skies

The extraterrestrial radiation is attenuated by scattering due to aerosols and molecules, and absorption due to ozone and water vapour. Direct beam and diffuse beam are treated separately. There are three simplifying assumptions.

1. Absorption by water vapour only affects direct beam radiation.
2. Aerosol scatters solar radiation but does not absorb.
3. Multiple scattering effects are ignored - only simple scattering is considered.

The direct beam radiation is specified by

$$DB = I_o \cos z\ (T_{oz}\ T_{RS} - A_w)\ T_A \tag{1}$$

in which I_o is the solar constant (1353 Wm^{-2}) (Thekaekara and Drummond 1971), z is the solar zenith angle, T_{oz}, T_{RS} and T_A are the transmittances due to absorption by ozone, Rayleigh scattering and scattering by aerosols, and A_w is the absorptance due to water vapour. The transmittances and water vapour absorption depend strongly on relative optical air mass.

The diffuse term has two components; one due to Rayleigh scattering, and the other due to aerosol. The former is defined as

$$D_R = I_o \cos z\ 0.5\ T_{oz}\ (1 - T_{RS})\ T_A \tag{2}$$

where the scattering is assumed to be isotropic. The diffuse contribution from aerosol is given by

$$D_A = I_o \cos z\ T_{oz}\ T_{RS}\ (1 - T_A)\ B_a\ W_o \tag{3}$$

where B_a is the ratio of forward to total scattering, set equal to 0.85, and W_o is the ratio of scattering to total extinction, set equal to unity. Therefore incoming solar radiation is given by

$$K{\downarrow}_o = DB + D \tag{4}$$

Multiple reflections between the ground surface and atmosphere are ignored.

b. Effect of Cloud

Clouds can form a significant barrier to the penetration of incoming solar radiation. Clouds reflect radiation strongly, the reflectance depending on cloud thickness and solar zenith angle. Actual cloud transmissions vary with cloud type, and, based on work by Haurwitz (1948), can be calculated using

$$T_{ci} = (1/K{\downarrow}_o)\ (a/AM)\ (\exp -bAM) \tag{5}$$

with a and b varying with cloud type (Table 1). Transmission for a single cloud layer is calculated by

$$T_{Li} = (1 - C_i) + T_{ci}\ C_i \tag{6}$$

For n layers,

$$T = \prod_{i=1}^{n} [\ (1 - C_i) + T_{ci}\ C_i] \tag{7}$$

TABLE 1. Values of a and b (after Haurwitz) to evaluate cloud transmittance.

Cloud type	Fog	N_s	S_t	S_c	A_s	A_c	C_s	C_i
$a(X10)^2$	1.791	1.302	2.767	4.035	4.535	6.105	10.128	9.558
b	0.028	-0.167	0.159	0.104	0.063	0.112	0.148	0.079

The effect of multiple reflection between the ground and cloud base is accomodated by the definition of incoming solar radiation,

$$K\downarrow = K\downarrow^1 \; (1 + \alpha_c \;\; \alpha_g \; CT) \qquad (8)$$

where α_c and α_g are the cloud base and ground albedo, and $K\downarrow^1$ is the incidence irradiance before reflection by the ground.

2. Longwave and Net Radiation

Longwave radiation components are calculated as functions of air temperature, and summed with solar components to obtain net radiation. An albedo of 0.2 was assigned to calculate reflected solar radiation from

$$K\uparrow = 0.2 \; K\downarrow \qquad (9)$$

The Swinbank-Paltridge model (Swinbank, 1963), was used to calculate incoming longwave irradiance from

$$L\downarrow = L\downarrow_0 + (1 - 0.7) \; \varepsilon \; \sigma \; T_c^{\,4} \; (CT) \qquad (10)$$

Here, $L\downarrow_0$ is the cloudless sky value, given by Swinbank's formula

$$L\downarrow_o = 5.31 \times 10^{13}\ c\ T_a^6 \tag{11}$$

and $(1 - 0.7)\ \varepsilon\ \sigma\ T_c^4\ (CT)$ incorporates cloud effects. Paltridge and Platt (1976) suggest that a mean value of 60 Wm^{-2} could be used for $\varepsilon\sigma T_c^4$, thus,

$$L\downarrow = L\downarrow_o + 60\ CT \tag{12}$$

Paltridge suggests that temperature based models overestimate longwave radiation by about 20 Wm^{-2} during the day in the summer. Hence, this value is subtracted from estimated flux values during daylight hours only.

The outgoing longwave flux is estimated from the Stefan-Boltzman law

$$L\uparrow = \varepsilon\ 5.67 \times 10^{-8}\ T^4 \tag{13}$$

where ε is the surface emmisivity assigned the value of 1.0.

CHAPTER III

PROCEDURES

1. Precipitable Water

Precipitable water was determined from radiosonde records of pressure, temperature and relative humidity data at several heights in the atmosphere once a day at 1200 GMT. Precipitable water, defined by

$$w = \frac{1}{g} \int_{P_z}^{P_o} q \, dP \tag{14}$$

was evaluated from

$$w = \frac{1}{g} \sum_{i=1}^{n} \overline{q}_i \, \Delta P_i \tag{15}$$

where g is the gravitational constant, q is specific humidity, P is pressure, and n is the number of layers considered in the atmosphere.

2. Solar Radiation

a. Cloudless Skies

Hourly extraterrestrial radiation values are calculated from

$$I_o \cos z = 1353 \cos z / RV^2 \tag{16}$$

in which RV is the radius vector (Table 2) and the cosine of the zenith angle is obtained from

$$\cos z = \sin L \sin d + \cos L \cos d \cos HA \tag{17}$$

where L is station latitude, d is declination (Table 2), and HA is hour angle, obtained from local apparent time.

The transmission function for the scattering and absorbing media are calculated as follows. The transmission due to ozone can be defined as

$$T_{oz} = 1 - A_{oz}(x) \tag{18}$$

with x = 0.38 AM and

$$A_{oz}(x) = \frac{0.02118\,x}{1 + 0.042\,x + 0.000323\,x^2} + \frac{1.082\,x}{(1 + 138.6\,x)^{0.805}} + \frac{0.0658\,x}{1 + (103.6\,x)^3} \tag{19}$$

Following the method used by Davies and Idso (1978), AM (air mass) can be calculated using

$$AM = (1/\cos z) + 15\,(19.885 - z)^{-1.253} \tag{20}$$

TABLE 2. Values of solar declination (degrees) and radius vector. Radius vector values are in the second row for each date.

