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

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Abstract

Potential evapotranspiration (PET) can be accurately determined with a Penman-Monteith model, however this model requires many different inputs which are not measured at most climatic stations. The agricultural region of the Canadian Prairies is a large geographic region of similar dry continental climate (cold semi-arid to subhumid) and could benefit from simple, yet accurate models for determination of evapotranspiration. The purpose of our study was to develop simple (limited data) ET models to estimate ET that was calculated using the ASCE standardized reference Penman-Monteith equation. We used daily weather data from 2003 and 2004 from ten stations across the agricultural region of the prairies. We compared our developed models to other published simple models by Baier-Robertson, Hargreaves, and Linacre. All models used the standardized reference evapotranspiration as the comparison standard. Using individual climatic stations within and outside the data set used to develop our models, we compared averages, standard errors, regression parameters r^2 , slope, and intercept, as well as the coefficient of efficiency accuracy of fit. Of the temperature based models (which included calculated extraterrestrial radiation), our model and Hargreave's model were the most accurate. Temperature-humidity models improved the estimate of evapotranspiration, compared to temperature based models. The Linacre and the Baier-Robertson temperature and temperature-humidity models were not accurate and are not recommended for estimating evapotranspiration in the Canadian Prairies. Incorporation of temperature, humidity and wind speed into a physically based model resulted in the most accurate and precise estimation of standardized reference evapotranspiration.

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INTRODUCTION

Potential evapotranspiration (PET) is a required parameter for hydrological and agricultural projects. Although PET is related to free-water evaporation and may be measured using evaporation pans or atmometers (Thom et al. 1981), it is more commonly calculated from climatic parameters that affect it (e.g., temperature, relative humidity). 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 daylength to characterize seasonal change in water balance then to delineate 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 evapotranspiration 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 evapotranspiration models developed. The one model that is the most widely accepted is the Penman-Monteith (PM) model (Shuttleworth 1993). This model 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. As a minimum, the PM model requires daily measurements of net radiation (summation of net short-wave and long wave), 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. The need for models with fewer data requirements exists especially given the large amounts of historical data that are frequently limited to just temperature or at most, temperature and humidity.

There are many variations for calculation of ET via the Penman-Monteith method. Currently the Standardized Reference Evapotranspiration equation (ET_{sz}) has been recommended for use by the Environmental and Water Resources Institute of the American Society of Civil Engineers (ASCE 2002). This method is very similar to a number of variations of the PM method and attempts to standardize the use of one method amongst many users. The equation provides an internationally accepted determination of evapotranspiration for a well-watered short (ET_{os}) or tall grass surface (ET_{rs}).

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), many of these models have not been verified against ET_{sz} 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 humidity as well as temperature and radiation data. Given the great amount of historical data for the Canadian Prairies, and the number of current climate stations that do not measure solar radiation, wind speed, or humidity, there continues to be a need for simple yet representative ET models.

The purpose of our paper is to develop and verify simple ET models that will accurately represent standardized reference crop evapotranspiration for short crop surfaces (ET_{OS} , as calculated by the ASCE method) for the agricultural region of the prairies. Towards this the objectives are to:

- 1) verify the accuracy of the following published models:
 - Baier-Robertson temperature ET (ET_{BR1});
 - Baier-Robertson temperature and humidity ET (ET_{BR2});
 - Linacre temperature (ET_{L1});
 - Linacre temperature and humidity (ET_{L2}); and
 - Hargreaves temperature (ET_H).

- 2) improve upon the existing simple models by using the following combinations of parameters:
 - Temperature and R_a (extraterrestrial radiation, $MJ\ m^{-2}\ d^{-1}$);
 - Temperature, relative humidity, and R_a ; and
 - Temperature, relative humidity, R_a and wind speed.

Models will be developed based upon multiple regressions (regressed against ET_{OS}) and physically based principles. The developed models will be compared to the published models and ET_{OS} .

The regional focus of our paper on the Canadian prairies was intentional. We believed greater accuracy could be achieved in the developed models when the weather data reflected a similar climate. In our case, the subhumid to semi-arid prairie region is characterized by warm-dry summers and high PET relative to the remainder of Canada.

METHODOLOGY

Two years (2003 and 2004) of daily data were obtained from ten climatic stations across the agricultural region of the prairies. These data were used to calculate the daily standardized reference evapotranspiration for a short crop (ET_{OS} , ASCE, 2002). The temperature, relative humidity, and wind speed data used in this calculation were also used to calculate ET for five other published models that are commonly used for limited data sets and to develop regression- and physically -based models with ET_{OS} as the predicted variable. All models were compared to select those most representative for the agricultural region of the prairies. The accuracy of our developed models were further evaluated by considering individual climate station data from within and outside the dataset used for developing the models.

The ASCE Standardized Reference ET publication (ASCE 2002) suggested procedures for the calculation of reference evapotranspiration with missing data. For missing humidity, solar radiation, or wind speed, they suggested that one procedure is to obtain this data from a nearby

station (within 100 km), however the emphasis of our study is to test and develop simple equations. A second method suggested by ASCE (2002) is to use the daily difference between maximum and minimum air temperature to account for missing solar radiation as outlined by Hargreaves and Samani (1982). This is one of the equations we use in our paper. Thirdly, ASCE (2002) suggested that observed hours of sunshine can be used to calculate solar radiation; however that is not a commonly collected parameter. For missing humidity data, ASCE (2002) suggested a constant offset from that of the minimum daily temperature; again this is a feature employed in some of the published models being tested (e.g. Linacre 1977).

