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Climatic factors that limit daily evapotranspiration in sorghum*

Kenneth G. Hubbard

Department of Agricultural Meteorology, University of Nebraska - Lincoln, L. W. Chase Hall, Lincoln, Nebraska 68583-0728, USA

ABSTRACT: Actual evapotranspiration from sorghum falls far below potential evapotranspiration in semiarid conditions. This study investigated whether adding a new model response to wind run and saturation-air vapor pressure deficit could further explain differences between model estimates and field observations of soil water in the root zone. A mathematical model of evapotranspiration and concurrent soil water status is employed at North Platte, Nebraska, and Stratton, Colorado, USA. The simulations performed at North Platte for sorghum (*Sorghum vulgare* L.) exhibited a high correlation to the actual observations. At Stratton the model overestimated evapotranspiration by 30%. The contributions of various atmospheric terms to potential evapotranspiration are examined and 2 methods, the threshold and reduction factor methods, of limiting transpiration estimates from the sorghum crop are tested. The introduction of thresholds to limit the wind run and the vapor pressure deficit did not change water loss by the amount required to match soil water measurements. Introduction of atmospheric reduction factors that cause a reduction of evapotranspiration with increase of saturation-air vapor pressure deficit beyond 2.3 kPa and wind run beyond 440 km d^{-1} improved the model simulation and corresponding statistics: the variance explained between measured and observed soil water at Stratton for the new formulation was 99 % and the root mean square error (RMSE) was reduced to 4.8 mm. It is shown that reduction factors do improve the daily model of evapotranspiration and are consistent with the concept of stomatal closure under environmental stress. Tests on independent soil water observation data sets resulted in an explanation of 93 % of the variance (RMSE = 13.7 mm) at North Platte in 1990 and 96 % of the variance (RMSE = 11.5 mm) at Walsh, Colorado.

INTRODUCTION

Models for estimating soil water under a variety of crops have recently been reported in the literature (e.g. Kunkel 1990, Robinson & Hubbard 1990, Steiner et al. 1991). These models make use of various climatological methods to estimate potential evapotranspiration (ET_p). A discussion of such empirical methods for estimating ET_p, was presented by Rosenberg et al. (1983). The methods require one or more of the ambient weather measurements of such variables as solar radiation, wind speed, temperature and humidity. The resulting estimates of potential evapotranspiration are only a function of the existing weather and can be considered as an atmospheric demand placed upon growing plants.

Monteith (1963) presented a method to estimate evaporation from surfaces at optimal (ET_p) or limited water supply (ET) based upon the vapor pressure gradient (leaf minus air) and 2 resistance terms that describe the resistance to vapor escaping from the leaf and an aerodynamic resistance. Stomatal regulation mechanisms reported in the literature for sorghum are subject to interpretation and apparently require further study (see for example Krieg 1983). Later studies have shed further light on the behavior of stomatal resistance in sorghum (Garrity et al. 1984, Krieg & Hutmacher 1986). Pettigrew et al. (1990) found for several crops, including sorghum, that canopy CO_2 exchange rate declined in the afternoon consistent with increase in stomatal resistance due to increase in vapor pressure deficit. Aphalo & Jarvis (1991) concluded that water

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vapor saturation deficit is the best variable to describe stomatal responses to humidity. Steiner et al. (1991) used leaf area index to estimate canopy resistance from well-watered sorghum. The resistance method of calculating potential evapotranspiration gave closest agreement to lysimeter measurements. Other equations used in their study to calculate evapotranspiration seriously overestimated the sorghum water use by as much as 20 to 40 %.

Performance of the model described by Robinson & Hubbard (1990) was reported for 20 separate examples involving 5 crops, 9 locations, and 2 years of data in the High Plains region of the USA. The root mean square error (RMSE) for the total soil water in the root zone was found to range from 13 to 86 mm with the majority of RMSE ranging from 14 to 46 mm. For the most part the variance explained by the model was in excess of 70 %. The sites involved in this earlier study were all in Nebraska, South Dakota or Wyoming and varied widely with respect to timing and amount of precipitation, temperature, and humidity.