Date	Jan.	Feb.	Mar.	Apr.	May	June	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
1	-23.07	-17.32	-7.88	+4.24	+14.84	+21.95	+23.17	+18.24	+8.58	-2.88	-14.18	-21.68
	0.983	0.985	0.991	0.999	1.008	1.014	1.017	1.015	1.009	1.001	0.993	0.986
9	-22.22	-14.92	-4.8	+7.28	+17.15	+22.87	+22.47	+16.1	+5.62	-5.97	-16.64	-22.75
	0.983	0.987	0.993	1.002	1.010	1.015	1.017	1.014	1.007	0.999	0.991	0.985
17	-20.9	-12.25	-1.65	+10.2	+19.15	+23.37	+21.35	+13.68	+2.57	-8.97	-18.8	-23.34
	0.984	0.988	0.955	1.004	1.011	1.016	1.016	1.012	1.005	0.997	0.989	0.984
25	-19.15	-9.38	+1.5	+12.94	+20.82	+23.42	+19.84	+11.04	-0.54	-11.84	20.6	-23.42
	0.984	0.990	0.997	1.006	1.013	1.016	1.016	1.011	1.003	0.994	0.987	0.983

The transmission due to aerosols is obtained from

$$T_A = 0.91^{AM} \tag{21}$$

and the transmission due to Rayleigh scattering is a function of air mass and can be obtained from Table 3. The absorption by water vapour can be described by

$$A_w(Y) = 2.9\ Y\ /\ ((1 + 141.5\ Y)^{0.635} + 5.925\ Y) \tag{22}$$

with Y defined as air mass times the precipitable water.

b. Effect of Cloud

It is difficult to correctly estimate cloud amounts from the ground. Low clouds may obscure medium or high clouds from the observer's view, or, medium clouds may obscure the high clouds.

Meteorological observations do not consider this, as total cloud amount cannot exceed 10/10, whereas in reality, 30/10 is possible if three cloud layers are present. An attempt can be made to correct for this problem, allowing CL, CM, and CH to represent "reported" low, medium and high cloud amounts, and C_m and C_H to be the middle and high level values corrected for the "observer's window", such that

$$CL = CL \tag{23}$$

$$C_M = CM\ /\ (1 - CL) \tag{24}$$

$$C_H = CH\ /\ (1 - CL - CM) \tag{25}$$

TABLE 3. Transmissivity after Rayleigh scattering. Values are expressed as a function of air mass m.

m	.0	.02	.04	.06	.08
1	.8973	.8830	.8696	.8572	.8455
2	.8344	.8240	.8141	.8047	.7957
3	.7872	.7790	.7711	.7635	.7563
4	.7493	.7425	.7360	.7297	.7236
5	.7177	.7120	.7064	.7010	.6958
6	.6907	.6857	.6809	.6762	.6716
7	.6671	.6627	.6586	.6543	.6502
8	.6463	.6424	.6386	.6348	.6312
9	.6276	.6241	.6207	.6173	.6140
10	.6108	.6076	.6045	.6015	.5984
11	.5955	.5926	.5897	.5889	.5842
12	.5815	.5788	.5762	.5736	.5711
13	.5686	.5661	.5637	.5613	.5589
14	.5566	.5543	.5521	.5498	.5476
15	.5455	.5434	.5413	.5392	.5371
16	.5351	.5331	.5311	.5292	.5273
17	.5254	.5235	.5217	.5198	.5180
18	.5162	.5145	.5127	.5110	.5093

Cloud transmissions are calculated using equations 5, 6, and 7 consecutively, resulting in T, which is the transmission factor for the entire cloud cover. This value is used to correct incoming cloudless solar radiation for cloud effects with

$$K{\downarrow} = K{\downarrow}_0 \, T \qquad (26)$$

Albedo values of 0.6 and 0.2 respectively were assigned to the albedo of the cloud base and ground.

3. Longwave and Net Radiation

From the various radiation fluxes, the surface radiation balance Q* was calculated from

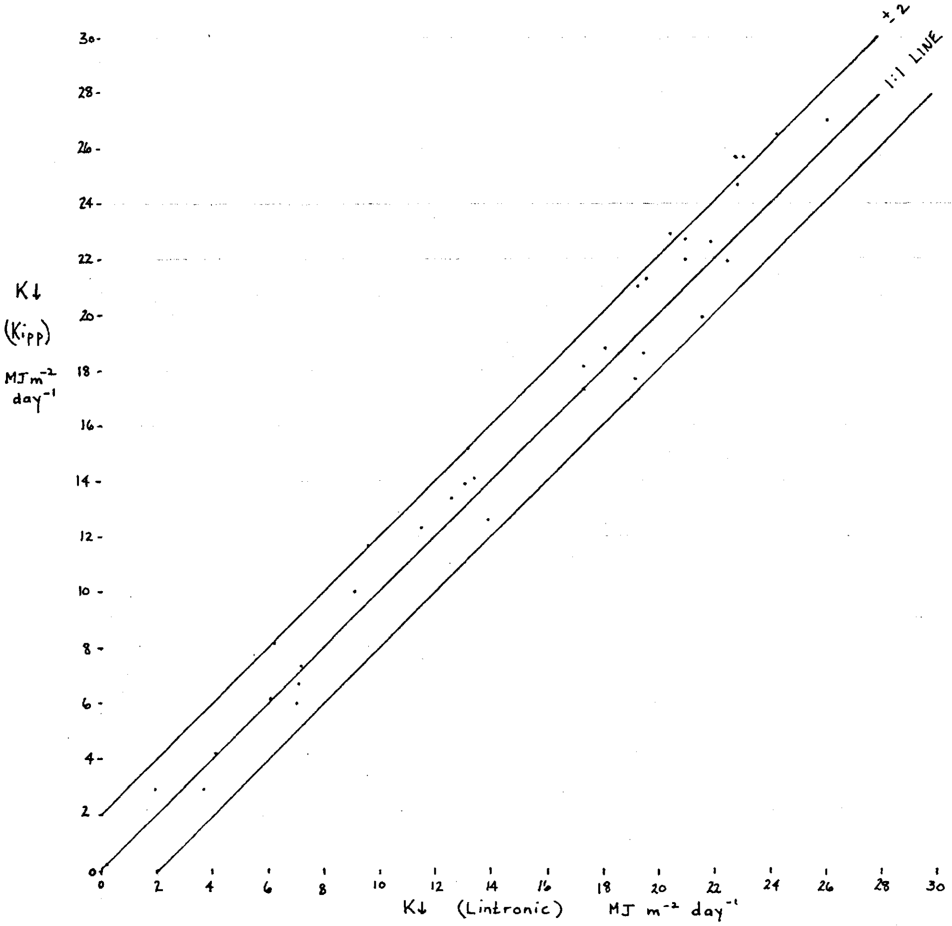
$$Q^* = K{\downarrow} - K{\uparrow} + L{\downarrow} - L{\uparrow} \qquad (27)$$

