INFLUENCE OF CLOUD COVER ON EVAPOTRANSPIRATION DEMAND

O.J. Mudiare¹, D.M. Gray² and G.A. McKay³

ABSTRACT

The paper assesses the role of cloud cover in moderating the latent energy LE available for evapotranspiration during the Prairie growing season. The influence of clouds was examined by studying the effects on LE of differences in net radiation and in ambient temperature under clear-sky and cloudy conditions. Estimates were obtained using empirical relationships and climatological records for the Bad Lake Watershed which is located in the semi-arid region of southwestern Saskatchewan.

The study demonstrates the strong relationship between net radiation and evapotranspiration potential. Cloud cover on rain-free days over grass cover reduced the evapotranspiration demand on the average, seasonally, by an estimated 13 mm or 7.5% of the seasonal rainfall. On average, the suppressive effect of clouds during light rainfall days was 25 mm, equal to about 25% of the amount of precipitation produced by the clouds. The thicker clouds associated with heavier, but less frequent rainfalls, gave average seasonal reductions of about 12 mm. The combined effect of the cloud cover for all events over an average growing season was equivalent to a water-consumption suppression of about 50 mm or 29% of the seasonal precipitation.

¹Lecturer II, Department of Agricultural Engineering, Ahmadu Bells University, Zaria, Nigeria; ²Chairman and Professor, ³Senior Research Scientist, Division of Hydrology, University of Saskatchewan, Saskatoon, Saskatchewan.
INTRODUCTION

Crop production in the semi-arid regions of the Prairie Provinces is frequently limited by the lack of moisture. Nevertheless the production record for dryland farming is impressive. That is often credited to the moisture storage capacity of Prairie soils and moisture conservation practices. The influence of cloud cover in suppressing evapotranspiration is rarely considered. The magnitude of their effects in humid climates may be small compared to other water budget terms, but in semi-arid climates they can assume considerable significance. A quantitative assessment of these effects is the subject addressed in this paper.

Also of importance are the frequency and timing of light rainfalls during the growing season that reduce the evapotranspiration demand while contributing little to soil moisture. The 1980 crop year in Saskatchewan provides an example. Drought conditions prevailed the preceding winter. As of June 16th soil moisture available to Saskatchewan crops was generally low, in the order of 25-40% (by weight) on fallow and 15-20% on stubble. Despite light summer precipitation a respectable crop was harvested -wheat production being 8% above 1979 (Edey, 1981). In the year there were sufficient periods of cloud and light precipitation during the summer to produce a good crop - but insufficient to recharge soil moisture at depth.

Summer rainfall on the Prairies is usually convective and highly variable with respect to time and space (McKay, 1970). The semi-arid climate causes many weather systems that are relatively unproductive insofar as the amount of rain they produce, however these systems may manifest crop production through the cloud cover and temperature changes accompanying an event. The uncertain nature of Prairie summer rainfall is confirmed by Dyck (1977) who found that 78% of the summer rainstorms produced less than 6.5 mm of precipitation, and that only 35% of the storms produced rain over a network of 109 km².

Clouds reduce the water demand of plants by reducing the radiative, latent and sensible energy fluxes. They also inhibit extreme leaf temperatures that affect photosynthesis. Their probable effects on evapotranspiration demand, hence soil moisture availability, are examined herein by comparing the suppressing effect of cloud cover for three weather types: days that are rain-free, with light rainfall (< 6.5 mm) and with heavier rains. This is done by computing the latent energy available for evapotranspiration on such days and comparing the quantities with estimates for clear-sky days.

COMPUTATIONAL PROCEDURES

The computations were conducted over the growing season months, May-August, for the 11-year period, 1972-1982, using hydrometeorological data recorded at the Bad Lake Climatological Station. The model used to calculate the daily latent energy flux LE was a simplified form of the evapotranspiration equation given by Blad (1983) in which the canopy and aerodynamic resistances are omitted and is of the form:
where: \( RN = \) net radiation,
\( \gamma = \) psychrometric constant,
\( A = \) slope of the saturated vapor pressure curve, usually taken at the ambient air temperature, and
\( RH = \) relative humidity.

Equation 1 gives a measure of the latent energy available for evaporation and transpiration; it does not necessarily provide a good estimate of "actual evapotranspiration" inasmuch as it assumes the vapor pressure difference across the substomatal openings of a plant is the same as that between the leaf surface and some reference point in the air above. It's main value and the manner it is used herein is for indexing changes in latent energy due to changes in the ambient environment, principally net radiation. Mudiare (1985) conducted a sensitivity analysis of factors affecting evapotranspiration from grass in a Prairie environment using 6-years of measurements at Bad Lake. He found that LE was sensitive to different variables in the following order of decreasing importance: net radiation, vapor pressure difference, canopy diffusion resistance, reference height and roughness height for momentum, and crop displacement height. The results of this analysis demonstrated that an increase in daily \( RN \) of 5% increased LE by approximately 11%; a change in magnitude approximately equal to that caused by increasing all other variables in the same amount.

