Evapotranspiration of Irrigated Winter Wheat — Southern High Plains

T. A. Howell, J. L. Steiner, A. D. Schneider, S. R. Evett

Abstract. *Models of water use for irrigation scheduling and for crop growth simulation require validation of the evapotranspiration (ET) submodel. In this study ET was measured for irrigated winter wheat (*Triticum aestivum *L.) at Bushland, Texas, in the semi-arid Southern High Plains for the 1989-1990, 1991-1992, and 1992-1993 winter wheat cropping seasons using weighing lysimeters that contained undisturbed monoliths 3 × 3 × 2.3 m deep of Pullman clay loam soil (Torrertic Paleustolls). Weather data from a nearby station were used to compute daily ET values for a reference alfalfa crop (hypothetical) using the ASCE Manual No. 70 equations based on the Penman-Monteith equation and several other widely used "potential" or "maximum" ET models. Linear regressions between ET estimated from widely used equations and the reference alfalfa ET equation indicated that direct comparisons with computed ET values could not be reliably predicted with simple ratios. For the computed reference alfalfa ET base, peak basal crop coefficients (K_{cb}) varied from 0.88 to 1.00 for the three seasons and were lower than those reported from other locations. Peak mean crop coefficients (K_c) varied from 0.83 to 0.94 for the three seasons. Seasonal ET varied from 791 to 957 mm for the three seasons. Evapotranspiration and crop coefficients for winter wheat varied considerably with season.*

Keywords. *Climate, Crop coefficient, Crop simulation modeling, Crop water use, Evaporation, Evapotranspiration, Irrigation, Irrigation scheduling, Lysimeters, Soil water, Water balance, Wheat, Yield.*

Wheat is the third largest irrigated crop in the United States and a major irrigated crop in India, Pakistan, and China (Musick and Porter, 1990). In the 41-county Texas High Plains area, winter wheat production area averaged 4000 km² or 20% of the total irrigated area for the 1985-1989 period (Musick et al., 1990). In the Southern High Plains (high plains of Texas, New Mexico, and Oklahoma and portions of southeastern Colorado and southwestern Kansas), winter wheat is widely grown under dryland, fully irrigated, and deficiently irrigated regimes and produced primarily for grain and secondarily for winter beef cattle forage. Fall and winter grazing of winter wheat in this region requires planting about three to six weeks earlier (in August to early September) than the optimum planting time for grain only (late September to mid October). Cattle are removed from wheat pasture prior to floral initiation to avoid yield reductions (Winter and Thompson, 1987).

Irrigated wheat yields in the Texas High Plains averaged 274 g m^{-2} for the 1968-1988 period (Musick et al., 1990), but have increased to about 400 g m^{-2} since the adoption of semi-dwarf wheat cultivars. However, research plot yield at Bushland from 1968 to 1988 averaged 575 g m^{-2} (Musick and Porter, 1990). Sprinkler irrigation is expanding in the region (Musick et al., 1988) necessitating accurate (evapotranspiration) ET values for efficient irrigation management with the low irrigation capacities.

As summarized by Musick and Porter (1990), winter wheat seasonal ET at Bushland, Texas, averaged 710 mm (Jensen and Sletten, 1965; Schneider et al., 1969; Musick and Dusek, 1980; Musick et al., 1984; Eck, 1988). Peak daily ET averaged 8 to 9 mm d^{-1} (Musick and Porter, 1990) similar to that reported for fall-sown spring wheat in Arizona (Erie et al., 1973, 1982), lysimeter measured ET of fall-sown spring wheat at Brawley, California (Ehlig and LeMert, 1976), winter wheat in western Kansas (Musick et al., 1963), and winter wheat in eastern Colorado (Shawcroft and Croissant, 1986).

Evapotranspiration measurement methods are summarized by Hatfield (1990). Lysimeters remain the standard ET method, particularly for calibration of eddy correlation, Bowen ratio energy-balance, soil water balance, etc. Jensen et al. (1990) reviewed methods for estimating ET and recommended the Penman-Monteith equation (Monteith, 1965) as presented by Allen et al. (1989) as the preferred method for daily reference ET. They proposed that 0.5 m be the "standard" alfalfa height and 0.12 m be the "standard" height for grass for reference ET models. The crop coefficient, K_c, is defined as the ratio of actual crop ET to reference crop ET (Burman et al., 1980). Generally, either alfalfa or grass is the reference crop. Reference ET in practice becomes a hypothetical computed value depending on weather data and the following specific crop parameters: (1) albedo, (2) emissivity, (3) crop height, and (4) leaf resistance. The