4. Measurements

At the pasture site, K↓ and Q* were measured directly. A Lintronic pyranometer was used to measure K↓, with an estimated accuracy of 10%, with least accuracy occuring during large zenith angles. Q* was measured using a Swissteco net radiometer, with about 5% accuracy. Both sensors were mounted 1 m above the ground.

A check was run on the Lintronic using a Kipp pyranometer (5% accuracy). Figure 2 shows that the measurements correlate within a error range of $\pm$ 2MJm^{-2} day $^{-1}$. This is satisfactory especially

FIGURE 2 : COMPARISON OF RESULTS FROM TWO PYRANOMETERS



since the Kipp sensor outputs hourly integrated values, whereas the Lintronic outputs hourly spot measurements.

CHAPTER IV

RESULTS AND DISCUSSION

Only data for Ft. St. John for the hours when pasture site readings were taken were used. These hourly intervals, which varied in length each day, were summed daily and converted to MJ m^{-2} day^{-1}. Calculated and measured daily results were plotted for incoming solar and net radiation (Figures 3 and 4). Five and ten day running means were tabulated to check the validity of the model over longer time intervals (Figures 5, 6, 7 and 8).

1. Incoming Shortwave Radiation

Figure 3 indicates that calculated and measured values of incoming solar radiation agree to within ± 4 MJ m^{-2} day^{-1}, 90% of the time. This error margin diminishes to ± 2 MJ m^{-2} day^{-1} (80% of the time) using the five day and ten day (92% of the time) means. This indicates that as the averaging period increases, model performance improves.

Davies and Schertzer (1974), in a study in southern Ontario, obtained similar results. The five stations monitored in that project were situated within 16 km of cloud observing sites, with three stations utilizing on-site recordings. Daily plots agreed to within 20%, with five and ten day calculated means generally falling within 10% and 5%

FIGURE 3 : INCOMING SOLAR RADIATION - CALCULATED VS. MEASURED
MAY TO AUGUST, 1977
[SUNSET PRAIRIE PASTURE, B.C.]

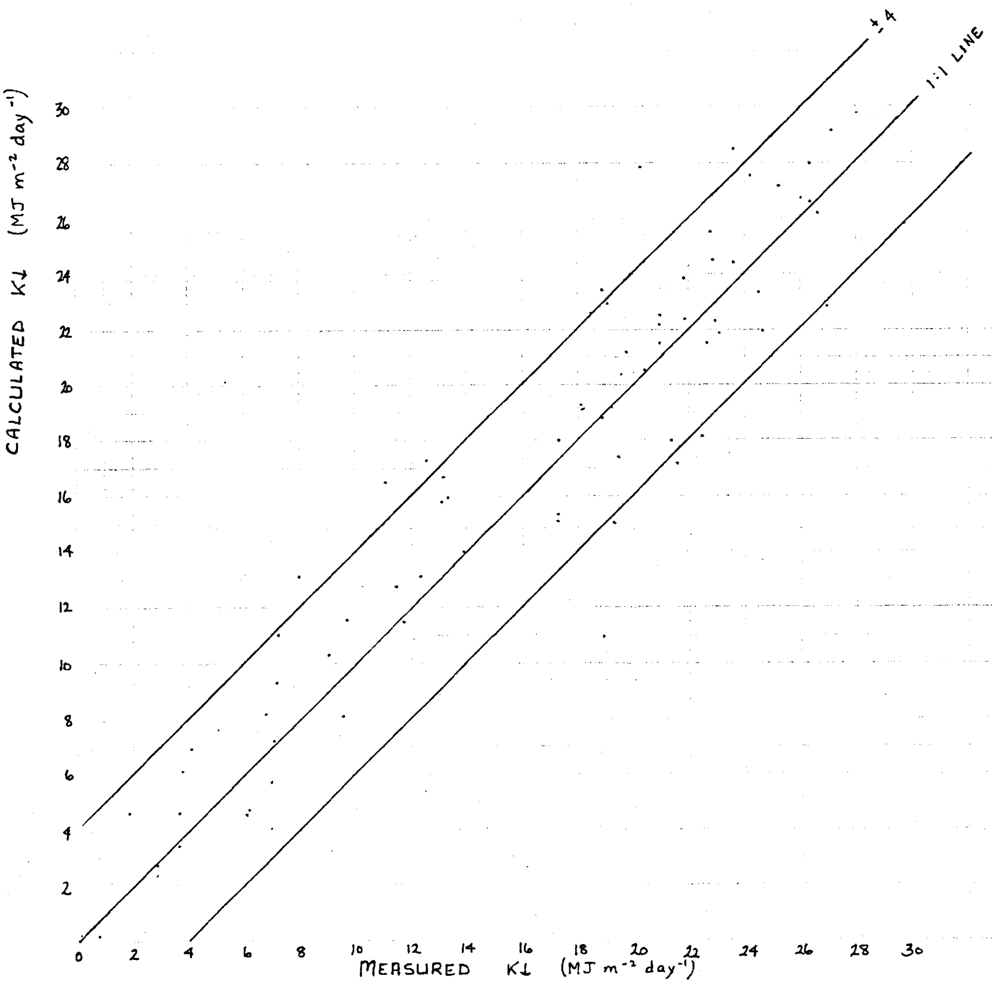


FIGURE 4: NET RADIATION - CALCULATED VS. MEASURED
MAY TO AUGUST, 1977
[SUNSET PRAIRIE PASTURE, B.C.]