Existing Evapotranspiration Models

The four published models (6 equations) used to calculate potential evapotranspiration for a well-watered short crop surface that varied between 0.10 and 0.15 m in height are:

1. Standardized Reference Evapotranspiration, ET_{os} (ASCE 2002):

$$ET_{os} = \frac{0.408 \Delta (R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 u_2)} \quad (1)$$

where:

ET_{os} = standardized reference crop evapotranspiration for short surfaces, (mm d^{-1}),

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

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

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

u_2 = mean daily or hourly wind speed at 2-m height (m s^{-1}),

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

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

Δ = slope of the saturation vapor pressure-temperature curve at T ($\text{kPa } ^{\circ}\text{C}^{-1}$),

$$\Delta = \frac{2504 \exp((17.27 T)/(T + 237.3))}{(T + 237.3)^2}$$

γ = psychrometric constant ($\text{kPa } ^{\circ}\text{C}^{-1}$),

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

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

2. Hargreaves, ET_H (Hargreaves and Samani 1985; Hargreaves et al. 1985; ASCE 2002):

$$ET_H = 0.0023 (T_{\max} - T_{\min})^{0.5} (T + 17.8) R_a \quad (2)$$

where:

ET_H = reference ET for well-watered short crop (mm d^{-1}),

T_{\max} = Daily maximum air temperature ($^{\circ}\text{C}$),
 T_{\min} = Daily minimum air temperature ($^{\circ}\text{C}$),
 T = mean daily air temperature, $T = (T_{\max} + T_{\min})/2$,
 R_a = extraterrestrial radiation, mm d^{-1} (R_a in $\text{MJ m}^{-2} \text{d}^{-1} \cdot 2.45^{-1}$) as described in ASCE (2002).

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

$$ET_{BR1} = 0.094(0.928 T_{\max} + 0.933 (T_{\max} - T_{\min}) + 0.0486 R_a - 87.03) \quad (3)$$

$$ET_{BR2} = 0.094(-0.0228 T_{\max} + 1.09 (T_{\max} - T_{\min}) + 0.0506 R_a + 2.33 (e_s - e_a) - 42.28) \quad (4)$$

where:

ET_{BR1} and ET_{BR2} = potential evapotranspiration (mm d^{-1}) 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)

T_{\max} = maximum daily temp, ($^{\circ}\text{F}$)

T_{\min} = minimum daily temperature, ($^{\circ}\text{F}$)

R_a = daily extraterrestrial solar radiation, ($\text{cal cm}^{-2} \text{d}^{-1}$)

e_s = saturated vapour pressure at $(T_{\max} + T_{\min})/2$ and expressed in mb, and

e_a = vapour pressure (mb) at average dew point temperature, calculated at $(T_{\max} + T_{\min})/2$

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

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

where:

ET_{L2} = grass reference evapotranspiration (mm d^{-1}) calculated using measured dew point temperature;

T_m = is an elevation adjustment, $T_m = T + 0.006h$, where h is elevation (m),

T = mean daily temperature ($^{\circ}\text{C}$), $T = (T_{\max} + T_{\min})/2$,

T_d = dew point temperature ($^{\circ}\text{C}$), and

L = latitude in degrees.

Where dew point temperature is not available the following equation may be substituted to calculate ET_{L1} :

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

where;

T_{rd} = the mean daily range of temperature ($^{\circ}\text{C}$) and

T_{ra} = difference between the mean temperatures of the warmest and coldest month of the year ($^{\circ}\text{C}$).

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. This is not a limitation for the current study area.

As most of the above models (Eqs. 2 to 6) were developed for a short crop surface (as opposed to a tall crop), this was the standard used within our study.

Procedure

Only climatic stations from the agricultural region of the three Prairie Provinces were used and only those that had the necessary daily data to enable calculation of ET_{os} (Eq. 1) during April 1 to Oct 31 (Table 1). The same data were used to calculate ET for Eq. 2 to 6 and to develop statistical and physically-based models involving temperature, relative humidity wind, and R_a . These latter models were compared to Eq. 2 to 6 to see if any improvement in accuracy was made. The degree of accuracy of our developed models were further evaluated by considering their accuracy (against ET_{os}) for individual climate stations from within and from without the data set used to develop them.

The models were developed using a wide distribution of climate stations across the three prairie provinces and included three soil climatic zones (Brown, Dark Brown, and Black). However, it was difficult to find climate stations with the appropriate data in the more humid eastern part of Saskatchewan and within Manitoba.

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

Statistically based;

ET_t , as a function of air temperature and extra terrestrial solar radiation (R_a);

ET_{tr} , as a function of temperature, humidity, and R_a

Physically based;

ET_{Ht} , as a function of air temperature and R_a , using a modified Hargreaves equation;

ET_{atr} , as a function of temperature, humidity, and R_a , using a modified ET_{os} equation; and

ET_{atru} , as a function of temperature, humidity, windspeed, and R_a , using a modified ET_{os} equation.