In this paper, a mathematical model of crop water loss was used in 2 semi-arid climates to examine apparent upper limits on transpiration from sorghum (*Sorghum vulgare* L.) due to high winds and large saturation air-vapor pressure deficits. Some methods of simulating limited daily transpiration in high stress situations are proposed and examined. The study sites, North Platte, Nebraska, and Stratton, Colorado, are climatically similar in several respects. Stratton is located about 200 km SSW of North Platte. During the summer months, these sites lie very nearly along the same isolines of maximum, minimum, and average temperature (Climate Atlas 1983). Likewise, the isolines for monthly precipitation during the summer also pass nearly through these sites. The isolines for mean dewpoint temperature run more nearly north and south with dewpoints at Stratton averaging 2 to 3 °C below those at North Platte. According to the atlas solar radiation is generally higher at Stratton. There is not enough long-term wind data to assess the differences in wind at the 2 sites but researchers with field experience at both sites indicate Stratton is the windier of the two (Gary Peterson pers. comm.). Thus, while the sites are quite similar in temperature and precipitation, they differ considerably in atmospheric moisture, winds and solar radiation.

DATA

The study sites examined in this paper are located in the vicinity of North Platte and Stratton respectively. Soil characteristics were taken from publications of the U.S. Soil Conservation Service and augmented by observations taken on site. The characteristics of the soils used for this study are given in Tables 1 & 2. Weather data used in this study were collected by automated weather stations located within 1 km of the study sites. The data collection system described in Hubbard (1987) was employed. The weather data values were daily averages or totals of solar radiation (MJ m^{-2}), air temperature (°C), wind run (km d^{-1}) and air humidity (%). The daily potential evapotranspiration was calculated from the Penman combination equation:

$$\rho_w L_v ET_p = [\Delta(R_n - G) + \gamma f(U)(e_s - e_a)]/(\Delta + \gamma) \quad (1)$$

where net radiation (R_n), soil heat flux (G), wind function ($f(U)$), saturation vapor pressure (e_s), and vapor pressure of air (e_a) were calculated as discussed in Robinson & Hubbard (1990). Other terms in the equation are the psychrometric constant (γ) and slope of the saturation vapor pressure curve (Δ) with respect to temperature. The symbols ρ_w and L_v are the density of liquid water and the latent heat of vaporization respectively. For R_n and G in units of MJ m^{-2} d^{-1}, ρ_w in kg m^{-3} and L_v in MJ kg^{-1}, the units of ET_p are m d^{-1}. The wind function is the same as that from Robinson & Hubbard (1990):

$$f(U) = 7.1 + 0.068\,U.$$

When U is expressed in km d^{-1} the wind function has units of MJ (kPa m^2 d)$^{-1}$.

Table 1. Percent by volume of clay, sand, and silt in soils at North Platte, Nebraska, and Stratton, Colorado

Location	Soil constituents (% by volume)		
	Clay	Sand	Silt
North Platte	20	30	50
Stratton	25	35	40

Table 2. Water-holding characteristics of soil at both North Platte and Stratton by depth at saturation (S), field capacity (FC), and wilting point (WP)

Layer (mm)	Soil water (% by volume)					
	North Platte			Stratton		
	S	FC	WP	S	FC	WP
0-25	0.40	0.30	0.11	0.33	0.30	0.08
25-300	0.40	0.30	0.11	0.33	0.30	0.08
300-600	0.40	0.30	0.10	0.38	0.35	0.11
600-900	0.40	0.30	0.11	0.33	0.30	0.09
900-1200	0.40	0.30	0.11	0.33	0.27	0.09
1200-100	0.40	0.27	0.10	0.33	0.25	0.09
1500-1800	0.40	0.28	0.11	0.33	0.24	0.10