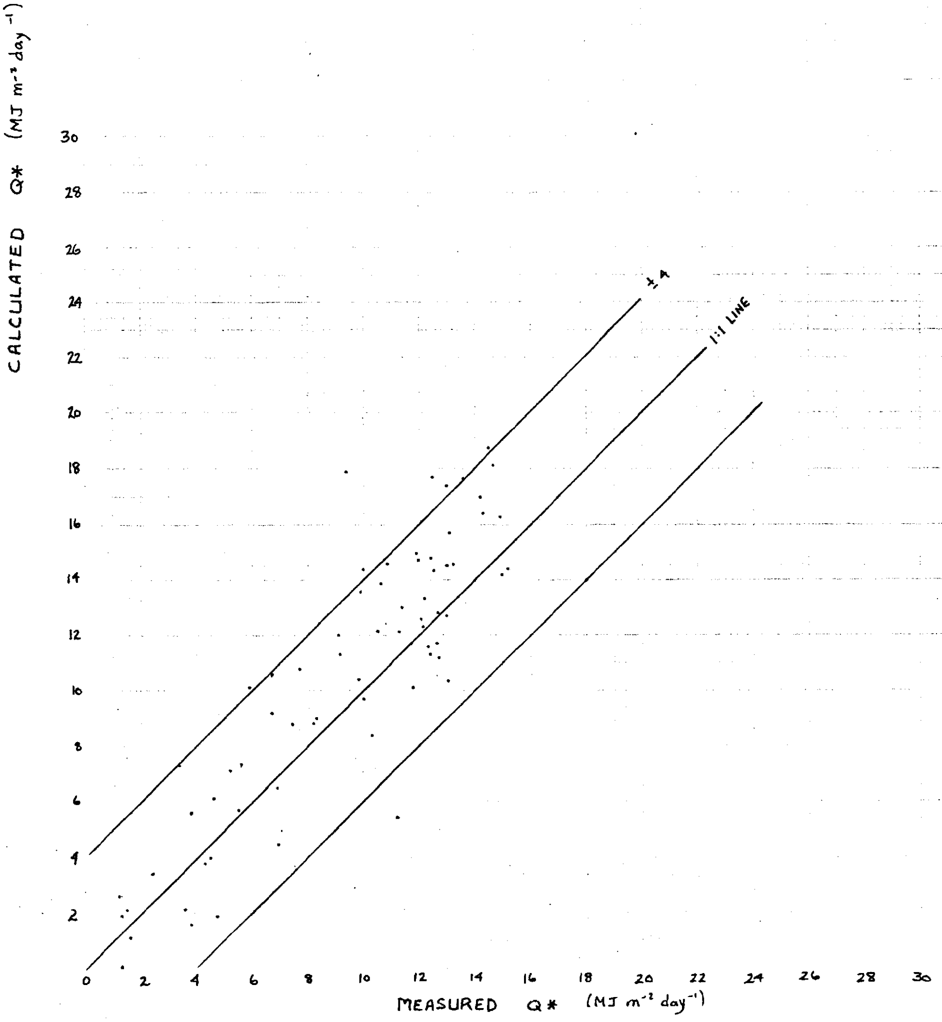


FIGURE 5: INCOMING SOLAR RADIATION 5 DAY MEANS (RUNNING MEANS) MAY TO AUGUST 1977

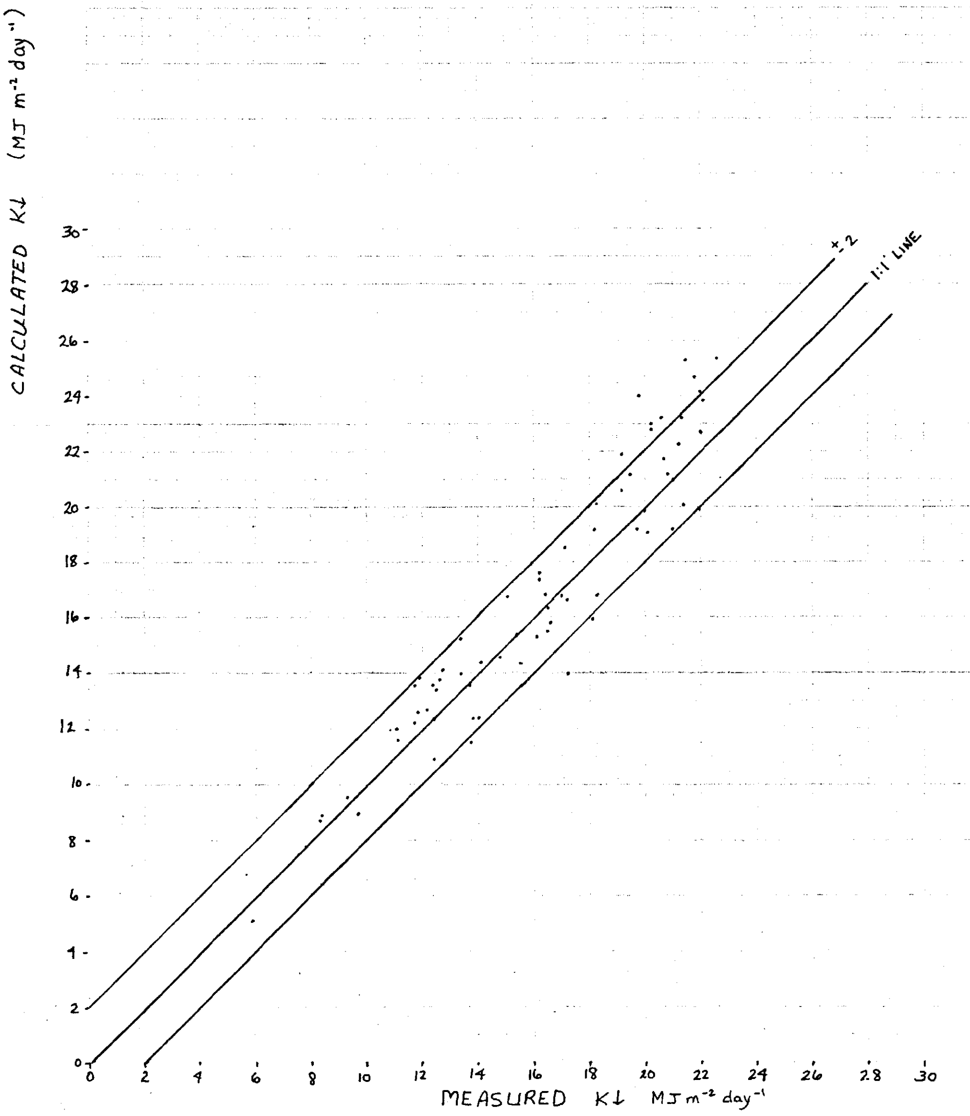


FIGURE 6: NET RADIATION 5 DAY MEANS (RUNNING MEANS) MAY TO AUGUST 1977