The procedures used in the study to estimate \( R_N \) and \( A \) of Eq. 1 are briefly discussed below.

Net Radiation

Net radiation, the difference between the net incoming short-wave radiation and the net long-wave radiation, can be expressed by the equation:

\[
R_N = (1-A)R_s + \varepsilon \varepsilon_A T^4 - \varepsilon \varepsilon_a T_s^4
\]

where: \( A = \) albedo of the surface,
\( R_s = \) incident incoming short-wave radiative flux,
\( \varepsilon = \) emissivity of the surface,
\( \varepsilon_a = \) emissivity of the atmosphere,
\( \sigma = \) Stefan Boltzmann constant, and
\( T_z, T_s = \) air and plant surface temperatures respectively.

Davies (1965, 1967) and Davies and Idso (1979) demonstrated from analyses of both day-time and daily values of net radiation that the net short-wave component \([(1-A)R_s]\) is the dominant flux and that plots of \( R_N \) against \( R_s \) are approximately linear with high correlation coefficients. These findings indicate that variations in albedo over vegetative surfaces during the summer months are small and do not vary widely under normal sky conditions (Stanhill et al., 1966; Davies and Buttimor, 1969). For practical purposes then, Eq. 2 may be reduced to the form:

\[
R_N = CR_s + B
\]
where \( C \) and \( B \) are coefficients whose values can be derived from field data. Davies and Buttimor (1969) note that this relationship can be applied also to sky conditions when the incoming long-wave radiation is not considered constant.

The coefficients of Eq. 3 were computed using 1201 days of record collected between 1972 and 1982 at Bad Lake, including rain and rain-free days, obtaining the expression:

\[
R_N = 0.455R_S - 0.153
\]

in which \( R_N \) and \( R_S \) are in \( \text{MJ m}^{-2} \text{day}^{-1} \). This expression gives results with a correlation coefficient, \( r = 0.92 \), and a standard error, \( S_{yx} = 1.22 \text{MJ m}^{-2} \text{day}^{-1} \).

**Incident "Clear-sky" Short-wave Radiation**

The amount of short-wave radiation penetrating the atmosphere and received by the earth's surface varies depending on latitude, season, time of day, topography, vegetation, cloud cover and turbidity of the atmosphere (Male and Gray, 1981). Solar radiation reaching the earth's surface has two components: a direct beam along the sun's rays, and a diffuse component scattered by the atmosphere but with the greatest flux coming from the direction of the sun. The direct clear-sky radiation incident to a slope \( I_d \) was calculated by the expression suggested by Garnier and Ohmura (1970) as:

\[
I_d = \left( \frac{I_o}{r^2} \right) \int p^m \cos(X \cdot S) dH
\]

where:

- \( I_o \) = solar constant,
- \( r \) = radius vector of the earth's orbit,
- \( p \) = mean transmissivity of the atmosphere,
- \( m \) = optical air mass,
- \( \cos(X \cdot S) \) = cosine of the angle of incidence of the sun's rays on the slope (\( X \) is the unit normal vector pointing away from the surface and \( S \) is the unit vector expressing the sun's position) and,
- \( H \) = hour angle measured from solar noon. The integral being taken over the duration of sunlight on the slope.

Values of \( I_o, r \) and \( m \) are given by List (1968). Mudiare (1985) compared "calculated" and "measured" short-wave radiation for 80 clear days at Bad Lake and found an average transmissivity of 0.65 (\( r = 0.93 \)) and this value for \( p \) was used in calculating \( I_d \) by Eq. 5.

The magnitude of the clear-sky diffuse component \( D_o \) was obtained from the expression given by List (1968):

\[
D_o = 0.5(1 - a_w - a_o)I_t - I_d
\]

where:

- \( a_w \) = radiation absorbed by water vapor (assumed to be 7%).
\[ a_o = \text{radiation absorbed by ozone (assumed to be 2%)}, \]
\[ I_t = \text{extra-terrestrial radiation on a horizontal surface and} \]
\[ \text{equal to } (I_o/r^2) \cos z_s \, dz, \text{where } z_s = \text{sun's zenith distance,} \]
\[ I_d = \text{direct beam short-wave component (Eq. 5)}. \]

The sum of \( I_d \) and \( D_o \) were used for \( R_s \) in Eq. 4 to calculate \( R_N \) for clear-sky conditions.