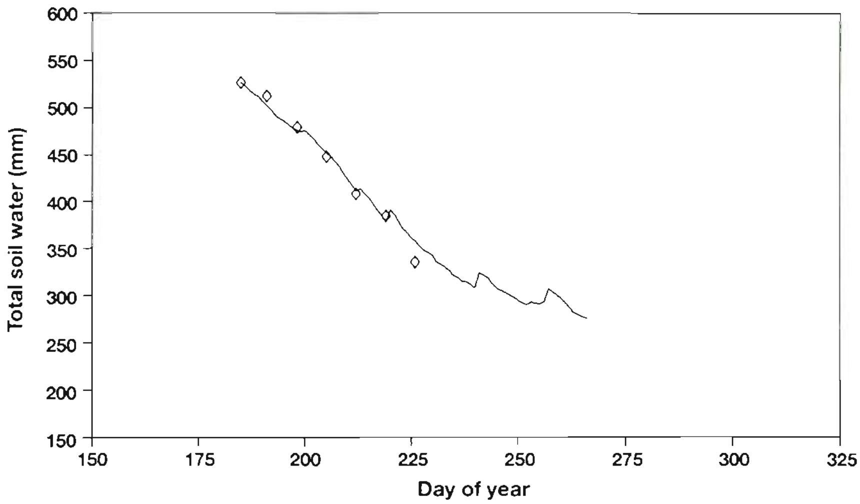

Fig. 1. Comparison between model and observed soil water for a sorghum field at North Platte, Nebraska, in 1989. Total water remaining in the first 180 cm. Observed soil water (◊) values are shown on measurement days and the daily values from the simulation are connected by straight lines

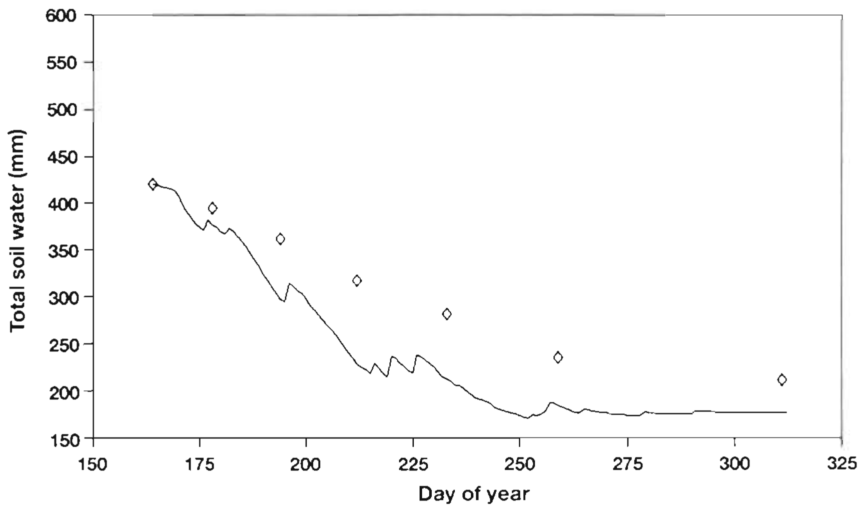

Fig. 2. Comparison between model and observed soil water for a sorghum field at Stratton, Colorado, in 1989. Total water remaining in the first 180 cm. Observed soil water (◊) values are shown on measurement days and the daily values from the simulation are connected by straight lines

Soil water measurements were taken with neutron moisture meters during the growing season of 1989 for sorghum. Neutron readings were taken at the midpoint of each 300 mm layer to a depth of 1800 mm. Total soil water to a depth of 1800 mm is shown in Fig. 1 for the observations collected during 1989 at North Platte. The estimates from a daily soil water balance model (Robinson & Hubbard 1990) are also shown for the growing season in Fig. 1. For the simulations the rooting depth was assumed to increase linearly with accumulation of growing degree days (GDD) to a maximum of 1800 mm at 1222 GDD. Daily precipitation in excess of selected thresholds (28 mm at North Platte and 38 mm at Stratton) was partitioned into daily run-off. The bulk density of the soil was 1.40 Mg m^{-3} at North Platte and 1.36 Mg m^{-3} at Stratton.

The fraction of the variance explained (r^2) was 0.99. This compared well with results at this location from 1987 where for sorghum the fraction of the variance explained was 0.99 and, likewise, at Clay Center, Nebraska (0.98).

The total observed soil water for the Stratton site is shown as a function of time in Fig. 2. The same version of the model was run for the Stratton site except that the inputs describing the physical characteristics of soil (wiling point, field capacity, etc.) were altered, consistent with the site, and the weather measurements used were those from the Stratton weather station. As can be seen the water use during the course of the season was over-estimated by about 30 %. The question raised by this data is how to account for the difference in observed and estimated water use in sorghum at the Stratton site.