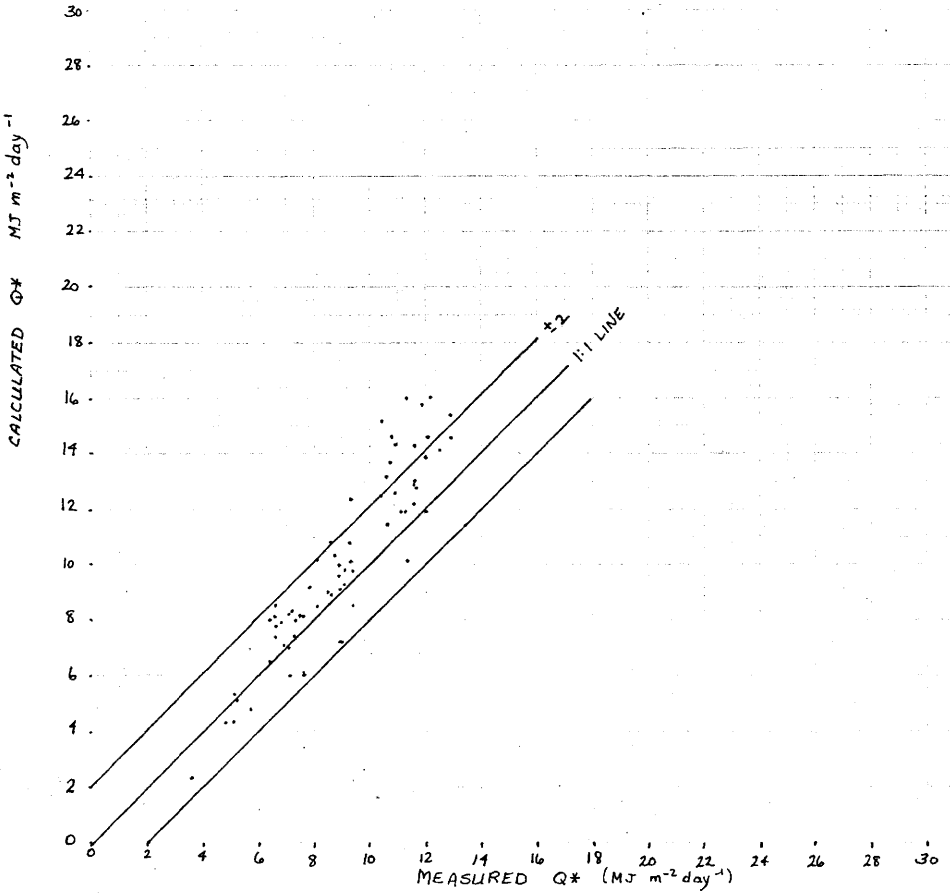


FIGURE 7: INCOMING SOLAR RADIATION 10 DAY MEANS (RUNNING MEANS) MAY TO AUGUST 1977

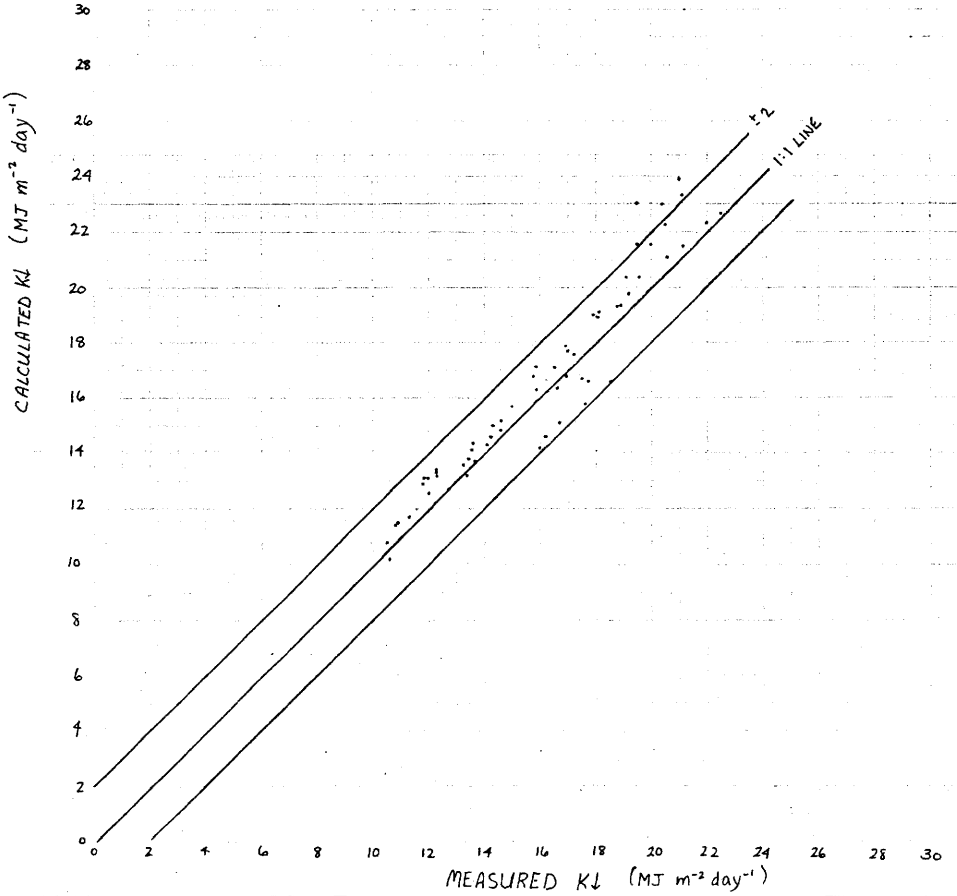
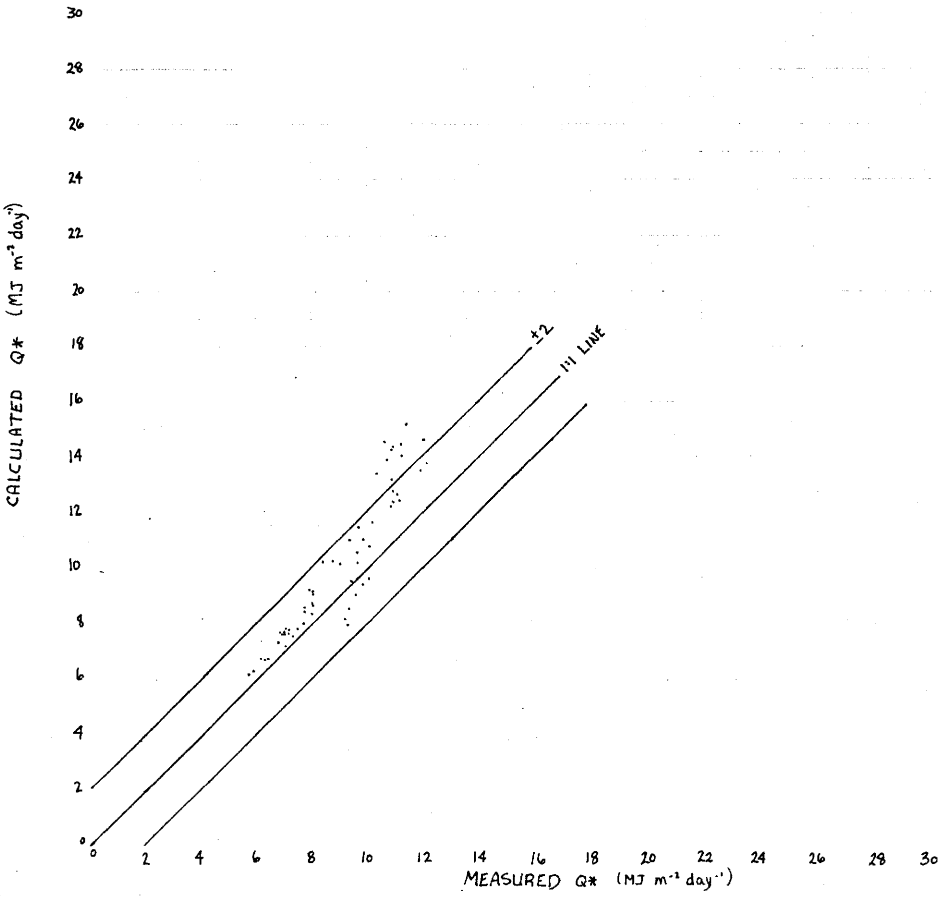