In this procedure of 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 ASCE and Hargreaves models) were investigated for improvement of fit.

To judge which set of parameters for the statistical and physical models and which of the published equations (Eq. 2 thru 6) produced the best fit against ET_{os} (Eq. 1), the following statistical parameters were compared for the data set used to develop the models:

- a) 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;
- b) m , the slope of the linear regression equation, the closer to 1.0 the more representative the predicted is of ET_{os} ;
- c) b , the y-intercept from linear regression equation, the closer to 0.0 the more representative of the ET estimate;
- d) SE, the standardized error; and
- e) E, coefficient of efficiency (Eq. 7).

Using climate data from a data set independent of the original data set used to derive the equations, models selected from the above process were compared for accuracy in estimating ET_{os} .

Table 1. Climate station location and identification.

Station	Prov	Lat	Long.	Elev.	WMO ID	Climate ID	Data	Other
Beaverlodge ^{1,2}	AB	55.2	119.4	746	71230	3070600	2003-04	AAFC
Lacombe ¹	AB	52.5	113.8	860	71242	3023722	2003-04	AAFC
Onefour ¹	AB	49.1	110.5	935	71116	3044923	2003-04	AAFC
Stavely ^{1,2}	AB	50.2	113.9	1364	71555	3036099	2003-04	AAFC
Vauxhall ¹	AB	50.1	112.1	779	71251	3036682	2003-04	AAFC
Elstow field ¹	SK	52.0	106.0	508	NA	NA	2003-04	research
Perdue field ¹	SK	52.0	107.6	596	NA	NA	2003-04	research
Scott ¹	SK	52.4	108.8	660	71489	4047240	2003-04	AAFC
Swift Current ^{1,2}	SK	50.3	107.7	825	71446	4028060	2003-04	AAFC
Morden ¹	MB	49.2	98.1	297	71564	5021849	2003-04	AAFC
Eston field ²	SK	51.0	108.8	610	NA	NA	2002-04	research
Lethbridge ²	AB	49.7	112.7	903	71509	3033897	2003-04	IMCIN
Strathmore ²	AB	51.0	113.3	967	71526	3036205	2004	IMCIN
Kernen Farm ²	SK	52.2	106.6	510	NA	4057155	1999	U.of S.
Outlook ²	SK	51.5	107.1	541	71551	4055736	2004	IMCIN

1; climatic station used to develop models. 2; climatic stations used to evaluate developed models. AAFC - Agriculture and Agri-Food Canada, Research, climatic stations of the authors; IMCIN - Irrigation Management Climate Information Network; U.of S - University of Saskatchewan.

Legates and McCabe (1999) suggest the use of the coefficient of efficiency (Eq. 7) to overcome limitations of use of the r^2 value in evaluating the ‘goodness-of-fit’ with hydroclimatic and hydrologic data sets. The coefficient of efficiency is defined as follows:

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

where;
O and P are the observed and predicted values.

The value E ranges from minus infinity to 1.0 with higher values indicating better agreement. A value of 0 for E indicates that the observed mean O is as good a predictor as the model, while negative values indicate that the observed mean is a better predictor than the model. This coefficient is similar to the coefficient of performance (James and Burgess 1982) that is also used for hydrological investigations, the difference being that the “1.0 –” is not present in their term.

Data Quality

As the paper is making comparisons between a model, accepted as a standard, with other models, it is critical that the climatic data being used in the models is appropriate, is accurate and of good quality. The following procedures were used to insure the climatic data sets were 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 a single parameter for a day was missing then it was estimated using information from dates before and after (if similar climatic conditions were apparent), or that from a very close (less than 25 km) climatic station;
- if an entire data set for one or more days was missing these were not estimated;
- temperature was checked for extreme unexplainable outliers, none were found;
- RH_{max} values were checked for instances of greater than 100%, where this occurred consistently over most of the data set a correction factor (Eq. 8) was applied (several stations needed correction);
- wind values were checked for shifts in values with time and where evident corrected to that of long term reasonable values (this was apparent for only one station);
- solar radiation (R_s) was checked, and if necessary corrected, against calculated clear sky radiation (R_o) as outlined by ASCE (2002). 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 are consistently higher or lower than the corresponding R_o values by more than 5%, then it could mean that the instrument measuring R_s does not have a proper calibration curve, has not been properly leveled or has become contaminated with dust. In that case R_s values may then be adjusted by multiplying R_s by the average value of R_o/R_s on clear days (ASCE 2002).

The following climate stations consistently had RH maximum values greater than 100% and were corrected with Eq 8; Morden, Outlook, Onefour, and Vauxhall. Before correction these stations all had maximum readings of between 103 and 110%.

$$RH_c = RH_{uc} - (RH_{smax} - 100) (RH_{uc} - RH_{smin}) (RH_{smax} - RH_{smin})^{-1} \quad (8)$$

where:

RH_c is the corrected RH value (%),

RH_{uc} is the uncorrected RH value,

RH_{smax} is the uncorrected maximum RH value that occurred for that station in the entire measurement set, and

RH_{smin} is the uncorrected minimum RH value that occurred for that station in the entire measurement set.