The reason for the large discrepancy between measured and estimated soil water could be in the soil water measurements, the weather measurements used to calculate ET_p or some problem due to making incorrect assumptions or leaving out important factors in the model. Volumetric soil water measurements obtained with a neutron probe meter for this study have a typical accuracy of ±0.02 (Parks & Siam 1979). These meters are calibrated to the above study sites, and 6 readings from 2 access tubes were used to calculate the observed soil water at any one time. This should lead to cancellation of errors and would not explain the differences between the 2 sites because the same techniques were used at both places. Inputs to the ET_p calculation (Meyer et al. 1989) can lead to errors. In this study all the sensors were calibrated and checked by site visits and even problems with the troublesome humidity measurement should have been minimized because new chips were installed in the humidity sensors at the beginning of the period. Therefore, the overestimation of water use at Stratton seems to point to a need to change the fundamental assumptions used in the model to calculate ET_p.

METHODS

The climatic factors at the North Platte and Stratton sites were examined for the 1989 growing season. It was reasoned that the apparent overestimate of ET_p as given by Eq. (1) was due to the greater evaporative demand at Stratton. The inputs to ET_p are weather variables. For this analysis Eq. (1) was rewritten to indicate the following 2 terms:

$$ET_p = E_R + E_a \quad (2)$$

where E_R is the term depending on R_n and G and will be referred to as the net radiation (R_n) or radiative term; E_a is the term depending on the wind function and the vapor pressure gradient and will be referred to as the aerodynamic term or the E_a term. The E_R term and the E_a term were tabulated for comparison of their relative contribution to ET_p at the 2 sites. The wind run (U) and the saturation air-vapor pressure deficit ($e_s - e_a$), also referred to as the vapor pressure deficit, were also summarized at each site to assess the relative contribution of these terms to the aerodynamic term, E_a.

Two methods were tested for reducing the estimates of ET at the Stratton site. The first method involved choosing thresholds for the wind run and the vapor pressure deficit beyond which their contribution to ET would be fixed. This method is similar to limits placed on the wind function in Steiner et al. (1991).

The second method is a modification of the above. The modification is the addition of reduction factors into the calculation of actual evapotranspiration in the model as follows:

$$ET = T + E \quad (3)$$

where T is the estimated crop evapotranspiration; and E is the estimated surface evaporation. The crop evapotranspiration, in turn, is estimated from ET_p as follows:

$$T = f K_c ET_p \quad (4)$$

Here K_c is a crop coefficient, determined from independent experiments (e.g. Wright 1982) by examining the ratio of T to ET_p in various growth stages for a well-watered crop. In this study growth stage was estimated according to the accumulation of growing degree days (base 10 and upper limit 30 °C). K_c values were also specified according to the accumulation of growing degree days and ranged from 0.0 at emergence to 1.17 at the end of the boot stage. The factor f is a ratio of actual to potential evapotranspiration that depends on available soil water content (Baier 1969). The f factor allows the model to simulate transpiration when the crop is not well watered and is referred to here as a soil water reduction factor. In the model f depends on the ratio of actual soil water (S) to potential available water capacity (AW_p) of the soil and is calculated as follows:

$$f = 1.0 \quad \text{if } S/AW_p > F$$

and $$f = S/(F \cdot AW_p) \quad \text{if } S/AW_p \leq F.$$

The factor f is equal to 1 at high plant-available soil water content (S) relative to the potential available water in the soil (AW_p). F is a threshold value and was found to range from 0.35 to 0.6 at different sites (Robinson & Hubbard 1990). F was taken as 0.35 at North Platte and 0.50 at Stratton. Baier (1969) concluded that actual soil water measurements over one season should be sufficient for selecting the most appropriate relationship. (Note $F = 1.0$ corresponds to relationship type C in Baier's publication and larger F values lead to smaller predicted ET.)

Soil evaporation on a given day (E) for the current version of the model is calculated after Hanks (1974) as:

$$E = E_p (d_o/d)^{0.5}$$

where the potential soil evaporation (E_p) for that day was taken as ET_p. The variable d_o was set to 1.0 on the day of the most recent wetting, and d is the number of days since the last wetting. The result is that soil evaporation decreases exponentially with time from the day of the last wetting.