**Slope of the Saturation-Vapor Pressure Curve - Clear-sky Conditions**

The value of \( \Delta \) used to estimate \( LE \) by Eq. 1 for clear-sky conditions was obtained from an estimate of the air temperature \( T_z \) calculated by the following expressions describing atmospheric emissivity:

\[ \varepsilon_a = 0.691 + 0.006 T_z \]
(Swinbank, 1963; Mudiare, 1985),

and

\[ \varepsilon_a = 0.642 \left[ \frac{e_a}{(T_z + 273)} \right]^{1/7} \]
(Brutsaert, 1975, 1982),

in which \( e_a \) is in Pa and \( T_z \) in °C. Pelton (1967) suggested that vapor pressure does not usually vary widely over a period of a day in the Prairie region. Hence, mean daily vapor pressure and temperature measurements were used with Eq. 7b to obtain an initial estimate of \( e_a \) and this value used in Eq. 7b to obtain \( T_z \) for clear-sky conditions. The slope \( \Delta \) corresponding to \( R_z \) was obtained using the equation describing the relationship between saturated vapor pressure and temperature given by Murray (1967), that is:

\[ \Delta = \frac{d e_s(T)}{dT} = 2.5 \times 10^4 \exp[17.27 \frac{T}{(T + 237.3)}/(T + 237.3)^2 \]

in which \( e_s(T) \), the saturated vapor pressure is in mb and \( T \) is in °C.

**RESULTS AND DISCUSSION**

**Effects of Cloud Cover on Incident Global Radiation**

In previous discussions it was emphasized that the principal factor controlling evaporation and evapotranspiration demands in a Prairie environment is net radiation, which in turn is strongly affected by the attenuation of solar and ground radiation by cloud cover. To illustrate differences in attenuation by cloud cover associated with two weather types, namely; rain-free days and days with rain, comparisons were made between measured daily global radiation (direct + diffuse) \( R_s \), extraterrestrial radiation \( I_t \), and the ratio of the number of bright sunshine hours \( n \) to the number of possible sunshine hours \( N \). These comparisons assumed the variables were related in linear form as:
where \( a \) and \( b \) are coefficients that vary with time, latitude and atmospheric conditions. The best-fit values of \( a \) and \( b \) for the growing season months for Bad Lake are given in Table 1. An analyses of variance of the data showed that in each month the magnitude of the intercept \( "a" \) was significantly higher and the magnitude of the slope \( "b" \) was significantly lower on rain-free days than on rain days \( (P = 95\%) \). The findings suggest on heavy overcast days \( (n/N = 0, 0.1, 0.2, 0.3, \text{ etc.}) \) that clouds accompanying rainfall activity are more effective in suppressing global short-wave radiation. This result was expected since the type of cloud is an important factor affecting the attenuation of radiation through the atmosphere. For example a thin cirroform cloud might transmit 85% of incoming global radiation whereas a thick, dark nimbostratus cloud (or precipitation cloud) only 20%. Also, showery clouds generally have greater vertical development than clouds that do not produce precipitation.

\[ R_s = I_t \left[ a + b(n/N) \right] \]

Table 1. Values of the regression coefficients "a" and "b" of Eq. 9 for Bad Lake Climatological Station, May-August, 1972-1982 inclusive.

<table>
<thead>
<tr>
<th>Month</th>
<th>Weather Type</th>
<th>Coefficient</th>
<th>Weather Coefficient</th>
<th>r</th>
<th>S_yx</th>
<th>Number of days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>a</td>
<td>b</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>May</td>
<td>rain free</td>
<td>0.282</td>
<td>0.472</td>
<td>0.937</td>
<td>0.044</td>
<td>230</td>
</tr>
<tr>
<td></td>
<td>rain days</td>
<td>0.197</td>
<td>0.592</td>
<td>0.950</td>
<td>0.053</td>
<td>96</td>
</tr>
<tr>
<td>June</td>
<td>rain free</td>
<td>0.271</td>
<td>0.471</td>
<td>0.918</td>
<td>0.045</td>
<td>186</td>
</tr>
<tr>
<td></td>
<td>rain days</td>
<td>0.202</td>
<td>0.566</td>
<td>0.945</td>
<td>0.051</td>
<td>127</td>
</tr>
<tr>
<td>July</td>
<td>rain free</td>
<td>0.288</td>
<td>0.448</td>
<td>0.929</td>
<td>0.036</td>
<td>197</td>
</tr>
<tr>
<td></td>
<td>rain days</td>
<td>0.200</td>
<td>0.554</td>
<td>0.961</td>
<td>0.044</td>
<td>135</td>
</tr>
<tr>
<td>August</td>
<td>rain free</td>
<td>0.248</td>
<td>0.484</td>
<td>0.945</td>
<td>0.040</td>
<td>210</td>
</tr>
<tr>
<td></td>
<td>rain days</td>
<td>0.204</td>
<td>0.536</td>
<td>0.944</td>
<td>0.054</td>
<td>79</td>
</tr>
</tbody>
</table>