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first two parameters affect net radiation and energy partitioning into soil heat flux. Crop height affects the aerodynamic characteristics of the crop that influence sensible and latent heat exchange between the crop canopy and the atmosphere. Leaf resistance affects the reference crop surface resistance to latent heat transfer to the atmosphere. Energy partitioning of net radiation (R_n) into soil heat flux (G) is implicitly assumed to be a small component for reference crops, and G is usually estimated by simple relationships to air temperature or R_n itself. Canopy development and soil surface wetness affect the crop coefficient as summarized in Ritchie and Johnson (1990). The definition of reference ET for fall, winter, and spring conditions is certainly far from reality where grass or alfalfa would be dormant in most temperate climates and probably their crop characteristics would not be similar to those required for the reference ET calculations. Wright (1982) defined basal crop ET as the ET from the crop at its current development stage with a dry soil surface (several days after the last irrigation or rainfall) but with sufficient soil water for maximum transpiration.

The objectives of this article are to report and summarize daily and seasonal ET data for irrigated winter wheat at Bushland, Texas, during the 1989-1990, 1991-1992, and 1992-1993 cropping seasons; to report peak daily ET rates for irrigated winter wheat from weighing lysimeters; and to present and discuss basal crop coefficients for winter wheat at Bushland.

Materials and Methods

The study was conducted at the USDA-ARS Laboratory at Bushland, Texas (35°11′N Lat; 102°06′W Long; 1170 m elevation above MSL). The ET of irrigated winter wheat was measured with weighing lysimeters (Marek et al., 1988) during the 1989-1990, 1991-1992, and 1992-1993 winter wheat growing seasons. There were two lysimeter fields planted to winter wheat in each season. One field was always fully irrigated to meet ET demands and only that field data are reported herein. Each lysimeter field is approximately 44 000 m^2 (210 m E-W × 210 m N-S), and the lysimeter is centered in each field. The predominate wind direction is southwest to south-southwest, and the unobstructed fetch in this direction exceeds 1 km.

Table 1 summarizes agronomic and management details. The wheat was planted flat in all years, and all field operations were preformed with standard 4.6-m-wide row-crop field equipment and standard 4.3-m-wide combines, except in the immediate 30-m^2 area at each lysimeter where hand-cultural methods were required. Fertility and pest control were applied uniformly to the field area.

Irrigations were applied with a 10-span lateral move sprinkler system (Lindsay) with an end-feed hose and above-ground, end guidance cable. The sprinkler system was aligned north-south, irrigated east-west, or west-east. The system was equipped with gooseneck fittings and spray heads (Senninger Super Spray 360°) with medium grooved spray plates on drops located about 1.5 m above the ground and 1.52 m apart. In 1992 at the end of the season, low angle (6°) impact sprinklers (Senninger 3006) spaced 6 m apart on top of the lateral-move pipeline were used in an attempt to minimize additional lodging of the exceptionally tall wheat crop. The irrigations were scheduled to maintain the soil water profile adequately supplied with water to minimize soil water deficits from reducing ET or yield. The soil water content profile was maintained at about 80% or greater of the extractable soil water.

Plant samples from 0.5-m^2 areas in the 1989-1990 period and 1.0-m^2 areas in the later seasons were obtained periodically to measure crop development. These field samples were taken at sites about 10 m away from the lysimeters in areas of the field representative of the lysimeter vegetation. Leaf area index (LAI) and above-ground dry matter (DM) were measured. Final grain yield was measured by harvesting all the wheat heads in the lysimeter (9 m^2), and dry matter at harvest was measured from adjacent plant samples (2 m^2). All grain samples were threshed with a head thresher in the laboratory. In addition, field yield strips were cut by a combine in both east-west and west-east passes, and the grain was weighed with a field grain cart equipped with a scale. Grain samples were obtained from the combined grain and oven dried to determine the moisture content. All grain yield data are reported at 14% water content (wet basis).