The second method for reducing the transpiration estimates was to introduce 2 additional reduction factors into Eq. (4), for vapor pressure deficit (f_v) and for wind run (f_u), resulting in the following equation:

$$T = f_v f_U f_s K_c ET_p. \quad (5)$$

The term f from Eq. (4) has been denoted in Eq. (5) as f_s to note its dependence on soil water status. The 2 atmospheric reduction factors were calculated in the following manner:

$$\begin{aligned} f_U &= 1.0 && \text{if } U < U_1 \\ f_U &= 1 - (U - U_1)/(U_2 - U_1) && \text{if } U_1 \le U \le U_2 \text{ and} \\ f_U &= 0.01 && \text{if } U > U_2 \end{aligned}$$

The vapor pressure deficit reduction factor was calculated as follows:

$$\begin{aligned} f_v &= 1.0 && \text{if } D < D_1 \\ f_v &= 1 - (D - D_1)/(D_2 - D_1) && \text{if } D_1 \le D \le D_2 \text{ and} \\ f_v &= 0.01 && \text{if } D > D_2 \end{aligned}$$

where the term D refers to the vapor pressure deficit and the subscripts 1 and 2 represent threshold values of U and D at which these functional relationships as used in the model exhibit a change in slope.

The reduction factors are equivalent to simulating the resistance terms in a Monteith approach. Monteith (1963) gave the following equation for estimating ET:

$$\rho_w L_v ET = [\Delta(R_n + G) + \rho_a C_p(e_s - e_a)/r_a]/[\Delta + \gamma(r_a + r_c)/r_a] \quad (6)$$

where ρ_a and C_p are the density and specific heat capacity of air; r_a and r_c are the aerodynamic and canopy resistances.

It can be shown that the use of Eq. (5) is comparable to using the resistance approach Eq. (6) to calculate evapotranspiration. To show this, Eq. (1) is substituted into Eq. (5) and equated to Eq. (6), then equating coefficients of like terms, the following equations for the aerodynamic and canopy resistance are derived:

$$r_a = \rho_a C_p/[\gamma f(U)] \quad (7)$$

$$r_c = r_a[(\Delta + \gamma)/\gamma][1 - f_v f_U f_s K_c]/[f_v f_U f_s K_c] \quad (8)$$

These are the aerodynamic and canopy resistance used (implicitly) in calculating daily ET in this study. Using these equations to calculate daily resistances and substituting in Eq. (6) will result in the same evapotranspiration estimate as that given by the model where Eq. (5) was used. Some small differences will arise because of evaporation (E) in the model that is not accounted for by the Penman-Monteith approach. Obviously, E is often negligible compared to T for dryland conditions in semiarid environments, because the soil is not often wetted. The effect of reducing water loss at the upper end of atmospheric demand is present in both Eqs. (5) and (6). For a well-developed canopy ($K_c = 1$) with adequate soil water ($f_s = 1$) and less demanding atmospheric conditions ($f_U = f_v = 1$) the canopy resistance, from Eq. (8), in the model will approach zero. This causes the Penman Monteith (Eq. 6) to reduce to the familiar form of the Penman equation (Eq. 1). It is conceded that Eqs. (7) and (8) are not mechanistically derived but, considering the current lack of information in the literature, it is not clear how better to include a wide range of environmental factors like vapor pressure gradient, wind speed, and soil water status on a daily basis.

The reduction factor approach has been successfully used in regard to estimating ET from soil water availability (Baier 1969, Robinson & Hubbard 1990). In this paper a test is conducted to determine whether the additional reduction factors defined above can be used to empirically include the physical factors involved.

RESULTS

The radiative term (E_R) was found to contribute a maximum of 5 mm d^{-1} to the total estimated ET_p at both North Platte and Stratton. These low values of E_R could not explain the overestimation of ET_p at the Stratton site, so efforts at determining thresholds were focused on the E_a term.

The difference in wind regimes at the North Platte and Stratton sites can be seen in Fig. 3. The histograms shown are for the same time period for which the model was run at these sites (see Figs. 1 & 2) so the total number of counts in the 2 frequency distributions are not equal. It can be seen that there are only a few events at North Platte where the daily wind run exceeds 440 km d^{-1}. At Stratton, the number of events with more than 440 km d^{-1} wind represents a significant portion of the frequencies in the histogram. Based on this obvious difference between the 2 sites a wind threshold was set on U in Eq. (1) such that any values that exceeded 440 km d^{-1} were set back to 440 km d^{-1}.