This equation resulted in a linear correction based upon the RH value, such that the highest values would become '100 %' and the lowest values would change. One station, Elstow, had maximum RH values of 96.5 and whereas most other stations had some values of 100. In this case all RH values were adjusted upwards by 3.5%.

The following stations required correction of their R_s readings so that a match was obtained against R_0 ; 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).

The wind speeds at Scott between Jan 1, 2003 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 (2002).

According to the procedure of ASCE (2002) the calculation of e_a was to be done with the RH value that occurred at the same time as T_{max} (this would be RH_{min}) and the same time as T_{min} (this would be RH_{max}). However, for data obtained from AAFC, RH_{min} and RH_{max} were measured at 8 am and 4 pm or 5 pm, respectively. Whether this would constitute a large misrepresentation in the calculation of ET_{os} was explored using data sets from one of our stations, Eston. Using 8 am and 4 pm RH values resulted in the average ET_{os} differing by 0.002 mm d^{-1} . This difference was not significant and so either method for obtaining RH_{min} and RH_{max} was utilized.

RESULTS AND DISCUSSION

Station Climate Summary

On average, the ET_{os} values during the warm season (April to October) of 2003 were 0.5 mm d^{-1} greater than those in 2004. This was due to the higher temperature, slightly greater wind speed, lower humidity and greater solar radiation of 2003 (Table 2). Long-term temperature averages (1960-1990, from Canadian Gridded Climate Data 2001) for the same approximate longitude and latitudes as these 10 stations (Table 2) is 11.3°C confirming that 2003 was generally warmer than average and 2004 cooler than average. The warmest and coldest stations (not including Morden or Perdue) are 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.

Table 2. Climatic averages (April 1 to Oct 31) during 2003 and 2004 at climate stations used to develop evapotranspiration models.

Station	Prov	Year	T °C	RH %	u ₂ m s ⁻¹	R _s MJ m ⁻² d ⁻¹	ET _{os} mm d ⁻¹	missing days
Beaverlodge	AB	2003	10.0	63	2.6	16.0	3.1	0
Lacombe	AB	2003	10.9	68	2.3	17.3	3.2	0
Onefour	AB	2003	14.3	51	3.8	18.5	4.8	0
Stavely	AB	2003	11.7	55	3.3	18.0	3.9	0
Vauxhall	AB	2003	13.4	61	3.0	18.6	3.9	0
Elstow	SK	2003	12.0	66	3.2	16.5	3.6	3
Perdue	SK	2003	13.8	60	3.4	17.7	4.3	2
Scott	SK	2003	12.0	69	3.0	17.5	3.5	0
Swift	SK	2003	13.5	64	3.0	16.9	3.7	0
Morden	Mb	2003	13.1	65	2.6	16.7	3.3	43
Beaverlodge	AB	2004	9.8	67	2.3	15.7	2.8	0
Lacombe	AB	2004	9.8	68	2.1	16.5	2.8	0
Onefour	AB	2004	12.5	59	3.6	18.4	4.0	3
Stavely	AB	2004	10.1	61	3.1	17.6	3.2	0
Vauxhall	AB	2004	12.2	64	2.6	18.4	3.5	0
Elstow	SK	2004	9.8	69	3.1	15.6	3.1	5
Perdue	SK	2004	13.2	60	3.3	19.7	4.4	78
Scott	SK	2004	9.8	71	2.9	16.7	2.9	0
Swift	SK	2004	11.1	72	2.9	16.9	3.0	0
Morden	Mb	2004	12.2	71	2.6	16.4	3.0	0
Average*	Average	2003	12.5	62	3.0	17.4	3.7	
Average*	Average	2004	10.6	66	2.8	17.0	3.2	

Missing days; days in which data is not present and ET not calculated.

*averages do not include Morden, or Perdue.

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 vapour pressure calculated at T_{max}), T_{max} - T_{min} or eT_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 a r² of 0.70, whereas using e_{smax} resulted in a r² of 0.71). Multiplying R_a by Δ slightly improved the fit. The following temperature based statistical model was chosen as it provided the best linear fit;

$$ET_t = 0.012 T + 0.133(T_{max} - T_{min}) + 0.705 \Delta R_a - 0.673, \quad r^2 = 0.78, \quad SE = 0.88 \quad (9)$$

A physically based temperature model was constructed by varying the two coefficients (0.0023 and 17.8) in the Hargreaves model (Eq. 2) until ET_{Ht} as regressed against ET_{os} had a slope of 1.0 and an intercept of 0:

$$ET_{Ht} = 0.0020 (T_{max} - T_{min})^{0.5} (T + 24.2) R_a 2.45^{-1}, \quad r^2 = 0.77, \quad SE = 0.90 \quad (10)$$

For temperature and humidity based models the following humidity parameters provided the statistical models (along with R_a) with the greatest fit; RH, RH_{\min} , and $e_s - e_a$. The vapour deficit ($e_s - e_a$) had the greatest role in representing ET_{os} and if considered alone resulted in a r^2 of 0.80. The following statistical temperature-humidity model was chosen as providing the best linear fit:

$$ET_{tr} = 0.881 (e_s - e_a) - 0.043 RH + 0.547 \Delta R_a + 4.10, \quad r^2 = 0.91, \quad SE = 0.58 \quad (11)$$

Utilizing temperature in place of either RH or $e_s - e_a$ resulted in a slightly lower r^2 . However, with temperature, there were more negative ET_{tr} values at low ET_{os} and the overall relationship was less linear.