FIGURE 8: NET RADIATION 10-DAY MEANS (RUNNING MEANS) MAY TO AUGUST 1977



respectively of the measured mean values. (Davies et al, 1975).

The study by Suckling and Hay (1977), based on a similar model, resulted in daily calculated values falling within ± 15% of the measured values. The previously common trend of increasing accuracy with increased averaging periods was apparent.

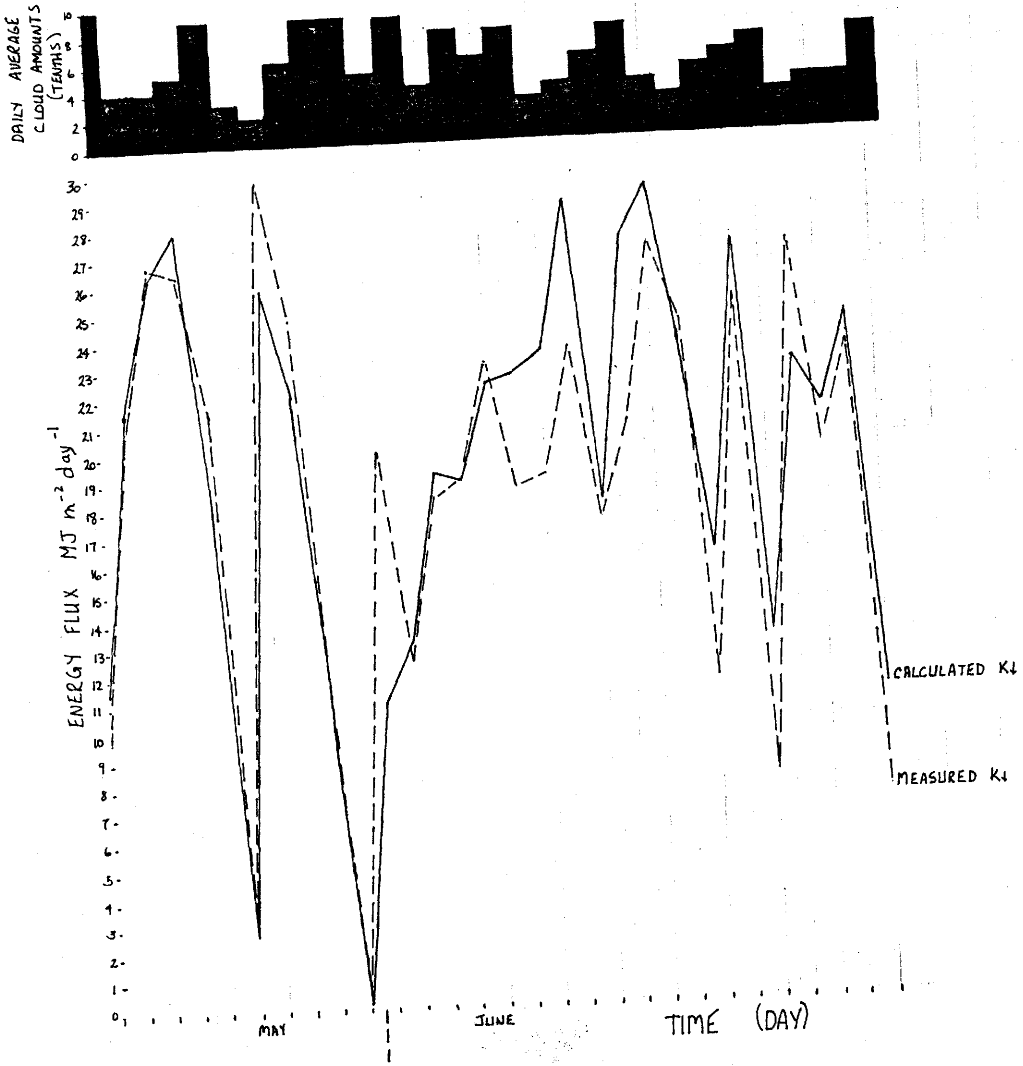
The results obtained in this paper, therefore, compare favourably with results obtained elsewhere in Canada. This is reasonable, due to the similarity of the models utilized, although geographic location and distance from cloud observations were the main variances from previous studies.