The saturation-air vapor pressure deficit ($e_s - e_a$), referred to as simply the vapor pressure deficit, for North Platte and Stratton appears in Fig. 4. It can be noted that the vapor pressure deficit did not exceed 2.3 kPa on many occasions at the North Platte site. At Stratton, the vapor pressure deficit exceeded this value more frequently. The threshold value for vapor pressure deficit was arbitrarily taken as 2.3 kPa. Any values ex-

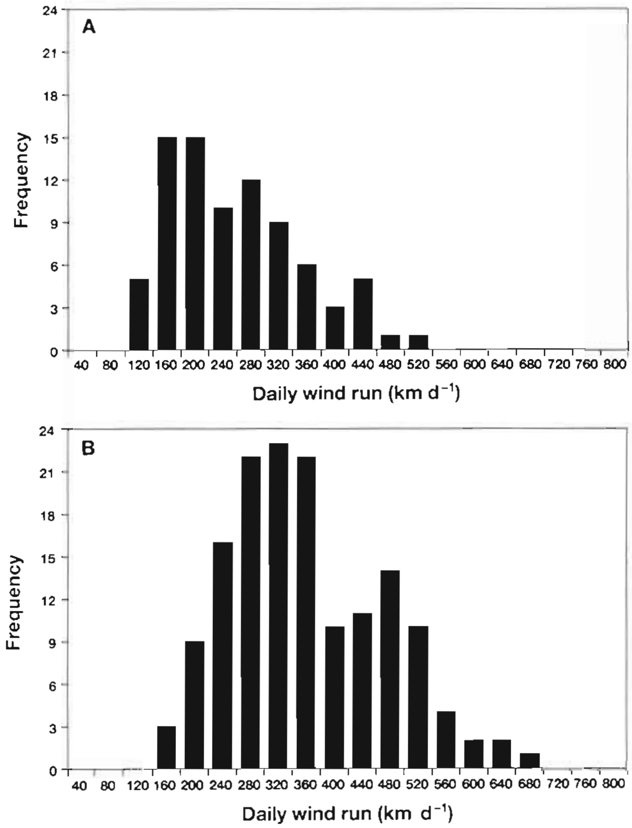

Fig. 3. Frequency of wind speeds during the 1989 simulation period at (A) North Platte and (B) Stratton. Wind run is calculated from midnight to midnight

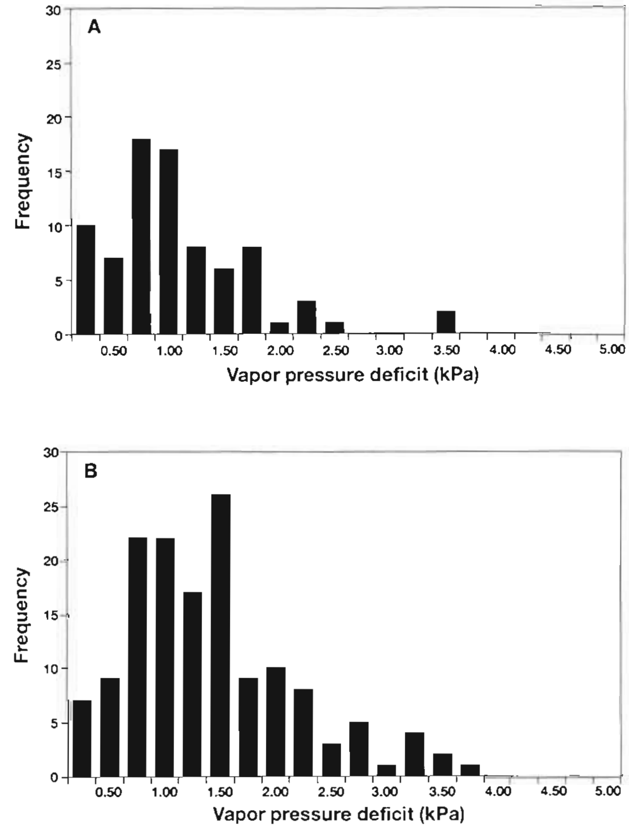

Fig. 4. Frequency of average daily (midnight to midnight) vapor pressure deficits during the 1989 simulation period at (A) North Platte and (B) Stratton

ceeding this threshold were set back to the threshold prior to use in Eq. (1). Both the vapor pressure deficit and wind run analyses indicate a more arid climate at Stratton as compared to North Platte.

