Estimation of standardized reference evapotranspiration on the Canadian Prairies using simple models with limited weather data

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Potential evapotranspiration (PET) can be accurately calculated with a Penman-Monteith model, however this model requires inputs that are not all measured at most weather stations. The agricultural region of the Canadian Prairies is a large geographic region of dry continental weather (cold semi-arid to subhumid) and could benefit from simple, yet accurate empirical models for determination of evapotranspiration (ET). The purpose of our study was to develop simple (limited data) ET models to estimate standardized reference evapotranspiration. We used daily weather data from 2003 and 2004 from ten stations across the agricultural region of the prairies to develop temperature, temperature-relative humidity, and temperature-relative humidity-wind speed models. Our models were developed by regression using the ASCE (2005) standardized reference model for a well-watered short crop surface (ET_{os}) as the 'observed' variable. We compared our developed models to other published simple models by Baier-Robertson, Hargreaves, and Linacre. To verify the accuracy of the models (relative to ET_{os}), we considered averages, standard errors, regression parameters (r^2, slope, and intercept), as well as the coefficient of efficiency. Of the temperature based models, our model and Hargreave's model were the most accurate. Our temperature-relative humidity model improved the estimate of evapotranspiration compared to temperature based models. The Linacre and the Baier-Robertson temperature and temperature-relative humidity models were not accurate and are not recommended for estimating evapotranspiration in the Canadian Prairies. Incorporation of temperature, relative humidity, and wind speed into our statistically developed model resulted in the most accurate and precise estimation of standardized reference evapotranspiration. **Keywords:** potential evapotranspiration, Canadian Prairies, temperature, relative humidity, models.

Bien que le modèle de Penman-Monteith permette un calcul précis de l'évapotranspiration potentielle (ETP), ce dernier requiert des données qui ne sont pas mesurées par la plupart des stations météorologiques. La zone agricole des Prairies canadiennes est une vaste région géographique au climat continental sec (froid semi-aride à subhumide) et celle-ci bénéficierait grandement de modèles empiriques pour la détermination de l'évapotranspiration qui soient à la fois simples et précis. Le but de notre étude était donc de développer des modèles ET simples et ne requérant que des données limitées pour estimer une évapotranspiration de référence standardisée. Nous avons utilisé les données météorologiques journalières de 2003 et 2004 provenant de dix stations à travers la région agricole des Prairies pour développer des modèles de température, température – humidité relative et, température – humidité relative – vent. Nos modèles ont été développés par régression en utilisant le modèle standardisé de référence ASCE (2005) avec comme variable 'observée' une culture de surface courte et bien arrosée (ET_{os}). Nous avons comparé les modèles ainsi développés avec d'autres modèles simples publiés par Baier-Robertson, Hargreaves et Linacre. Pour vérifier l'exactitude de ces modèles (comparativement à ET_{os}), nous avons considéré les moyennes, les erreurs standards, les paramètres de régression (r^2, pente et ordonnée à l'origine), de même que le coefficient d'efficacité. De tous les modèles basés sur la température, notre modèle de même que le modèle de Hargreaves se sont révélés les plus précis. Notre modèle de température – humidité a permis d'améliorer les estimations de l'évapotranspiration comparativement aux modèles basés sur la température. Les modèles de température et de température – humidité de Linacre et de Baier-Robertson n'étaient pas précis et ne sont donc pas recommandés pour estimer l'évapotranspiration dans les Prairies canadiennes. L'incorporation de la température, de l'humidité et de la vitesse du vent dans notre modèle statistique nous a permis d'obtenir l'estimation la plus juste et précise de l'évapotranspiration de référence standardisée. **Mots clés**: évapotranspiration potentielle, Prairies canadiennes, température, humidité relative, modèles.

INTRODUCTION

Potential evapotranspiration (PET) is a required parameter for hydrological and agricultural projects. Although PET is related to free-water evaporation and may be estimated from measurements using evaporation pans or atmometers (Thom et al. 1981), it is more commonly calculated from climatic parameters (e.g., temperature, relative humidity) and related to readily available soil water transpired through a specified vegetated surface (ASCE 2005). Early work by Thornthwaite (1948) proposed the concept of evapotranspiration (ET), which was based upon the idea that radiation is a common forcing factor for long-term air temperature and evaporation, and therefore temperature is a predictor of PET. Thornthwaite (1948) used air temperature and day-length to characterize seasonal change in water balance and then delineated climate zones based on this soil water balance. For applications where ET is needed for short durations of a few days or hours, temperature alone proved to be inadequate to predict ET (Pelton et al. 1960). Thornthwaite recognized that his simple approach lacked "mathematical elegance" in that it was not understood why the relationship to radiation was spatially variable. Further development of the ET concept recognized the underlying factors needed to better predict ET. In the same year, Penman (1948) reported on an approach that recognized not only the radiative forcing parameter but also the aerodynamic restrictions to evaporation. Penman simplified this aerodynamic term using a wind speed function.

Since the work of Thornthwaite and Penman, there have been many ET models developed. The one model that is the most widely accepted is the Penman-Monteith (PM) model (Shuttleworth 1993) which provides sufficient accuracy for use in general hydrological and crop irrigation applications. A disadvantage of this physically based model is the large number of parameters needed to calculate ET. The minimum requirements for the PM model are daily measurements of solar radiation, relative humidity, air temperature, and wind speed at the 2-m height. Although electronic instrumentation and automatic data recording have increased the availability and ease of obtaining the parameters needed to drive the PM model, it still requires resources to train personnel to install and maintain the equipment. Historical data for a given location are frequently limited to just temperature or temperature and relative humidity requiring ET estimation using models with fewer data requirements than the PM model.

There are different procedures for the calculation of ET via the Penman-Monteith method. Currently the standardized reference evapotranspiration equation has been recommended for use by the American Society of Civil Engineers (ASCE 2005). This method is a variation of the PM method and attempts to standardize the use of one method amongst many users. The equation provides a recommended determination of reference ET for a well-watered short (ET_{os}) or tall grass surface. It needs to be recognized that there is a difference between that of 'potential evapotranspiration' and that of 'reference evapotranspiration'. Potential ET is that considered from a wet surface that is non-specific as to crop type. Reference ET refers to the ET from a reference grass surface of specific characteristics and that is well watered (Allen et al. 1998).

Although there are a number of models for calculating daily ET using temperature or temperature and relative humidity (RH) along with extraterrestrial solar radiation (R_a) (e.g., Baier and Robertson 1965; Linacre 1977; Hargreaves and Samani 1985), the performance of many of these models has not been compared to ET_{os} across the whole of the Canadian Prairies. Grace and Quick (1988) compared several models for calculating PET in the semiarid climate surrounding Lethbridge, Alberta. The models performed similarly under low wind speed and moderate humidity. However, model estimates differed widely under dry, windy conditions - conditions typical of much of the semiarid climatic region within the Canadian Prairie. For the semiarid climate of southern Alberta, they recommended estimating PET with models using wind and especially relative humidity as well as temperature and radiation data. Droogers and Allen (2002) found that including a rainfall term with a modified monthly Hargreaves method (Hargreaves and Samani 1985) significantly improved its estimation of the FAO-56 Penman-Monteith method for global arid regions. Given the great amount of historical data for the Canadian Prairies, and the number of current weather stations that do not measure solar radiation, wind speed, or relative humidity, there continues to be a need for simple yet representative daily ET models.