A physically based temperature-humidity model was developed (ET_{atr}). The model was based upon the format of the ET_{os} equation, using R_a to replace $R_n - G$, and 2.94 m s^{-1} (average wind speed from the 10 climate stations) to replace u_2 as a constant. To force the model to have a slope of 1.0 and an intercept of zero, the equation was multiplied by 1.084 and 0.074 was subtracted:

$$ET_{atr} = 1.084 \left[\frac{0.408 \Delta (R_a) + \gamma \frac{900}{T + 273} 2.92 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 (2.92))} \right] - 0.074, \quad r^2 = 0.90, \quad SE = 0.61 \quad (12)$$

For a model involving temperature, humidity, and wind it makes sense to utilize only a physically based model based upon the ASCE (2002) equation, as the only parameter missing is that of R_s . The following model had R_a replacing $R_n - G$ and was adjusted by multiplying 1.049 and adding 0.133 to the equation:

$$ET_{atru} = 1.049 \left[\frac{0.408 \Delta (R_a) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 u_2)} \right] + 0.133, \quad r^2 = 0.93, \quad SE = 0.50 \quad (13)$$

Evaluation of Developed and Published ET Models

The fit (relative to ET_{os}) of the statistical and physical models (Eq. 9 to 13) are compared against the published ET models (Eq. 2 to 6), using the same ten climate stations from which the models were developed (Fig. 1, Table 3). Of the temperature based equations, ET_t , ET_{Ht} and ET_H had the best and similar fit (greatest r^2 and E, lowest SE values, and best slope and intercept values) to the data. Although the fit of the Hargreaves model (ET_H) was similar to our temperature based model (ET_t), its intercept was not zero and this resulted in a slightly lower average ET estimate. The Baier-Robertson (ET_{BR1}) and the Linacre (ET_{L1}) temperature models had the poorest fit as evidenced by the comparison parameters in Table 3. The Baier-Robertson model underestimated ET_{os} by 1.2 mm d^{-1} and the Linacre model overestimated ET_{os} by 1.7 mm d^{-1} . Visual comparison of the temperature models (Fig. 2) for daily data from Lacombe confirmed the fitting parameters in Table 3; ET_{L1} consistently overestimated daily ET_{os} by about 2 mm d^{-1} ; ET_{BR1} tended to more greatly over- or under-estimate ET_{os} whereas, overall, ET_t and ET_H followed more closely the daily variations of ET_{os} . 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 in Fig. 2 would shift downwards resulting in a fit similar to other models. The coefficient of efficiency (E) showed more clearly than the r² value the poor fit of ET_{BR1} and ET_{L1}.

Of the temperature and humidity based equations, the statistical model, ET_{tr}, and the physical model, ET_{atr}, provided the best and essentially equal fits (Table 3). The Linacre model (ET_{L2}) provided the poorest fit, overestimating ET by 0.5 mm d⁻¹. Although the average ET of the Baier-Robertson model (ET_{BR2}) was similar to ET_{os}, it's SE was much larger than the other models (1.05 as compared to 0.60 for ET_{tr}). Consideration of how these ET models compare on a daily basis is illustrated in Fig. 3 for data from Stavely. ET_{BR2} consistently provided the lowest ET estimates, ET_{L2} provided the highest, whereas our developed models (ET_{tr} and ET_{atr}) provided the best estimates of ET_{os}. All models provided good agreement with daily changes in ET_{os}.

Adding wind speed to the physically based model (ET_{atru}) further improved the fit while decreasing SE to 0.50 from 0.61 for ET_{atr}. Demonstration of the ability of the models (EqS. 10 to 14) to estimate ET_{os} is shown in Fig. 1, where daily estimates from all ten climate stations used to develop the models are displayed. The statistically based models, ET_t and ET_{tr}, are slightly curvilinear at low ET values and develop negative ET_{os} values as they approach zero, whereas the physically based models (ET_{Ht}, ET_{atr}, and ET_{atru}) tend to be linear throughout (Fig. 1). As more parameters were added to the models the 'cloud' of points became more compact about the linear regression line (i.e., precision was increased). Generally, the spread of points about the regression line increased as ET increased. However, the precision of the physically based model, ET_{atru}, is noticeably superior to the other models, especially at higher ET rates.