\( a \) = Correlation Coefficient  
\( b \) = Standard error of linear regression of \( R_s/I_t \) versus \( n/N \)  
\( r \) = rain free - days with no measurable rainfall and \( n/N < 0.75 \)

Estimates of solar radiation using the coefficients in Table 1 in Eq. 9 and estimates of transmitted clear-sky radiation by Eqs. 5 and 6 were used to compute the average reduction in radiation on cloudy and light-rain days as shown in Table 2. The monthly mean daily suppressions ranged from 25 to 45 per cent of the clear-sky radiation with the largest values occurring on days with light rain.
Table 2. Suppression of "potential" or clear-sky global radiation on cloudy days with and without light rain in MJ m⁻² day⁻¹

<table>
<thead>
<tr>
<th>Month</th>
<th>Without Rain a</th>
<th>With Light Rain b</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Range</td>
</tr>
<tr>
<td>May</td>
<td>7.44</td>
<td>0.0-14.2</td>
</tr>
<tr>
<td>June</td>
<td>7.76</td>
<td>0.0-14.8</td>
</tr>
<tr>
<td>July</td>
<td>7.32</td>
<td>0.0-15.4</td>
</tr>
<tr>
<td>August</td>
<td>6.80</td>
<td>0.0-12.4</td>
</tr>
</tbody>
</table>

a) days with no measurable rainfall and n/N ≤ 0.75
b) days with rainfall ≤ 6.5 mm

A more detailed indication of the suppressive effects of cloud cover is provided in Fig. 1 in which measured solar radiation and computed clear-sky radiation are plotted along with rainfall depth. This shows that incoming solar radiation suppressions of 30% by cloud are not unusual. On some rainy days the suppressions appear inconsistent which is to be expected for no attempt was made to relate the rainfalls to the time of day. The rain may have been nocturnal, the weather being sunny during the day.

Figure 1. Measured solar radiation, computed clear-sky radiation and rainfall depth for July, 1982, Bad Lake, Saskatchewan.
Effects of Cloud Cover on Evaporation and Evapotranspiration Demand

The daily evapotranspiration at Bad Lake for the period 1972-1982, inclusive, was calculated by Eq.1 using measured values of net radiation, mean relative humidity, and mean air temperature and compared with the corresponding amounts under clear-sky conditions. A summary of the suppressive effects of different weather types is given in Table 3.

Table 3. Evapotranspiration suppression and rainfall statistics for Bad Lake, 1972-1982. Units are mm.

<table>
<thead>
<tr>
<th>Factor</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evapotranspiration Suppression</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Cloudy weather</td>
<td>2.2</td>
<td>3.1</td>
<td>2.7</td>
<td>4.9</td>
<td>12.9</td>
</tr>
<tr>
<td>- Cloud with light rain (&lt;6.5 mm)</td>
<td>5.0</td>
<td>8.4</td>
<td>6.6</td>
<td>6.2</td>
<td>26.2</td>
</tr>
<tr>
<td>- Cloud with heavier rain (&gt;6.5 mm)</td>
<td>2.9</td>
<td>2.8</td>
<td>3.9</td>
<td>2.0</td>
<td>11.6</td>
</tr>
<tr>
<td>Totals</td>
<td>10.1</td>
<td>14.3</td>
<td>13.2</td>
<td>13.1</td>
<td>50.7</td>
</tr>
<tr>
<td>Average Rainfall</td>
<td>40.8</td>
<td>48.4</td>
<td>51.4</td>
<td>33.2</td>
<td>173.8</td>
</tr>
<tr>
<td>Rainfall + Suppression</td>
<td>50.9</td>
<td>62.7</td>
<td>64.6</td>
<td>46.3</td>
<td>224.5</td>
</tr>
</tbody>
</table>

The computed suppressions are not large, but could prove very significant when crop water supplies are critical. On average they equal 29% of the seasonal precipitation and cloud cover during light rain events which accounts for over 50% of the total suppression. Adding the seasonal suppression (26.2 mm) to the depth of rain (60 mm) produced by light rains and comparing the sum (86.2 mm) with the seasonal rainfall (178.3 mm) gives a measure of the importance of these weather systems to the amount of water available for crop production.