The purpose of our paper is to develop simple daily ET models that will represent standardized reference ET for short crop surfaces (ET_{os}, as calculated by the ASCE method) for the agricultural region of the prairies. Therefore, our objectives are to:

1. Compare the performance of the following published models for estimating daily ET:
   - (a) Baier-Robertson temperature ET (ET_{BR1});
   - (b) Baier-Robertson temperature and relative humidity ET (ET_{BR2});
   - (c) Linacre temperature (ET_{L1});
   - (d) Linacre temperature and relative humidity (ET_{L2}); and
   - (e) Hargreaves temperature (ET_H).
2. Develop and compare the performance of simple models for estimating daily ET by using the following combinations of parameters:
   - (a) Temperature and extraterrestrial radiation;
   - (b) Temperature, relative humidity, and extraterrestrial radiation; and
   - (c) Temperature, relative humidity, extraterrestrial radiation, and wind speed.
3. Recommend the empirical models that best estimate ET_{os} for the agricultural region of the prairies.

We assumed our empirical equations would apply across the Canadian Prairies because of fairly similar climate across this broad region. This region has a sub-humid to semi-arid climate that is characterized by cold-dry winters and warm summers within which the majority of precipitation occurs.

METHODOLOGY

All models, published and developed, were compared against the standardized reference evapotranspiration equation for a short crop (ET_{os}, ASCE 2005). The models were developed and tested using daily data from 15 weather stations across the agricultural region of the prairies (Table 1). With the exception of another six stations in southern Alberta, these 15 weather stations represent all the accessible stations within the agricultural region of the prairies. There are likely other private stations (e.g., within the irrigation districts of Manitoba) or other individual research stations, however in our search we either could not locate or could not access others. Although there are more than one hundred stations available through Environment Canada, most record only temperature and precipitation and do not measure all the parameters necessary to calculate ET_{os}. The data from each of the weather stations used in our study were reviewed for erroneous values and missing information. To accomplish objective 2, a subset of data (ten stations, years 2003 and 2004) was used to develop a set of regression based models with ET_{os} as the predicted variable. Another subset of data (five stations, various years) was used to compare the performance of the models and to help recommend the most suitable model for estimating ET_{os}. All the data necessary to calculate daily standardized reference ET for a short crop (ET_{os}, ASCE 2005) were recorded at these selected stations.

Table 1. Weather station locations and identification.

Station	Province	Latitude (°N)	Longitude (°W)	Elevation (m)	WMO ID	Climate ID	Years*	Affiliation**
Development								
Beaverlodge	AB	55.2	119.4	746	71230	3070600	2003-04 (0)	AAFC
Lacombe	AB	52.5	113.8	860	71242	3023722	2003-04 (31)	AAFC
Onefour	AB	49.1	110.5	935	71116	3044923	2003-04 (3)	AAFC
Stavely	AB	50.2	113.9	1364	71555	3036099	2003-04 (6)	AAFC
Vauxhall	AB	50.1	112.1	779	71251	3036682	2003-04 (1)	AAFC
Elstow field	SK	52.0	106.0	508	NA	NA	2003-04 (8)	Research
Perdue field	SK	52.0	107.6	596	NA	NA	2003-04 (80)	Research
Scott	SK	52.4	108.8	660	71489	4047240	2003-04 (0)	AAFC
Swift Current	SK	50.3	107.7	825	71446	4028060	2003-04 (2)	AAFC
Morden	MB	49.2	98.1	297	71564	5021849	2003-04 (43)	AAFC
Evaluation								
Eston field	SK	51.0	108.8	610	NA	NA	2003-04 (55)	Research
Lethbridge	AB	49.7	112.7	903	71509	3033897	2003-04 (2)	IMCIN
Strathmore	AB	51.0	113.3	967	71526	3036205	2004 (4)	IMCIN
Kernen farm	SK	52.2	106.6	510	NA	4057155	1999 (0)	U of S
Outlook	SK	51.5	107.1	541	71551	4055736	2004 (8)	IMCIN

* Numbers in parentheses are days of missing data.

** AAFC -Agriculture and Agri-Food Canada; IMCIN - Irrigation Management Climate Information Network; U of S - University of Saskatchewan; Research - weather stations for authors research

Existing evapotranspiration models

We used four published models to calculate PET for a well-watered short crop surface that varied between 0.10 and 0.15 m in height.

Standardized reference evapotranspiration: ET_{os} (ASCE 2005):

$$ET_{os} = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{C_n}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \tag{1}$$

where:

ET_{os} = standardized reference ET for short surfaces of 0.12 m (mm/d),

R_n = calculated net radiation at crop surface (MJ m^{-2} d^{-1}),

G = soil heat flux density at soil surface (MJ m^{-2} d^{-1}),

T = mean daily air temperature at 1.5 to 2.5-m height, $(T_{max} + T_{min})/2$ (°C),

T_{max} = daily maximum air temperature (ºC),

T_{min} = daily minimum air temperature (ºC),

u_2 = mean daily or hourly wind speed at 2-m height (m/s),

e_s = saturation vapor pressure at 1.5 to 2.5-m height as average of saturation vapor pressure at maximum and minimum air temperatures (kPa),

e_a = mean actual vapor pressure at 1.5 to 2.5-m height (kPa),

Δ = slope of saturation vapor pressure-temperature curve at T (kPa/°C), given by:

$$\Delta = \frac{2504 \exp\left[\dfrac{17.27T}{T+237.3}\right]}{(T+237.3)^2}$$

γ = psychrometric constant = $0.000665P$ (kPa/°C),

P = atmospheric pressure (kPa),

C_n = numerator constant that changes with crop reference type (900 for short and 1600 for tall crop surfaces), and

C_d = denominator constant that changes with crop reference type (0.34 for short and 0.38 for tall crop surfaces).

Standardized reference ET is defined as the ET rate from a uniform surface of dense, actively growing vegetation that is not short of water and represents an expanse of at least 100 m (ASCE 2005).

Hargreaves: ET_H (Hargreaves and Samani 1985; Hargreaves et al. 1985):

$$ET_H = 0.00094(T_{\max} - T_{\min})^{0.5}(T + 17.8)R_a \tag{2}$$

where:

ET_H = reference ET for well-watered short crop (mm/d),

R_a = extraterrestrial radiation (MJ m^{-2} d^{-1}) as described in ASCE (2005).