Sources of discrepency on a daily basis could be due to several factors. Measurement errors due to instrument in accuracies may represent a small percentage. Inaccuracies in cloud estimates may account for some of the additional error, with the possibility of incorrect cloud transmission coefficients (Haurwitz, 1948) accounting for the remaining error.

Figure 9 demonstrates that the incoming solar radiation closely approximates the measured data over time, with both following average cloud amount relatively closely. In May, the model slightly underestimates the measured values, whereas in mid-June the model overestimates. During the months of July and August, the model overestimates slightly

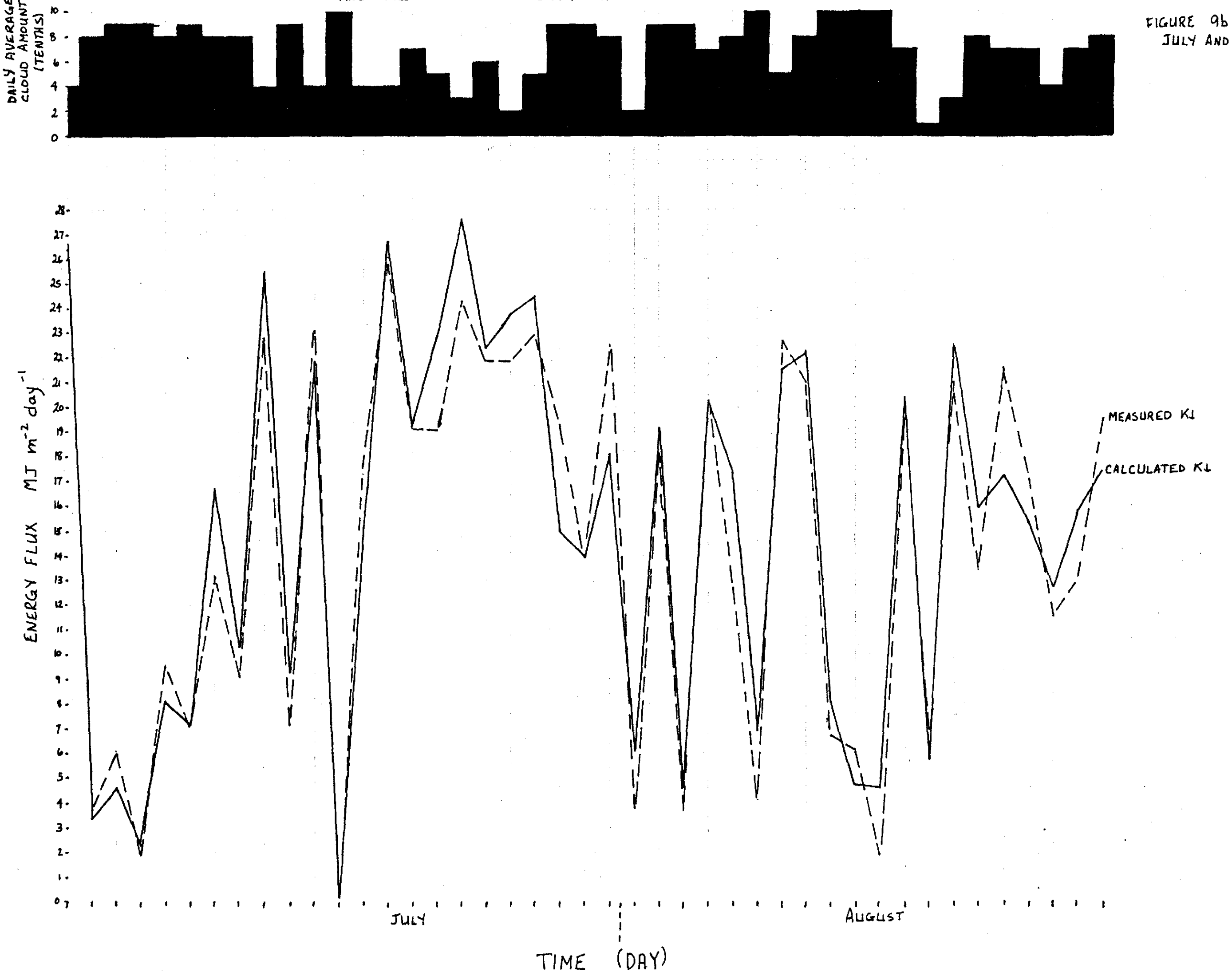
DAILY AVERAGE CLOUD AMOUNTS AND CALCULATED AND MEASURED INCOMING SOLAR RADIATION

FIGURE 9a : MAY AND JUNE 1977



DAILY AVERAGE CLOUD AMOUNTS AND CALCULATED AND MEASURED INCOMING SOLAR RADIATION

FIGURE 9b:
JULY AND AUGUST 1977



when there is less than 5/10 cloud present.

Cloud amounts may be misjudged by the observer (despite "observer window" corrections) and are only spot recorded once hourly. Cloud conditions at Ft. St. John at the time of observation may vary considerably from those at the pasture (50 km distance difference), influencing measured incoming solar radiation values at the pasture (which are spot measured hourly also) depending on wind directions and atmospheric conditions. Multiple reflections are ignored in the incoming solar radiation model, possibly influencing the calculated value. Five and ten day means provide the estimate required to minimize errors of this sort.