Table 3. Comparison of evapotranspiration model results at ten sites across the Canadian Prairies

Model	Eq No.	average	r ²	SE	Int	Slp	E
Temperature based							
ET _{os}	1	3.49	-	-	-	-	-
ET _t	9	3.49	0.78	0.88	0.00	1.00	0.78
ET _{Ht}	10	3.48	0.77	0.90	0.00	1.00	0.77
ET _H	2	3.32	0.78	0.88	0.16	1.00	0.77
ET _{BR1}	3	2.30	0.66	1.01	1.77	0.75	0.19
ET _{L1}	6	5.18	0.61	1.18	-0.12	0.70	-0.31
Temperature and Humidity							
ET _{tr}	11	3.43	0.91	0.58	0.00	1.00	0.91
ET _{atr}	12	3.49	0.90	0.61	0.00	1.00	0.90
ET _{BR2}	4	3.73	0.72	0.99	0.98	0.67	0.54
ET _{L2}	5	4.16	0.80	0.84	0.06	0.82	0.64
Temperature, humidity, and wind speed							
ET _{atru}	13	3.49	0.93	0.50	0.00	1.00	0.93

Regression parameters (r², SE, Intercept, and Slope) result from comparison of the model against ET_{os}. E is coefficient of efficiency. Data is from the same data set used to create the models are used for this comparison.

Comparison to Individual Climate Stations

To confirm the accuracy of the models, comparative statistics (to ET_{os}) were calculated for individual stations and years. Comparison statistics for the temperature model (ET_t) and the temperature-humidity model (ET_{tr}) are shown in Table 4. The average absolute difference for each site and year was generally about 0.2 mm d^{-1} , for both ET_t and ET_{tr} . For ET_t , Stavely in 2003 had the largest difference in average ET, with ET_t underestimating ET_{os} by 0.7 mm d^{-1} . For ET_{tr} , the Kernen station had the largest average difference, underestimating ET_{os} by 0.5 mm d^{-1} . The regression parameters (r^2 , SE, slope, and intercept) for stations from the independent data set were similar to the parameters from those stations used to develop the models recorded in Table 3, indicating the models have the potential to perform well across stations at least within the drier region of the prairies. The temperature-humidity model (ET_{tr}) provided better estimation of ET_{os} than the ET_t model (as judged by higher r^2 and E and lower SE values in both Tables 3 and 4). Slopes were generally within ± 0.10 of 1.00 and intercepts within ± 0.20 of zero. There were no apparent differences with stations that were not part of the main data set used to develop the models (e.g., Kernen, Lethbridge, Outlook, and Strathmore) and those within the main data set. To display an example of the degree of agreement between our developed models we arbitrarily selected 5 weeks from Kernen in 1999 (Fig. 4). The daily fluctuations of ET_{os} were closely followed by the developed models. However, sometimes ET_t better approximated ET_{os} , other times it was ET_{tr} or ET_{atru} . How well any model approximated ET_{os} was dependent upon what weather factor was dominating evapotranspiration.

Table 4. Comparison of Developed Simple ET models to ET_{os} for individual stations and years

Place & Year	ET_t						ET_{tr}					
	avd	r^2	SE	Int	Slp	E	avd	r^2	SE	Int	Slp	E
Beaverlodge 03	-0.12	0.75	0.86	0.15	0.99	0.75	0.14	0.88	0.59	-0.22	1.03	0.88
Beaverlodge 04	0.11	0.80	0.69	0.15	0.91	0.78	0.16	0.92	0.43	-0.16	1.00	0.91
Eston 02	-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 03	-0.25	0.87	0.75	-0.16	1.10	0.84	0.05	0.92	0.56	0.15	1.00	0.88
Eston 04	0.17	0.76	0.77	-0.50	1.07	0.75	0.07	0.87	0.57	-0.30	1.05	0.87
Kernen 99	-0.25	0.71	0.88	-0.01	1.08	0.69	-0.52	0.92	0.47	-0.45	1.31	0.77
Lethbridge 03	-0.34	0.75	0.96	0.30	1.01	0.72	-0.30	0.91	0.59	0.08	1.06	0.87
Lethbridge 04	-0.17	0.74	0.80	0.16	1.00	0.73	-0.30	0.88	0.53	-0.20	1.14	0.83
Outlook 04	0.02	0.78	0.75	0.07	0.97	0.78	-0.12	0.91	0.48	-0.20	1.10	0.90
Stavely 03	-0.74	0.80	0.91	0.24	1.16	0.65	0.13	0.90	0.65	0.19	0.92	0.88
Stavely 04	-0.44	0.70	0.86	0.26	1.06	0.62	0.10	0.90	0.49	0.06	0.95	0.90
Strathmore 04	0.05	0.88	0.58	-0.13	1.02	0.84	-0.06	0.94	0.41	-0.34	1.14	0.90
Swift Current 03	0.07	0.87	0.74	-0.19	1.03	0.87	0.08	0.90	0.65	0.27	0.91	0.88
Swift Current 04	0.24	0.77	0.73	-0.12	0.96	0.75	-0.15	0.92	0.44	0.02	1.05	0.91

avd: difference of average model ET to ET_{os} (negative value means modeled ET is lower than ET_{os})

r^2 : regression coefficient

SE: standard error of regression (ET_{os} is predicted value)

Int: intercept of regression line

Slp: slope of regression line

E: coefficient of efficiency

SUMMARY AND CONCLUSIONS

Using daily weather data from ten climate stations within the Canadian Prairies, simple models were developed from and compared to the standardized reference evapotranspiration equation, ET_{os} - a standardized Penman-Monteith equation. Our developed models were also compared to other published simple models; Baier-Robertson, Hargreaves, and Linacre. All models used ET_{os} as the comparison standard. Comparisons for accuracy of fit was done using regression parameters of the model ET relative to the standard ET (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:

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

There was very little difference between our statistically developed model, ET_t , and the Hargreaves model, ET_H . 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 but with a slightly increased SE. Of the temperature based models, either ET_t , ET_H or ET_{Ht} would be suitable for 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 60% error.