Baier-Robertson: ET_{BR1}, ET_{BR2} (Baier and Robertson 1965; Baier 1971):

$$ET_{BR1} = 0.157T_{\max} + 0.158(T_{\max} - T_{\min}) + 0.109R_a - 5.39 \tag{3}$$

$$ET_{BR2} = -0.0039T_{\max} + 0.1844(T_{\max} - T_{\min}) + 0.1136R_a + 2.811(e_s - e_a) - 4.04 \tag{4}$$

where:

ET_{BR1}, ET_{BR2} = PET (mm/d) calibrated to Penman's formula for a crop with an albedo of 0.25 and a crop coefficient of 1.0 throughout the growing season (Baier 1971).

Linacre: ET_{L1}, ET_{L2} (Linacre 1977):

$$ET_{L2} = \frac{\left(\frac{500T_m}{100-L}\right) + 15\left(T - T_d\right)}{80 - T} \quad (5)$$

where:

ET_{L2} = grass reference ET calculated using measured dew point temperature (mm/d),

T_m = temperature adjusted for elevation, $T_m = T + 0.006h$ (°C)

h = elevation (m),

T_d = dew point temperature (°C), and

L = latitude (°).

Where dew point temperature is not available, Eq. 6 may be used to substitute into Eq. 5 to to calculate ET_{L1}.

$$T - T_d = 0.0023h + 0.37T + 0.53T_{rd} + 0.35T_{ra} - 10.9 \quad (6)$$

where:

T_{rd} = mean daily range of temperature (°C) and

T_{ra} = difference between the mean temperatures of the warmest and coldest months of the year (°C).

To use either form of the Linacre equation, the station must have at least 5 mm of precipitation per month and the mean dew point depression ($T - T_d$) must be at least 4°C. The current study area satisfies these limitations.

As most of the above models (Eqs. 2 to 5) were developed for a short crop surface (as opposed to a tall crop), this was the standard used within our study.

Procedure

Weather stations from the agricultural region of the three prairie provinces representing three soil climatic zones (Brown, Dark Brown, and Black) were used in this study. Recorded at each station were the data necessary for the calculation of daily ET_{os} (Eq. 1) (Table 1). Data from the first group of stations listed in Table 1 were used to calculate ET using Eqs. 1 to 6 and to develop models involving temperature, relative humidity, wind, and extra-terrestrial solar radiation . Data from the second group of stations (Table 1) were used to compare the relative accuracy with which our developed models and the published simple models could represent ET_{os}.

Although we desired a representative distribution of weather stations across the agricultural potion of the Prairies, the majority of the stations with suitable data were located in western Saskatchewan and Alberta. There were a lack of suitable stations within eastern Saskatchewan and Manitoba; the ones used were the only accessible stations with full data sets.

Daily weather data from April 1 to October 31 for two years, 2003 and 2004, and from 10 weather stations (Table 1) were used to develop the following models:

1. ET_t as a function of air temperature and extra terrestrial solar radiation (R_a);
2. ET_{Ht} as a function of air temperature and R_a, using a modified Hargreaves equation; and
3. ET_{tr} as a function of temperature, humidity, and R_a
4. ET_{tru} as a function of temperature, humidity, wind speed, and R_a.

During model development, various parameters (e.g., T_{max}, T, RH_{max}, Δ, e_a) and various transformations (e.g., conversion of temperature or relative humidity to vapour pressures, multiplication of terms together, such as that done by the ET_{os} and Hargreaves models) were investigated for improvement of fit. Because about two-thirds of the daily rainfall totals were zero, we assumed the contribution of daily rainfall to the regression estimate of daily ET was minimal and therefore rainfall was not included in model development.

The following statistical coefficients of comparison were used to both select the best parameters during model development and to evaluate them, relative to Eq. 1:

1. r^2, the correlation coefficient for the linear regression equation of predicted vs observed (ET_{os}); the closer to 1.0 the better the fit;
2. m, the slope of the linear regression equation; the closer to 1.0 the more representative the prediction of ET_{os};
3. b, the y-intercept from the linear regression equation; the closer to 0.0 the more representative the ET estimate;
4. *SE*, the standardized error; and
5. *E*, coefficient of efficiency (Eq. 7).

Data from the first group of weather stations in Table 1 were used to develop the models, while the second group of weather stations was used to evaluate the developed models.

Legates and McCabe (1999) suggested using the coefficient of efficiency (Eq. 7) to overcome limitations when using r^2 for evaluating the 'goodness-of-fit' with hydroclimatic and hydrologic data sets. The coefficient of efficiency, *E*, is defined as:

$$E = 1.0 - \frac{\sum_{i=1}^{n}\left(O_i - P_i\right)^2}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2} \quad (7)$$

where:

O, P = observed and predicted values, respectively.

E ranges from minus infinity to 1.0 with larger values indicating better agreement. A value of 0 for *E* indicates that the observed mean $\bar{O}$ is as good a predictor as the model, while negative values indicate that the observed mean is a better predictor than the model. The *E* is similar to the 'efficiency of a model' by Nash and Sutcliffe (1970) that is also used for hydrological investigations.

Data quality and missing data

The following procedures were used to ensure that the climatic data sets were of good quality and as representative as possible:

- Only climatic data from April 1 to October 31 were used. These months have average monthly air temperatures greater than 0°C.
- If any single data parameter (e.g. maximum daily temperature) was missing for a day then that day was not used for either development or for evaluation. We preferred using actual rather than estimated data for developing and evaluating models.
- Temperatures were checked for unexplainable outliers.
- RH_{max} values were checked for values greater than 100%.
- Wind speeds were checked for consistently higher or lower velocities (systematic error) over a period of time.

- solar radiation (R_s) was checked by plotting daily values against calculated clear sky radiation (R_o) using procedures and equations described in Appendix D of ASCE (2005). The higher values of R_s should be representative of clear sky conditions and should be within 3 to 5% of the computed value, R_o. If these R_s values were consistently higher or lower than the corresponding R_o values by more than 5%, then it could have meant that the instrument measuring R_s had not been calibrated properly, had not been properly leveled, or had become contaminated with dust. In that case, R_s was adjusted by multiplying R_s by the average value of R_o/R_s on clear days (ASCE 2005).

No unexplainable outliers for temperature were found for any of the stations. Most stations had some RH_{max} values at or slightly less than 100% but not exceeding; however four stations (Morden, Outlook, Onefour, and Vauxhall) had numerous occurrences where RH_{max} was greater than 100% (103 to 110%). Because of the lack of any other correction information, we assumed that the error would be greater for higher values of RH and zero at the lowest value. Thus Eq. 8, that provided a greater correction weight to high values, was applied:

$$RH_c = RH_{uc} - \frac{\left(RH_{s\max} - 100\right)\left(RH_{uc} - RH_{s\min}\right)}{RH_{s\max} - RH_{s\min}} \tag{8}$$

where:

RH_c = corrected RH value (%),

RH_{uc} = uncorrected RH value (%),

RH_{smax} = highest uncorrected maximum RH value that occurred for that station in the entire measurement set (%), and

RH_{smin} = lowest uncorrected minimum RH value that occurred for that station in the entire measurement set (%).