Using the wind run and the vapor pressure deficit thresholds discussed above, the estimates of crop water loss and soil water were once again obtained from the model. No change was noted at North Platte. Only a modest improvement was made in the soil water estimates at the Stratton site indicating the model was still significantly overestimating transpiration. Smaller values of the wind threshold were tested but even in the extreme test where U_2 was set to zero, the E_a term still made a major contribution to ET_p

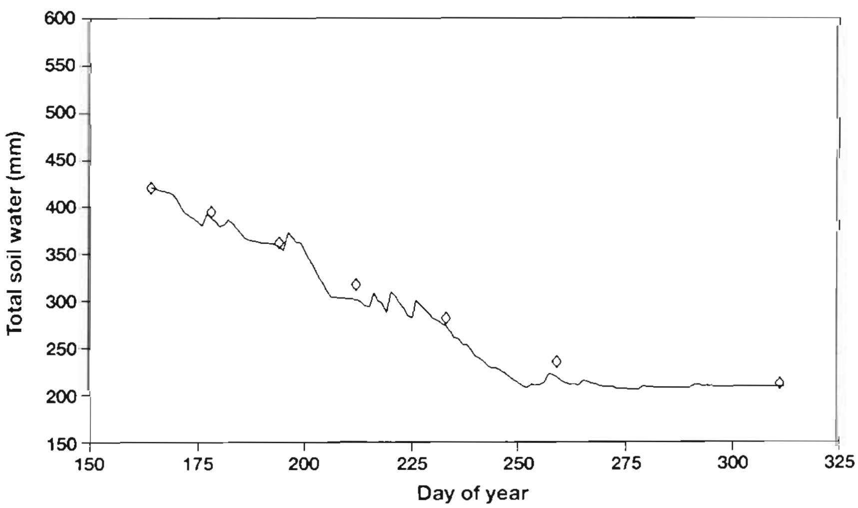

Fig. 5. Comparison between model (with atmospheric reduction factors) and observed soil water for a sorghum field at Stratton in 1989. Total water remaining in the first 180 cm. Observed soil water (◇) values are shown on measurement days and the daily values from the simulation are connected by straight lines. Values were simulated with the use of reduction factors

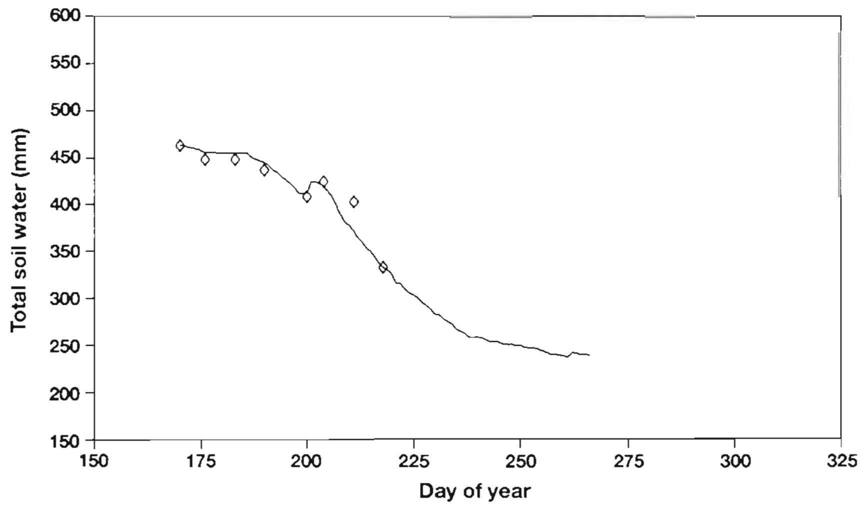

Fig. 6. Comparison between model (with atmospheric reduction factors) and observed soil water for a sorghum field at North Platte in 1990. Total water remaining in the first 180 cm. Observed soil water (◇) values are shown on measurement days and the daily values from the simulation are connected by straight lines