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

$$ET_{tr} \sim ET_{atr} > ET_{L2} > ET_{BR2}$$

ET_{tr} and ET_{atr} are recommended for estimating ET_{os} on the Prairies. Neither Linacre (ET_{L2} , Eq. 5) or Baier-Robertson (ET_{BR2} , Eq. 4) models are recommended for estimating ET_{os} due to their much poorer fit to the ET_{os} data (Table 3).

Incorporation of measured values of temperature, humidity and wind speed into a physically based model, ET_{atru} (Eq. 13) resulted in the most accurate and precise estimation of ET_{os} (Table 3).

In summary, the developed models of ET_t and ET_{tr} provided increased accuracy over published models, especially over 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 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 compliment of available data. The most accurate and precise model was ET_{atru} , which used temperature, humidity and wind speed. However, we recognize that few weather recording sites measure wind speed and/or humidity (dew point temperature).

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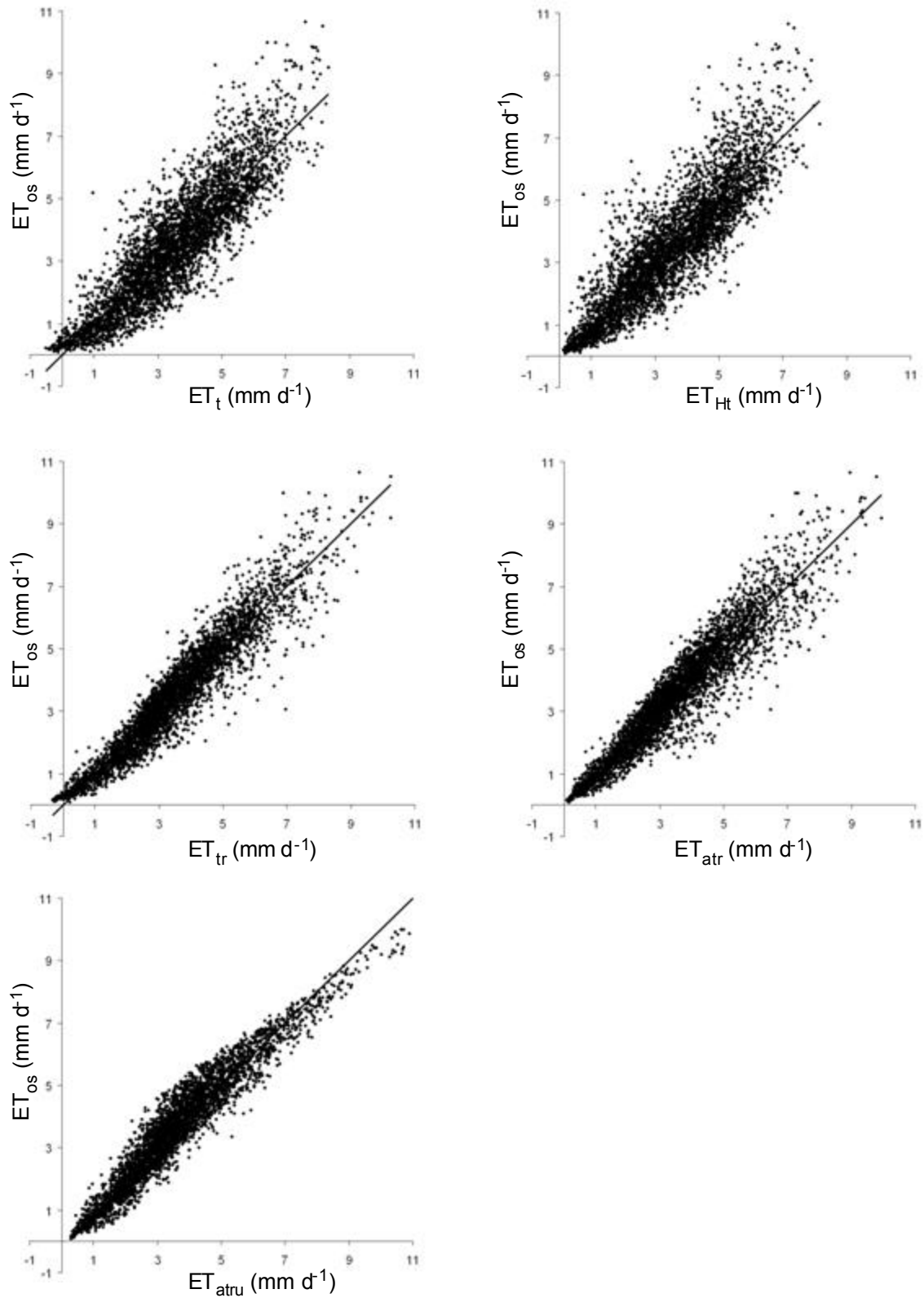


Fig. 1. Comparison of statistical and physically-based models of ET against ET_{os} using climate stations that the models were constructed from (Table 1).