The wind speeds at Scott, between January 1 and June 23, 2003, were much higher (by an average factor of 1.96) than the rest of the data set after June 23, 2003 or for similar dates in 2004. Thus the daily wind speed during this period was corrected by dividing it by 1.96. All wind speeds at Agriculture and Agri-Food Canada (AAFC) Research stations were recorded at 10 m; those at University Research stations at 3 m; and those at Lethbridge and Strathmore IMCIN stations at 2 m. All stations were corrected to 2 m height using the procedure described in ASCE (2005).

The following stations required correction of their R_s readings so that a match was obtained for days of maximum R_s (assumed clear-sky days) against calculated clear sky radiation, R_o: Scott (correction multiplication coefficient of 1.10), Lethbridge (1.05 for summer 2003 and 1.08 for summer 2004), Strathmore (1.05), and Outlook (0.90).

According to the procedure of ASCE (2005), e_a was calculated using the RH that occurred at the same time as T_{max} (approximately RH_{min}) and the same time as T_{min} (approximately RH_{max}). However, for data obtained from AAFC, RH_{min} and RH_{max} were measured at 8:00h and 16:00 or 17:00h, respectively regardless of when T_{max} and T_{min} occurred. Whether this would constitute a large misrepresentation in the calculation of ET_{os} was explored using hourly data sets from the station located at Eston. Using RH measured at 8:00h and 16:00h, RH values, as opposed to RH_{min} and RH_{max} values, resulted in the average ET_{os} differing by only 0.002 mm/d. This difference was deemed not large and so either method for obtaining RH_{min} and RH_{max} was utilized.

RESULTS and DISCUSSION

Station climate summary

On average, ET_{os} during the warm season (April to October) of 2003 was 0.6 mm/d greater than 2004 (Table 2). This was due to the higher temperature, slightly greater wind speed, lower relzative humidity, and greater solar radiation of 2003. The long-term temperature average for 1960-1990 (Canadian Institute for Climate Studies 2001) for the same approximate longitude and latitude as these 10 stations (Table 2) is 11.3°C confirming that 2003 was warmer than average and 2004 cooler than average. The warmest and coldest stations (not including Morden or Perdue due to their large number of missing data points) were Onefour and Beaverlodge, respectively, although for 2004, Elstow, Lacombe, and Scott had the same average temperature as Beaverlodge. Similarly, Onefour had the highest ET_{os} values (of the complete data sets) for both years and Beaverlodge and Lacombe the lowest ET_{os} values. This difference between Onefour and Beaverlodge is in part due to the extreme differences in latitude (Table 1), although Onefour is located in the driest part of the prairies in terms of low relative humidity and high wind speed. The highest average relative humidity occurred at Scott and Swift Current in 2004.

Developed ET models

For temperature based ET, the following parameters provided statistical models with the best fit: T or T_{max} or e_{smax} (saturated vapor pressure calculated at T_{max}), $T_{max} - T_{min}$ or e_d (saturated vapour deficit calculated from T_{max} and T_{min} that is $e_{smax} - e_{smin}$), and R_a. There was little difference between any of these combinations: T_{max} or e_{smax} had the greatest effect of the parameters (T_{max} regressed alone against ET_{os} resulted in an r^2 of 0.70, whereas using e_{smax} resulted in an r^2 of 0.71). Multiplying R_a by Δ improved the fit (for Eq. 9 from an r^2 of 0.71 to 0.78). From these parameters the following temperature based model was chosen:

$$ET_t = 0.134\left(T_{\max} - T_{\min}\right) + 0.0109T + 0.708\Delta R_a - 0.669$$

$$r^2 = 0.78, \qquad SE = 0.90 \tag{9}$$

Use of T_{max} or e_{smax} in place of T resulted in similar r^2 and SE values, however we wished to keep similar parameters for all our developed models and the parameter T provided the best fit for the temperature and humidity model (Eq. 11).

A modified Hargreaves model was developed by altering the coefficients within the published version (0.0023 and 17.8 of Eq. 2) until ET_{Ht} as regressed against ET_{os} had a slope of 1.0 and an intercept of 0:

$$ET_{Ht} = 0.000816\left(T_{\max} - T_{\min}\right)^{0.5}\left(T + 24.4\right)R_a$$

$$r^2 = 0.77, \qquad SE = 0.90 \tag{10}$$

For the temperature and relative humidity based model, the following humidity parameters provided the developed model (along with ΔR_a) with the best fit; RH, RH_{min}, and e_s-e_a. The vapor deficit (e_s-e_a) had the greatest role in representing ET_{os}

Table 2. Climatic averages (April 1 to October 31) during 2003 and 2004 at weather stations used to develop ET models.

Station	Year	T (°C)	RH (%)	u_2 (m/s)	R_s (MJ m^{-2} d^{-1})	ET_{os} (mm/d)	Missing days*
Beaverlodge	2003	10.0	63	2.6	16.0	3.1	0
Lacombe	2003	12.9	67	2.3	17.6	3.3	31
Onefour	2003	14.3	51	3.8	18.5	4.8	0
Stavely	2003	11.7	55	3.3	18.1	3.9	2
Vauxhall	2003	13.4	61	3.0	18.6	3.9	1
Elstow field	2003	12.0	63	3.2	16.5	3.7	3
Perdue field	2003	13.8	60	3.4	17.7	4.3	2
Scott	2003	12.0	69	3.0	17.5	3.5	0
Swift Current	2003	13.4	64	3.0	16.9	3.7	2
Morden	2003	13.1	65	2.6	16.7	3.3	43
Beaverlodge	2004	9.8	67	2.3	15.7	2.8	0
Lacombe	2004	9.8	68	2.1	16.5	2.8	0
Onefour	2004	12.5	59	3.6	18.4	4.0	3
Stavely	2004	10.0	60	3.1	17.7	3.2	4
Vauxhall	2004	12.2	64	2.6	18.4	3.5	0
Elstow field	2004	9.8	66	3.1	15.6	3.2	5
Perdue field	2004	13.2	60	3.3	19.7	4.4	78
Scott	2004	9.8	71	2.9	16.7	2.9	0
Swift Current	2004	11.1	72	2.9	16.9	3.0	0
Morden	2004	12.2	71	2.6	16.4	3.0	0
Average**	2003	12.4	61	3.2	17.4	3.8	
Average**	2004	10.7	66	2.9	17.0	3.2	

* Missing days - days in which ET was not calculated due to missing data.

** Averages do not include both data years for Lacombe, Morden, and Perdue due to their large number of missing data days.

and if considered alone resulted in an r^2 of 0.80. Equation 11 was chosen as the statistical temperature-relative humidity model that provided the best linear fit, while still retaining the same structure as Eq. 9:

$$ET_{tr} = 0.051\left(T_{\max} - T_{\min}\right) + 0.131T + 0.846\Delta R_a - 3.18e_a + 1.28$$
$$r^2 = 0.91, \qquad SE = 0.56 \qquad (11)$$

Removal of Δ from R_a resulted in the r^2 decreasing to 0.86 and the SE increasing to 0.72.