2. Net Radiation

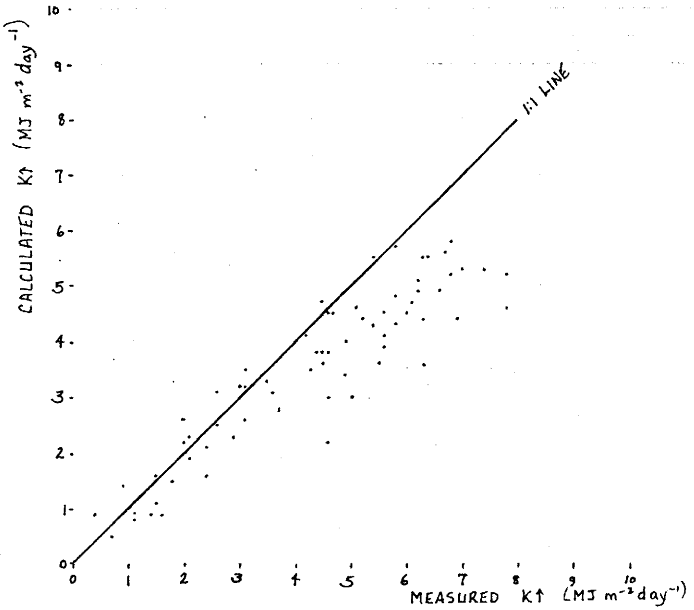
About 90% of the daily calculated values lie within 4 MJ m^{-2} day^{-1} of measured values (Figure 4). The values, in this respect, follow the same trend as the ones observed in Figure 3 for incoming solar radiation. Using five and ten day running means reduces the error margin to $\pm$ 2MJ m^{-2} day^{-1} with close to 80% of the points lying within this region in both Figures 6 and 8. This is also similar to the results for incoming solar radiation. One must consider the possibility that, due to the breakdown of Q^* into K^* and L^*, errors incurred with $K\downarrow$ will be brought through from the first part of the model in addition to errors in calculating or measuring $K\uparrow$ and L^*. The $K\uparrow$ component may contain possible inaccuracies if the albedo used by the model for the surface is not a reasonable estimate. The model used 0.2 to represent the albedo of the prairie grasses. Figure 10 indicates that perhaps this value of 0.2 should be higher, whereas, as the model stands presently, Q* (calculated) will likely be slightly reduced. When the outgoing longwave radiation flux was calculated, air temperature was used, due to the absence of the surface temperature measurements needed for more accurate results. Measurement errors may be as great as 25%, although 5-10% would probably be a more reasonable figure.

3. Comparison of Incoming Solar and Net Radiation

On a daily basis (Figures 3 and 4), the Q* scatter (of measured against calculated values) is closer to a 1:1 fit than is the K↓ fit, but with the five and ten day means, Q* correlations are not as high as those for K↓.

On a daily basis, errors in Q* components may be inversely proportional to each other, giving a final calculated value which is close to the measured value, although this performance may be due to the accuracy of the models used in the calculation. However, over the five and ten day means, the relative error of Q* is greater than that of K↓. Therefore, the K↓ model performs better over five and ten day mean periods, than does Q*, indicating errors in reflected solar and longwave radiation calculations.

FIGURE 10: COMPARISON OF CALCULATED VS MEASURED REFLECTED SOLAR RADIATION



CHAPTER IV

CONCLUSION

The radiation models presented in this paper appear to simulate measured solar and net radiation values quite accurately. The degree of accuracy attained was higher than was expected due to the fact that the cloud observations required for the model were from a relatively distant station. This model has been used previously, resulting in decreased accuracy with increased distance from the cloud observations (Davies et al, 1975). Therefore the results which appeared in this paper may indicate that the methods used to calculate radiation are particularly suited to the Peace River Valley, although additional experimentation is recommended in this region before this can be conclusively stated.

List of Symbols

a	Haurwitz constant
AM	Air mass
A_{oz}	Absorption due to ozone
A_w	Absorption due to water vapour
b	Haurwitz constant
B_a	Ratio of forward to total scattering
C_H	Corrected high cloud amount
CH	High cloud amount
C_i	Cloud amount in layer i
CL	Low cloud amount
C_M	Corrected middle cloud amount
CM	Middle cloud amount
CT	Total cloud amount
d	Solar declination
D	Diffuse solar radiation
D_A	Aerosol scattering component of diffuse radiation
DB	Direct beam radiation
D_R	Rayleigh scattering component of diffuse radiation
ε	Emmisivity
g	Gravitational constant (9.8 ms^{-2})
HA	Hour angle
I_o	Solar constant
$K{\downarrow}_o$	Incoming cloudless solar radiation
$K{\downarrow}$	Incoming solar radiation
$K{\downarrow}'$	Incidence Irradiance before reflection by the ground
$K{\uparrow}$	Reflected solar radiation
L	Station latitude
$L{\downarrow}$	Incoming longwave radiation
$L{\downarrow}_o$	Incoming longwave radiation with clear skies
$L{\uparrow}$	Outgoing longwave radiation
P	Pressure
q	Specific humidity
Q^*	Net radiation
RV	Radius vector
σ	Stefan-Boltzman constant (5.67×10^{-8} Wm^{-2} K^{-4})
T	Transmission for n cloud layers
T_a	Air temperature
T_A	Transmittance due to scattering by aerosols
T_c	Cloud base temperature
T_{ci}	Cloud transmission for type i clouds
T_{Li}	Transmission for a single (i) cloud layer
T_{oz}	Transmittance due to absorption by ozone
T_{RS}	Transmittance due to Rayleigh scattering
W	Precipitable water
W_o	Ratio of scattering to total extinction
z	Zenith angle

REFERENCES

Atwater, MA. and P.S. Brown, Jr., 1974, "Numerical Computations of the Latitudinal Variation of Solar Radiation for an Atmosphere of Varying Opacity", Journal of Applied Meteorology, 13(3), 289-297.

Davies, J.A. and S.B. Idso, 1978, "Estimating the Surface Radiation Balance and Its Components", in J.F. Berber and B.J. Barfield, (editors), "Modification of the Aerial Environment of Plants", American Society of Agricultural Engineers Monograph. (in press).

Davies, J.A., and W.M. Schertzer, 1974, "Canadian Radiation Measurements and Surface Radiation Balance Estimates for Lake Ontario during IFYGL," Government of Canada, Department of the Environment, Canada Centre for Inland Waters, Great Lakes Division.

Davies, J.A., W.M. Schertzer, and M. Nunez, 1975, "Estimating Global Solar Radiation", Boundary Layer Meterology, 9(1), 33-52.

Haurwitz, B., 1948, "Insolation in Relation to Cloud Type", Journal of Meteorology, 5(3), 110-113.

List, R.J. (prepared by), 1966, "Smithsonian Meterological Tables", Smithsonian Institution.

Paltridge, G.W. and C.M.R. Platt, 1976, "Radiative Processes in Meteorology and Climatology" Developments in Atmospheric Science, 5, Elsevier, New York, 318 pp.

Suckling, P.W. and J.E. Hay, 1977, "A Cloud Layer-Sunshine Model for Estimating Direct, Diffuse and Total Solar Radition", Atmosphere, 15(4), 194-207.

Thekaekara, M.P. and A.J. Drummond, 1971, "Standard Values for the Solar Constant and its Spectral Components", Nature (London) Phys. Sci., 229, 6-9.