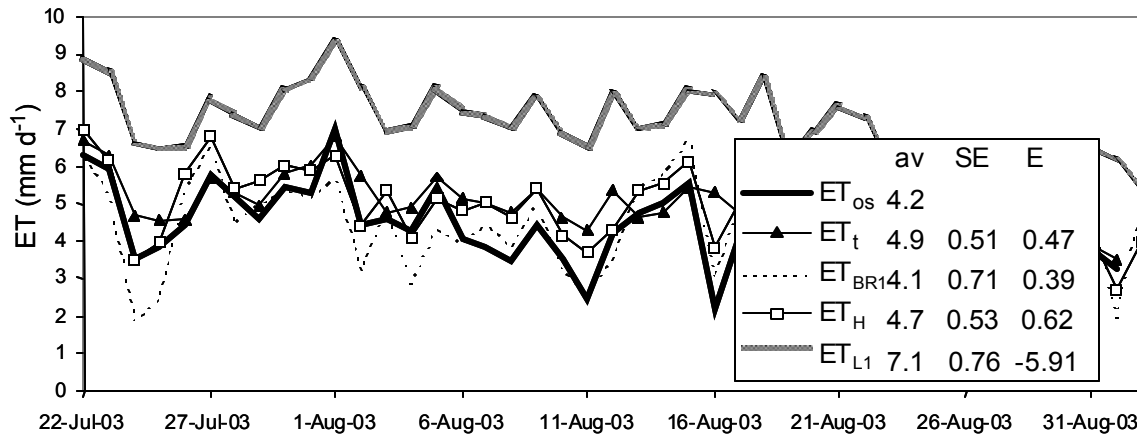


Fig. 2. Daily ET for ET_{os} and temperature based models for Lacombe, July 22, 2003 to Sept 2, 2003. (Int, Slp: Intercept and slope of regression line, respectively).

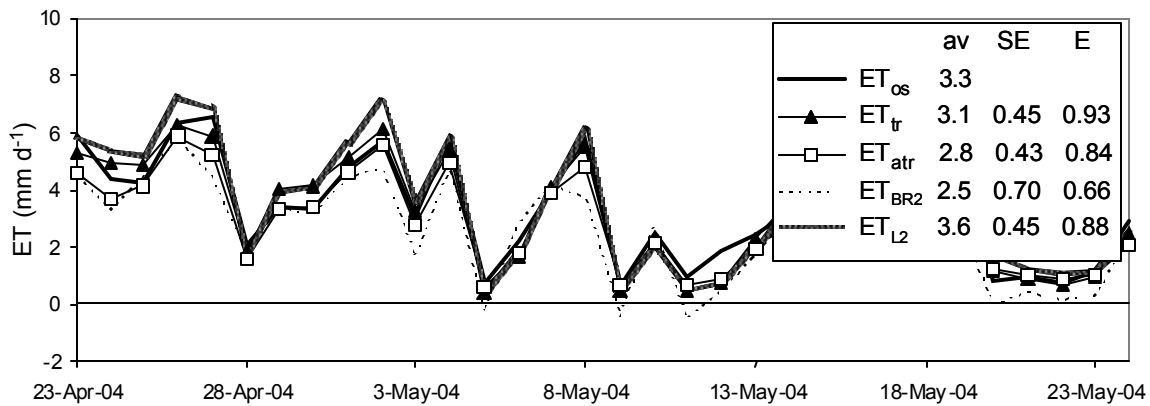


Fig. 3. Daily ET for ET_{os} and temperature-humidity based models for Stavelly, April 23 to May 24, 2004.

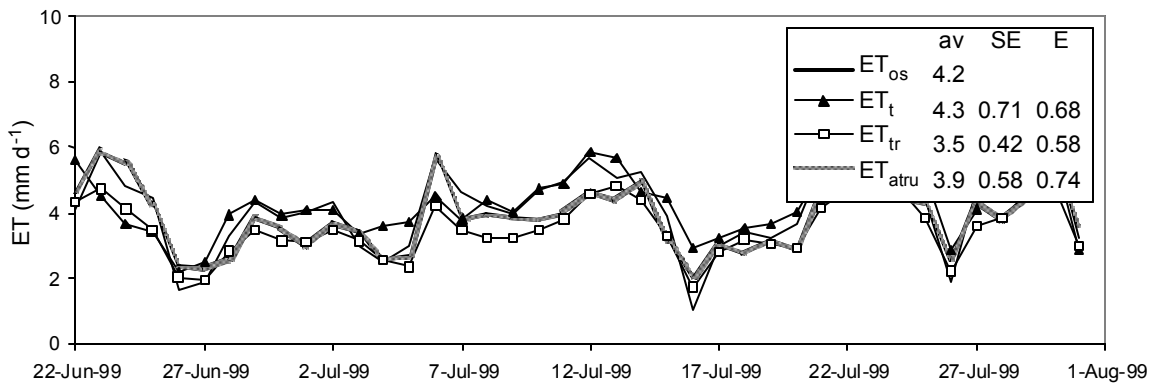


Fig. 4. Daily ET for ET_{os} and Developed models of ET_t, ET_{tr}, and ET_{atru} for Kernen, June 22, 1999 to July 31, 1999.