If temperature, wind, and relative humidity are available, but radiation is not measured, then Eq. 12 provides the best fit to ET_{os}.

$$ET_{tru} = 0.077\left(T_{\max} - T_{\min}\right) + 0.114T + 0.832\Delta R_a - 2.77e_a$$
$$+ 0.269u_2 + 0.053 \qquad r^2 = 0.94, \quad SE = 0.46 \quad (12)$$

Evaluation of published and developed ET models

The second data set (Table 1) was used to evaluate the fit (relative to ET_{os}) of the models. Of all the temperature-based equations, ET_t, ET_{Ht}, and ET_H had the best fit (greatest r^2 and E, lowest SE, slope nearest 1, intercept nearest 0) and ET_{BR1} and ET_{L1} the poorest fit (Table 3). The intercept of the Hargreaves model (ET_H) was not zero which resulted in a slightly lower average ET estimate (between 0.2 and 0.3 mm/d) than for our temperature based model (ET_t) (Table 3). Visually it appears that the Hargreaves model has a slightly better estimate of ET_{os} at low values (0 to 1 mm/d) than the ET_t method which provides some negative values in this range. However, for values >1 mm, ET_H tended to overestimate ET_{os} more than the ET_t method (Fig. 1). The Baier-Robertson model underestimated ET_{os} by 0.5 mm/d and the Linacre model overestimated ET_{os} by 1.7 mm/d. At Lacombe, ET_{L1} consistently overestimated daily ET_{os} by about 2 mm/d; ET_{BR1} tended to overestimate ET_{os} whereas, overall, ET_t and ET_H followed more closely the daily variations of ET_{os} (Fig. 2). The Linacre model (ET_{L1}) uses a mean annual difference in daily temperature and the mean monthly difference in temperature (Eq. 6); for the prairie stations these differences are about 12 and 25°C, respectively. If both of these were reduced to 5°C, then the ET_{L1} line would shift downwards resulting in a fit similar to the other models (Fig. 2). The coefficient of efficiency (E) showed more clearly than the r^2 value the poor fit of ET_{BR1} and ET_{L1}.

Of the temperature and humidity based equations, our statistical model, ET_{tr} (Eq. 11) provided the best fit (Table 3). The Linacre model (ET_{L2}) provided the poorest fit, overestimating ET by 0.8 mm/d. The Baier-Robertson model (ET_{BR2}) also overestimated ET by 0.7 mm/d and although its r^2 was only slightly less than ET_{tr}, its SE was larger and its coefficient of efficiency much smaller. Consideration of how these ET models compare on a daily basis is illustrated in Fig. 3 for data from Kernen farm. The Baier-Robertson model, ET_{BR2}, provided the lowest ET_{os} estimates and ET_{tr} the most reasonable; however ET_{L2} also provided generally reasonable values of ET_{os} at Kernen farm. The period of high ET_{os}, May 25 to May 29,

Table 3. Regression parameters used to compare model estimates to the standard, ET_{os}, for data sets used to develop (D) and to evaluate (E) the models.

Model	Eq. Number	Data set	Average	r^2*	SE	Intercept	Slope	E** (Eq. 8)
Temperature based								
ET_{os}	1	D	3.52	-	-	-	-	-
		E	3.79	-	-	-	-	-
ET_t	9	D	3.51	0.78	0.89	-0.01	1.00	0.78
		E	3.65	0.79	0.81	0.03	1.03	0.78
ET_{Ht}	10	D	3.50	0.77	0.91	0.00	1.01	0.77
		E	3.65	0.76	0.86	0.12	1.01	0.76
ET_H	2	D	3.32	0.78	0.90	0.16	1.01	0.77
		E	3.47	0.77	0.85	0.31	1.00	0.74
ET_{BR1}	3	D	3.02	0.74	0.97	1.55	0.65	0.46
		E	3.25	0.77	0.86	1.54	0.69	0.53
ET_{L1}	6	D	5.18	0.61	1.18	-0.12	0.70	-0.31
		E	5.82	0.61	1.11	-0.28	0.70	-0.82
Temperature and relative humidity based								
ET_{tr}	11	D	3.51	0.91	0.56	0.01	1.00	0.91
		E	3.68	0.89	0.58	0.06	1.01	0.89
ET_{BR2}	4	D	4.14	0.84	0.75	0.93	0.63	0.45
		E	4.34	0.85	0.69	0.95	0.65	0.51
ET_{L2}	5	D	4.24	0.81	0.83	0.01	0.83	0.63
		E	4.57	0.66	1.03	0.87	0.64	0.26
Temperature, relative humidity, and wind speed based								
ET_{tru}	12	D	3.50	0.90	0.46	0.02	1.00	0.94
		E	3.76	0.93	0.47	-0.10	1.03	0.93

* Regression parameters (r^2, SE, Intercept, and Slope) are from comparison of each model to ET_{os}.
** *E* - coefficient of efficiency.

to May 29, 1999 was the least well represented by any of the temperature-relative humidity models. During this period some higher than average wind speeds occurred.

Adding wind speed to the temperature-relative humidity model further improved the fit while decreasing SE to 0.46 from 0.56 for ET_{tr} (Eqs. 11 and 12). Demonstration of the ability of our developed models (Eqs. 9, 11, and 12) to estimate ET_{os} is shown in Fig. 1, where daily estimates from all weather stations used to develop and compare the performance of the models are displayed. Our developed models, ET_t, ET_{tr}, and ET_{tru}, are slightly curvilinear at low ET values and develop negative ET values as they approach zero (Fig. 1). This may have been avoided if we excluded days with T_{max} values less than 0°C (112 days in the data set used to develop the models). As more parameters were added to the models, the 'cloud' of points became more compact about the linear regression line (i.e., precision relative to ET_{os} was increased). With the exception of the model that included windspeed (ET_{tru}), the spread of points about the regression line increased as ET increased. The precision of the ET_{tru} model is noticeably superior to the other models, especially at higher ET rates. When these models are compared for a six week continuous period for the Lethbridge weather station (Fig. 4), they all provide a reasonable fit (most day-to-day differences relative to ET_{os} of less than 1 mm) with ET_{tr} providing the best overall fit.

Comparison to individual weather stations

The models, ET_t, ET_{Ht}, ET_{tr}, and ET_{tru}, were evaluated using stations independent of those used to develop the models (Fig. 1 and Table 4). For the stations used to evaluate the models, the average absolute difference between ET estimated by the models compared to ET_{os} was 0.16 mm/d for ET_t and 0.18 mm/d for ET_{tr}. For the data set used to develop the models, the average absolute difference was 0.29 mm/d for ET_t and 0.11 mm/d for ET_{tr}. With regards to r^2, SE, intercept, slope, and coefficient of efficiency, there were larger differences between individual weather stations than between the data sets used to develop or evaluate the models. For example, Stavely 2003 had the largest average difference between ET_t and ET_{os} (ET_t underestimated ET_{os} by 0.7 mm/d); whereas for Kernen farm 1999, ET_{tr} underestimated ET_{os} by the largest absolute amount, 0.4 mm/d. Stations used to develop or evaluate the models were equally represented by the models. Further, Fig. 1 shows weather stations not used to develop the models fell within the boundary of the stations used to develop the models.