Solar radiation, wind speed, air temperature, dew point temperature, relative humidity, and barometric pressure were measured at an adjacent weather station (Dusek et al., 1987) with an irrigated grass surface (cool season lawn mixture containing bluegrass, perennial rye-grass, etc.). The weather station is 1520 m^2 in area including the irrigation border surrounding the level plot. The weather station is immediately east of the east lysimeter field and slightly south of the north-south center of the lysimeter fields. The weather station grass was routinely mowed to a height of about 0.12 m and was fertilized and irrigated as needed to maintain vigor. The 100-m radius area immediately south and southeast from the weather station (direction of predominate winds) was in various fallow and wheat cover crops during these studies. Immediately northeast of the weather station, a three-span center pivot field was planted to various irrigated crops including corn and sorghum in 1989 and 1990 and corn in 1992 and 1993, but was in summer fallow in 1991 for perennial weed control. Solar radiation was measured with an Eppley PSP pyranometer; 2 m height wind speed was measured with a Met-One 014A cup anemometer; air temperature, dew point temperature, and relative humidity were measured in a standard Cotton Belt shelter (1.5 m above ground) with a variety of instruments (Dusek et al., 1993) Phys-Chem Campbell Scientific model 207, YSI model 9400 dew cell, Hygrometrix Campbell Scientific XN217, Rotronic MP100, R. M. Young model 41407 dew cell, and a ventilated psychrometer with a ceramic wet-bulb wick (Lourence and Pruitt, 1969); and barometric pressure was measured in the instrument shelter with a YSI model 2014 pressure transducer. All transducers were measured at 0.167-Hz (6 s) frequency by a Campbell Scientific CR-7X datalogger, signals were averaged for 15 min, and two 15-min means were composited into 30-min means. Daily (24 h) averages, maximum, or minimum values were determined from the 0.167-Hz samples. Data were transferred daily via telephone modem from the CR-7X to a laboratory personal computer. Daily solar radiation (R_s), maximum (T_{max}), and minimum (T_{min}) daily air temperature, average daily dew point temperature (T_{dew}),

Table 1. Agronomic and management data, phenological dates, yields and seasonal (planting to harvest) ET values

Parameter	Units	1989-1990 Season	1991-1992 Season	1992-1993 Season
Lysimeter field		Northwest	Northeast	Southwest
Row spacing	(m)	0.25	0.25	0.29
Row direction		East-West	North-South	East-West
Previous crop		Sorghum-1988 Fallow-1988-1989	Corn-1990 Fallow-1990-1991	Sorghum-1991 Fallow-1991-1992
Cultivar		TAM-200	TAM-107	MESA (Agripro)
Planting	(date)	89-283*	91-270	92-273
Emergence	(date)	89-291	91-280	92-283
Heading	(date)	90-129	92-118	93-125
Anthesis	(date)	90-136	92-129	93-133
Physiological maturity	(date)	90-165	92-171	93-172
Harvest	(date)	90-177	92-188	93-179
Plant density	(plants m^{-2})	190	193	131
Fertilizer	Rate [g(N) m^{-2}]	12.7	11.2	5.0 3.4 (aerial)
	(date)	89-264	91-241	92-259 93-088
Pest control	Chemical	Lorsban	Lorsban Dimetholate 2-4,D	2-4,D
	Rate [g(ai) m^{-2}]	0.056	0.023 0.056 0.11	0.11
	(date)	90-060	92-110 92-110 92-062	93-088
	(date)	90-091		
Lysimeter grain yield	(g m^{-2})	535	379‡	600
Lysimeter dry matter yield	(g m^{-2})	na†	1,588	na
Field dry matter yield	(g m^{-2})	na†	2,113	1,848
Evapotranspiration (ET_l)	(mm)	791	957	931
ET_r	(mm)	1,658	1,641	1,650
ET_o	(mm)	1,191	1,180	1,168
Water use efficiency§	(kg m^{-3})	0.68	0.40	0.65
Irrigations	(mm) (date)	10 89-286 18 89-294 20 89-300 16 89-304 17 89-324 16 89-326 38 90-094 15 90-109 23 90-114 27 90-116 27 90-117 26 90-129 29 90-135 31 90-136 30 90-141 23 90-142 27 90-145 29 90-150 39 90-152 22 90-156 38 90-161	21 91-273 26 91-276 11 91-282 21 91-291 15 92-057 23 92-072 22 92-076 33 92-079 26 92-083 27 92-097 23 92-101 17 92-104 30 92-113 26 92-122 28 92-125 21 92-128 28 92-134 31 91-136 28 91-140 23 91-143	38 92-276 11 92-283 16 92-287 17 92-297 32 93-089 25 93-092 21 93-097 22 93-102 23 93-106 24 93-110 37 93-113 26 93-117 22 93-126 23 93-131 28 93-134 21 93-139 23 93-144 21 93-147 24 93-154 21 93-158
Total	(mm)	521	479	475
Drainage	(mm)	0	61	0
Precipitation (lysimeter catch)	(mm)	186	534	343

* Year and day of year.
† Dry matter was not harvested to leave residue for subsequent fallow research.
‡ Plants lodged at heading.
§ Ratio of lysimeter grain yield to evapotranspiration.

2-m wind speed (U_{2g}), and average daily barometric pressure (P_b) were used in the subsequent calculations of reference ET. Missing climatic data were replaced with similar data from the primary Bushland weather station (mowed native grass surface cover). A few days of missing daily average dew point temperature data were replaced using the regression equation, $T_{dew} = -2.44 + (0.80\ T_{min})$, $r^2 = 0.837$, $S_{y/x} = 2.87°$ C, $-19 < T_{min} < 23$.