More precise computation would be possible had hourly or other shorter period data been used. For example, the use of daily rainfall amounts as an indicator of cloud cover left open the possibility that the day could be sunny, the rain having occurred in the dark. Both net radiation and evapotranspiration demand are occasionally anomalously high when compared to the occurrence of rain (Fig. 2). This can be attributed to the occurrence of nocturnal as opposed to diurnal rains with sunshine during the main part of the day. No attempt was made to consider the opacity or persistence of clouds. On the other hand it is unlikely that further refinement was necessary to prove the point that cloud cover has generally unrecognized importance.

The computed reductions in evapotranspiration potential may differ significantly from day-to-day and month-to-month. The relative frequency of daily reductions for July is shown in Fig. 3 which demonstrate the range of values that may be expected.
Figure 2. Net radiation flux, evapotranspiration and rainfall depth for July 1972, Bad Lake, Saskatchewan.

Figure 3. Relative frequency distribution of reductions in evapotranspiration potential for (a) cloudy, rain-free days and (b) days with light rain: July 1972 to 1982, Bad Lake, Saskatchewan.
The suppressions above are for grass and it is suspected the reductions for wheat would be of similar magnitude. The ratio of evapotranspiration for dryland wheat crops to that of native grass in southern Saskatchewan, as calculated for the 1969-71 crop years from data supplied by the Department of Soil Science, University of Saskatchewan ranged from 1.04 to 1.46, with a three year mean of 1.18. Banga (1981) obtained ratios of 0.77 to 1.16 with a mean of 1.0 for the 1975 crop growing at five locations in the Bad Lake Watershed.

The roles of clouds are implicit in most procedures for estimating evaporation and transpiration demands being incorporated in an average way in coefficients of equations. However, the type and frequency of cloud cover, even on a monthly basis can be quite variable, such that their effects on evapotranspiration may need to be more critically examined. This is particularly true in semi-arid climates where rainfalls are light and the ratio of the effect of clouds to precipitation high.

Light summer rains do not usually contribute directly to soil moisture storage, but they do provide increased moisture directly to leaves and increased humidity, thereby reducing the demand on soil moisture. Their potential value has been alluded to earlier in the text in commenting on the 1980 crop yield. Frequent light rains, with implicitly more cloud, can lead to higher yields than can occur in years with equivalent precipitation totals obtained from fewer but heavier rainstorms. This is not only due to superior evapotranspiration suppression, but also because clouds decrease the heat stress on plants.

The need for a more critical evaluation of the role of clouds and light rains results from the use of more advanced technology and to achieve economically competitive performance. It is also warranted by the findings of non-linearity in the relationship between evapotranspiration and crop yields (Stewart and Hagan, 1969; Musick et al., 1976; Stegman et al., 1980). Those observations and the variable nature of plant growth during a season highlight the need to know the moisture status on a daily basis. This can be achieved best by models that are sensitive to daily changes in cloud and rainfall as used here.

**SUMMARY**

Cloud cover reduces the evapotranspiration demand of Prairie crops. Estimated average seasonal reductions of 50 mm were found on the basis of 11 years of observations at the Bad Lake Climatological Station located in southwestern Saskatchewan. The reductions are primarily the result of reduced solar radiation, and thereby expressed in the net radiation flux. The correlation between net radiation and incident short-wave radiation was found to be about .92. Empirical expressions are presented that may be used to estimate incoming global radiation from extraterrestrial radiation and sunshine hours for the summer months and different weather types.
It is shown that clouds associated with rainfall activity are more effective than cloud cover on days without rain in reducing net radiation, hence the evapotranspiration potential. In July, for example, over an 11-year period cloud cover on rain-free and light rain days reduced the evapotranspiration potential on average by 2.7 and 6.6 mm. Over the summer months cloud cover accompanying light rain accounted for approximately 50% of the seasonal reduction. The importance of light rains as they affect the amount of water available for crop production in the region is emphasized.

Many conventional procedures for estimating evaporation and evapotranspiration demands allow for the effects of cloud in an average way through statistically-derived coefficients. As more precise information becomes necessary for efficient water use management, allowances should be made for the variable effects of clouds on a daily basis. This can be of particular importance in semi-arid environments where moisture is chronically in short supply and the suppression of evapotranspiration by clouds is significant compared to rainfall. The variable nature of Prairie weather systems and their associated cloud cover necessitates a modelling approach for that purpose.

REFERENCES