Reference ET as determined from non- ideal sites

ET_{os} represents the evaporation from a hypothetical grass crop that is not short of water. When these equations are applied to non-ideal surfaces such as a weather stations located in a rain-fed agricultural region, errors may occur due to temperature and relative humidity differences caused by the aridity of the site. As the soil dries, a greater proportion of incoming radiation is used to increase air temperatures rather than to evaporate water. As a result, the parameters driving the ET_{os} equations may result in an overestimation of reference evaporation. Overestimations in reference ET have been found to be as high as 25% in very arid regions (Temesgen et al. 1999). The effect of the overestimation in the agricultural region of the Canadian prairies is yet undetermined as few of the rain-fed stations exist where a close neighbouring station is irrigated. The models developed in this paper represent a range of conditions from semi-arid to sub-humid. Accordingly, the effect of aridity of the site will range from minimal at the sub-humid sites to potentially more significant in the semi-arid southern regions. Ultimately, some care in applying the models in arid regions or for applications requiring absolute accuracy should be applied.

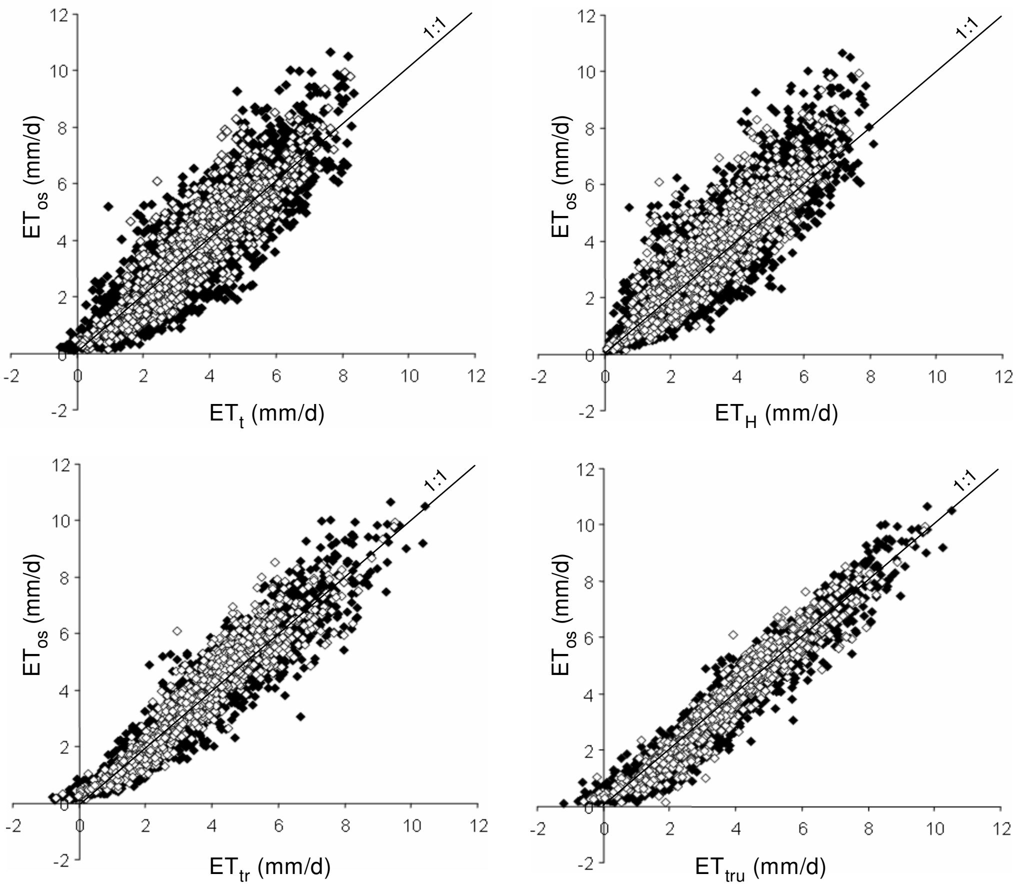

Fig. 1. Comparison of temperature (ET_t), Hargreaves (ET_H), temperature-relative humidity (ET_{tr}), and temperature-relative humidity-wind (ET_{tru}) models against ET_{os} using weather stations with which the models were developed (◆) and evaluated (◇) (Table 1).

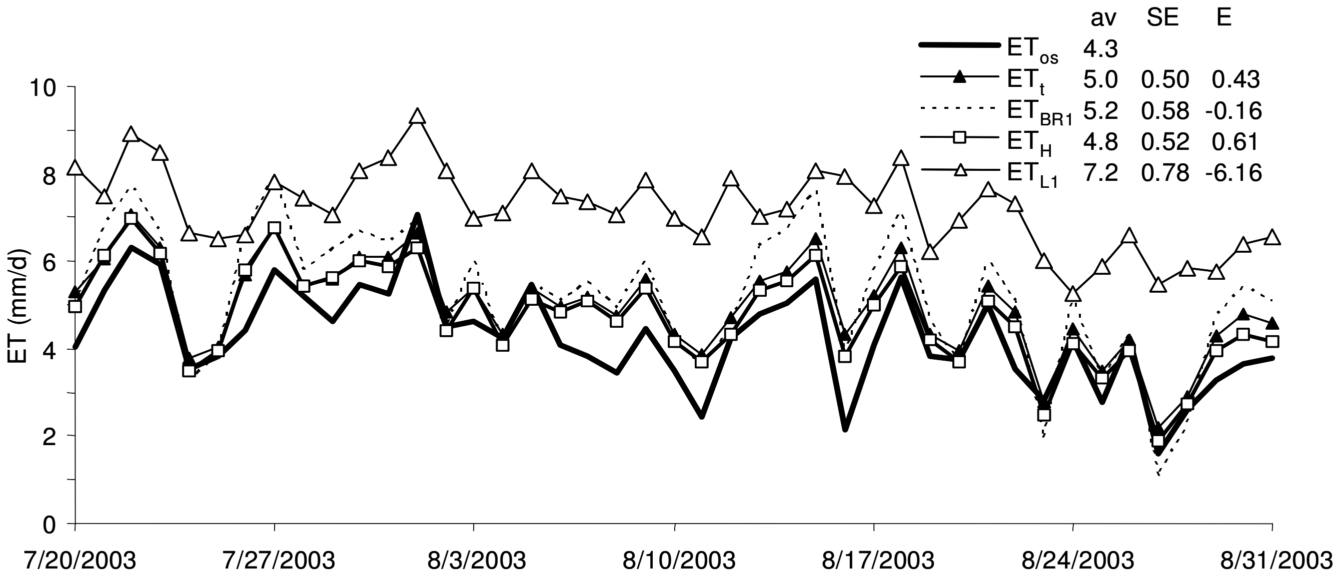

Fig. 2. Daily ET calculated using ET_{os} and temperature based models for Lacombe for July 20 - August 31, 2003.