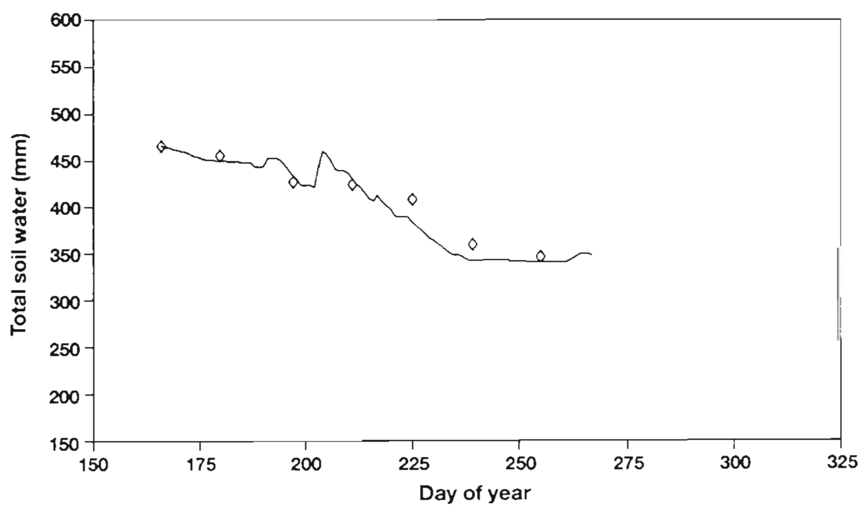

Fig. 7. Comparison between model (with atmospheric reduction factors) and observed soil water for a sorghum field at Walsh in 1990. Total water remaining in the first 180 cm. Observed soil water (◇) values are shown on measurement days and the daily values from the simulation are connected by straight lines

(34 %) at Stratton relative to the contribution (24 %) at North Platte. This is due to the differences in the magnitude and frequency of occurrence of vapor pressure deficit at the 2 sites.

The model was then modified so that the reduction factors (f_v and f_U) were incorporated into the transpiration calculation as in Eq. (5). U_1 and D_1 were taken as 440 km d^{-1} and 2.3 kPa consistent with the above discussion. U_2 and D_2 were taken as 490 km d^{-1} and 2.8 kPa respectively. The soil water estimates that resulted from making these changes are shown in Fig. 5 for the Stratton site. In this case the model was found to explain 99 % of the variance, and the RMSE was 4.8 mm compared to soil water of 521 mm in the 1.8 m profile at field capacity. The new model was then used at the North Platte site to determine the effects of using Eq. (5). The soil water estimates at North Platte were found to still closely follow the observed values. The variance explained remained at 99 % and the RMSE was reduced slightly to 6.9 mm.

Soil water estimates for the new model were compared to soil water observations taken in 1990 at North Platte and at Walsh. Walsh is located in the southeast corner of Colorado and, like Stratton, generally has high wind run and saturation air-vapor pressure deficit. No data for sorghum were available at Stratton in 1990. The results of the simulation for North Platte are shown in Fig. 6 along with the soil water estimates on measurement days. The variance explained by the model estimates was 93 % and the RMSE was 13.7 mm. Results of the simulation at Walsh are shown in Fig. 7. The variance explained by the model estimates was 96 % and the RMSE was 11.5 mm.

SUMMARY AND CONCLUSIONS

The 2 sites included in this study were found to differ significantly in term of the atmospheric demand (ET_p) placed on crops. The analysis showed that the radiative term (E_R) was not significantly different between the sites as was suggested by the patterns of solar radiation presented in the Climate Atlas. Both wind and vapor pressure terms were found to be quite different between the 2 sites studied and, together with the failure to adequately simulate conditions at Stratton, this suggested a need for upper limits or thresholds for these variables. Setting thresholds did not correct the problem of overestimating potential evapotranspiration at Stratton.

It is apparent that the sorghum crop at Stratton was not meeting the demands placed on it by potential evapotranspiration. Apparently, stomata were closing down in response to the stresses presented by the atmosphere. In a manner consistent with the resistance approach, reduction factors for high wind speeds and large vapor pressure deficits were introduced that lead to decreasing values of ET_p beyond the environmental thresholds selected. The simulation showed that the reduction factors were able to appropriately reduce evapotranspiration at Stratton while barely affecting the already acceptable estimates of evapotranspiration at North Platte. Further testing determined that these reduction factors gave satisfactory results in 1990 at both North Platte and Walsh. Because the reduction factors simulate a closing of stomatal openings at high atmospheric demand it is expected that they will be crop specific. The success in accurately simulating the evapotranspiration and remaining soil water under rain-fed conditions is encouraging but it does not prove that the thresholds used here are universal for sorghum grown at other locations. Although encouraging the matter requires further investigation into the climatic factors affecting evapotranspiration including physiological and environmental factors.

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