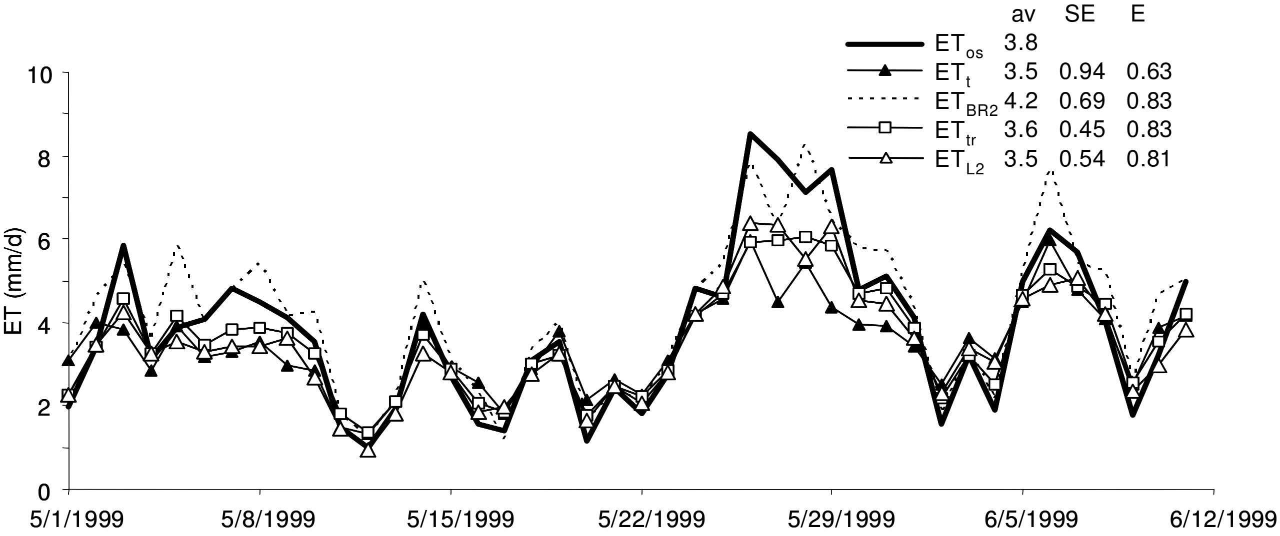

Fig. 3. Daily ET calculated using ET_{os} and temperature-relative humidity based models for Kernen farm for May 1 - June 11, 1999.

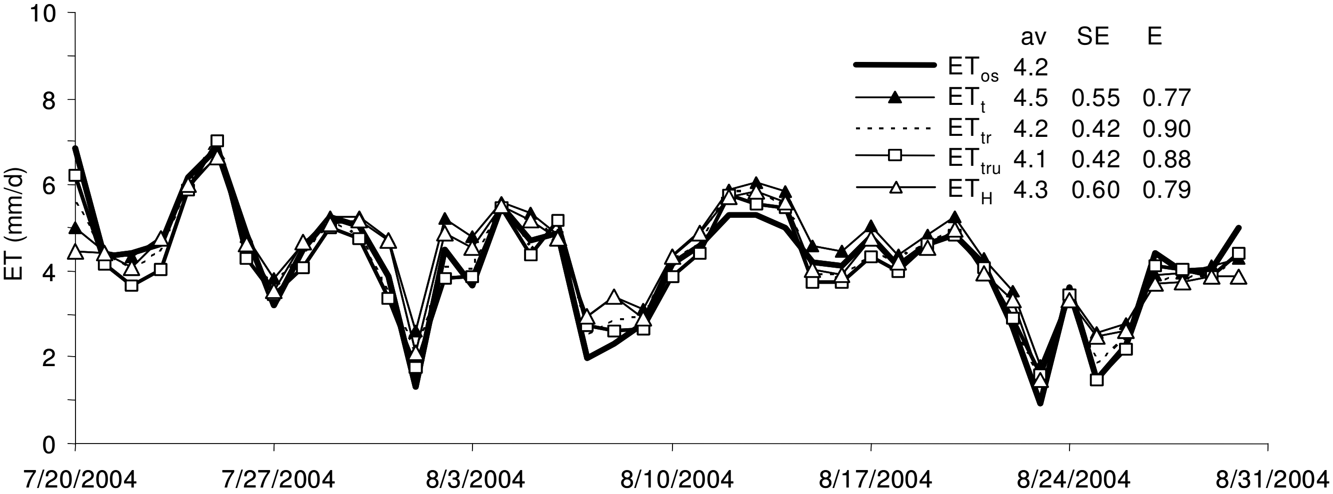

Fig. 4. Daily ET calculated using ET_{os} and developed models of ET_t, ET_{tr}, and ET_{tru} for Lethbridge for July 20 - August 30, 2004.

SUMMARY and CONCLUSIONS

Using daily weather data from 10 weather stations within the Canadian Prairies, empirical models were developed to estimate ET calculated by ET_{os} - a standardized reference equation used to calculate ET from a full complement of weather data and based on the Penman-Monteith equation. Using daily weather data from stations independent of those used to develop the models, our models were evaluated with regards to how well they estimated ET_{os}. In addition, our models were compared to other published simple models: Baier-Robertson, Hargreaves, and Linacre. All models used ET_{os} as the comparison standard. ET models were compared to the standard (ET_{os}) using average ET, r^2, SE, *E*, and regression equation parameters of intercept and slope.

Models based upon temperature (along with extraterrestrial radiation calculated from latitude) are listed from most accurate to least:

$$ET_t \approx ET_{Ht} \approx ET_H > ET_{BR1} > ET_{L1}$$

There was very little difference between our statistically developed model, ET_t, and the Hargreaves model, ET_H. The regression against the Hargreaves model did not have an intercept of zero (Table 3), but if the coefficients within the Hargreaves model were slightly modified as with ET_{Ht} (Eq. 10) then the intercept was zero. Of the temperature based models, ET_t, ET_H, or ET_{Ht} would be suitable to represent ET_{os} under prairie climatic conditions. Baier-Robertson (ET_{BR1}, Eq. 3) and Linacre (ET_{L1}, Eq. 6) temperature based models are not recommended for estimating ET_{os} for prairie conditions as they can result in a 30 to 50% error.

Temperature-humidity models improved the estimate of ET_{os} compared to temperature based models. Listing these models from most accurate to least:

$$ET_{tr} > ET_{BR2} \approx ET_{L2}$$

Table 4. Comparison of model estimates of ET for two models versus ET_{os} for individual stations by year.

		ET_t						ET_{tr}					
Station	Year	AVD*	r^2**	SE	Int	Slope	E	AVD	r^2	SE	Int	Slope	E
Development													
Beaverlodge	2003	-0.10	0.75	0.86	0.14	0.99	0.75	0.16	0.88	0.60	0.07	0.93	0.87
Beaverlodge	2004	0.12	0.80	0.69	0.14	0.91	0.78	0.17	0.93	0.41	0.03	0.93	0.91
Stavely	2003	-0.72	0.80	0.91	0.23	1.16	0.66	-0.06	0.90	0.64	0.28	0.94	0.90
Stavely	2004	-0.45	0.72	0.83	0.22	1.08	0.63	-0.11	0.93	0.41	-0.02	1.04	0.92
Swift Current	2003	0.10	0.87	0.74	-0.21	1.03	0.87	0.05	0.92	0.59	0.04	0.98	0.91
Swift Current	2004	0.25	0.78	0.73	-0.13	0.96	0.75	-0.11	0.93	0.41	-0.21	1.11	0.92
Evaluate													
Eston field	2002	-0.05	0.81	0.65	-0.09	1.07	0.80	0.15	0.85	0.58	0.13	0.87	0.82
Eston field	2003	-0.22	0.86	0.77	-0.07	1.04	0.85	-0.18	0.91	0.63	0.24	0.91	0.89
Eston field	2004	0.19	0.77	0.77	-0.51	1.07	0.75	0.24	0.89	0.52	-0.45	1.04	0.87
Kernen farm	1999	-0.23	0.71	0.88	-0.03	1.08	0.69	-0.44	0.91	0.50	-0.47	1.29	0.79
Lethbridge	2003	-0.32	0.75	0.96	0.29	1.01	0.72	-0.17	0.90	0.62	0.10	1.02	0.89
Lethbridge	2004	-0.16	0.74	0.80	0.16	1.00	0.73	-0.15	0.91	0.48	-0.19	1.09	0.89
Outlook	2004	0.05	0.78	0.75	0.04	0.97	0.78	-0.07	0.92	0.46	-0.19	1.08	0.91
Strathmore	2004	0.04	0.85	0.61	-0.18	1.07	0.84	-0.06	0.94	0.37	-0.27	1.10	0.94

* AVD = ET from model minus ET_{os}

** r^2 - regression coefficient; SE - standard error of regression; Int - intercept; E - coefficient of variation

ET_{tr} is recommended for estimating ET_{os} on the prairies. Linacre (ET_{L2}, Eq. 5) and Baier-Robertson (ET_{BR2}, Eq. 4) models are not recommended for estimating ET_{os} (Table 3).

Incorporation of measured values of temperature, relative humidity and wind speed into a model, ET_{tru} (Eq. 12) resulted in the most precise estimation of ET_{os} (Fig. 1, Table 3).

In summary, the developed models of ET_t and ET_{tr} provided increased representation of ET_{os} as compared to the models of Baier and Robertson (1965) and Linacre (1977) and are recommended for use within agricultural regions of the prairie provinces where daily weather data is limited to just temperature or temperature and relative humidity. Of course, the model of choice will depend upon the daily weather data collected. For greater accuracy and precision, choose the model that uses the full complement of available data. The most accurate and precise model was ET_{tru}, which used temperature, relative humidity and wind speed. However, we recognize that few weather recording sites measure wind speed and/or relative humidity (dew point temperature).

Our study was limited to the agricultural region of the prairies. Future studies could consider whether or not the information found in this study could be extended to other regions in Canada. Of particular interest is how applicable is the Hargreaves equation, or slightly modified versions of it, to other Canadian regions.

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NOMENCLATURE

C_d	denominator constant that changes with crop reference type (0.34 for short and 0.38 for tall crop surfaces)
C_n	numerator constant that changes with crop reference type (900 for short and 1600 for tall crop surfaces)
E	coefficient of efficiency
e_a	mean actual vapor pressure at 1.5 to 2.5-m height (kPa)
e_d	saturated vapor pressure deficit = e_a - e_s
e_s	saturation vapor pressure at 1.5 to 2.5-m height as average of saturation vapor pressure at maximum and minimum air temperatures (kPa)
e_{smax}	saturated vapor pressure calculated at T_{max} (kPa)
e_{smin}	saturated vapor pressure calculated at T_{min} (kPa)
ET_{BR1}	PET calibrated, using temperature only, to Penman's formula for a crop with an albedo of 0.25 and a crop coefficient of 1.0 throughout the growing season (mm/d)
ET_{BR2}	PET calibrated, using temperature and relative humidity, to Penman's formula for a crop with an albedo of 0.25 and a crop coefficient of 1.0 throughout the growing season (mm/d)
ET_H	Hargreaves reference ET for well-watered short crop (mm/d)
ET_{Ht}	modified Hargreaves reference ET for well-watered short crop (mm/d)
ET_{L1}	grass reference ET calculated using temperature (mm/d)
ET_{L2}	grass reference ET calculated using measured dew point temperature (mm/d)
ET_{os}	standardized reference ET for short surfaces, 0.12 m (mm/d)
ET_t	temperature and extraterrestrial radiation based model for ET (mm/d)
ET_{tr}	temperature, extraterrestrial radiation, and relative humidity based model for ET (mm/d)
ET_{tru}	temperature, extraterrestrial radiation, relative humidity, and wind speed based model for ET (mm/d)
h	elevation (m)
G	soil heat flux density at the soil surface (MJ m^{-2} d^{-1})
O_i	observed values
$\bar{O}$	observed mean
P_i	predicted values
P	atmospheric pressure (kPa)
R_a	extraterrestrial radiation (MJ m^{-2} d^{-1}) as described in ASCE (2005)
R_n	calculated net radiation at crop surface (MJ m^{-2} d^{-1})
R_s	solar radiation (MJ m^{-2} d^{-1})
R_0	calculated clear sky radiation (MJ m^{-2} d^{-1})
RH_c	corrected RH value (%)
RH_{max}	daily maximum RH (%)
RH_{min}	daily minimum RH (%)
RH_{uc}	uncorrected RH value (%)
RH_{smax}	highest uncorrected maximum RH value that occurred for that station in the entire measurement set (%)
RH_{smin}	lowest uncorrected minimum RH value that occurred for that station in the entire measurement set (%)
T	mean daily air temperature at 1.5 to 2.5-m height, (T_{max} + T_{min})/2 (°C)
T_d	dew point temperature (°C)
T_m	temperature adjusted for elevation, $T_m = T + 0.006h$
T_{max}	daily maximum air temperature (ºC)
T_{min}	daily minimum air temperature (ºC)
L	latitude (°)
T_{ra}	difference between the mean temperatures of the warmest and coldest months of the year (°C)
T_{rd}	mean daily range of temperature (°C)
u_2	mean daily or hourly wind speed at 2-m height (m/s)
Δ	slope of saturation vapor pressure-temperature curve at T (kPa/°C), given by: $$\Delta = \frac{2504\exp\left[\dfrac{17.27T}{T+237.3}\right]}{\left(T+237.3\right)^2}$$
γ	psychrometric constant = $0.000665P$ (kPa/°C)