Lysimeter mass was determined using a Campbell Scientific CR-7X datalogger to measure and record the lysimeter load cell (Alphatron S50) signal at 0.5-Hz (2 s) frequency. The load cell signal was averaged for 15 min, and composited to 30-min means. Daily ET was determined as the difference between lysimeter mass losses (from evaporation and transpiration) and lysimeter mass gains (from irrigation, precipitation, or dew) divided by the lysimeter area (9 m^2). Evapotranspiration for each 24-h period was multiplied by 1.02 to adjust the lysimeter area to the mid point between the two walls (10 mm air gap; 9.5 mm wall thickness; 9.18 m^2 area instead of 9.00 m^2 area). This correction would be applicable to full-cover crops, but would not be necessary for bare soil conditions. Nevertheless, it was applied to all data uniformly.

Daily reference ET for 0.5-m-tall alfalfa was computed as:

$$ET_r = \frac{\Delta(R_n - G)/\lambda + (8.64 \times 10^4)(\rho C_p/\lambda)(e_a - e_d)/r_a}{[\Delta + \gamma(1 + r_c/r_a)]} \quad (1)$$

where

ET_r = alfalfa (0.5 m tall) ET in mm d^{-1}

Δ = the slope of the saturated vapor pressure curve ($\partial e/\partial T$) in kPa° C^{-1}, R_n is net radiation in MJ m^{-2} d^{-1}

G = soil heat flux in MJ m^{-2} d^{-1} (positive when heat flux is into the soil)

λ = latent heat of vaporization in MJ kg^{-1}, is air density in kg m^{-3}

C_p = specific heat of moist air in MJ kg^{-1}° C^{-1} (1.013×10^{-3} MJ kg^{-1}° C^{-1})

e_a = mean saturated vapor pressure in kPa at T_{max} and T_{min} {$e_a = [e_s(T_{max}) + e_s(T_{min})]/2$ where $e_s(T)$ is saturated vapor pressure in kPa at temperature T}

e_d = saturated vapor pressure in kPa at mean daily dew point temperature (T_{dew})

r_a = aerodynamic canopy resistance in s m^{-1}

r_c = canopy surface resistance in s m^{-1}

γ = psychrometer constant in kPa° C^{-1} [(C_p P_b)/(0.622 λ), where P_b is barometric pressure in kPa]

In equation 1, R_n and G and the other parameters were calculated using the ASCE Manual No. 70 equations (Jensen et al., 1990) based on Allen (1986), Wright (1982, 1988), and Allen et al. (1989) (Appendix I) for 0.5-m-tall alfalfa. Reference ET for grass (0.12 m tall) (ET_o) was computed similarly (Allen et al., 1989) (Appendix I) using r_a and r_c appropriate for grass but with R_n and G computed the same as for the alfalfa.

Three forms of the combination equation (Penman, 1948) were also used to compute "reference" or potential ET as follows:

$$ET_{p48} = \frac{\Delta(R_n - G)/\lambda + \gamma(e_o - e_d)(6.43 + 3.453\ U_{2g})/\lambda}{(\Delta + \gamma)} \quad (2)$$

$$ET_{fao} = \frac{\Delta(R_n - G)/\lambda + \gamma(e_o - e_d)(6.43 + 5.556\ U_{2g})/\lambda}{(\Delta + \gamma)} \quad (3)$$

$$ET_{kim} = \frac{\Delta(R_n - G)/\lambda + \gamma(e_o - e_d)(4.82 + 6.385\ U_{2g})/\lambda}{(\Delta + \gamma)} \quad (4)$$

where R_n and G were used from the ASCE computations, and ET_{p48}, ET_{fao}, and ET_{kim} represent the wind functions derived from Penman (1948) for grass, from Doorenbos and Pruitt (1977) for grass, and from Wright and Jensen (1972) for alfalfa, respectively. Vapor pressure deficit (VPD) was computed similarly to that shown in the ET_r equation (eq. 1) for ET_{kim} (VPD = $e_a - e_d$), but the ET_{p48} and ET_{fao} equations (eqs. 2 and 3) used e_o computed at mean air temperature [$T = (T_{min} + T_{max})/2$; $e_o = e_s(T)$] to compute the VPD (VPD = $e_o - e_d$). The equilibrium "potential" ET for nonadvective conditions was computed using the Priestley and Taylor (1972) equation as:

$$ET_{pt} = \frac{1.26\,\Delta(R_n - G)/\lambda}{(\Delta + \gamma)} \quad (5)$$

The radiation-temperature-based ET equation developed by Jensen and Haise (1963) and modified as described later in Jensen et al. (1990) was computed as:

$$ET_{jh} = C_t(T - T_x)R_s/\lambda \quad (6)$$

where C_t and T_x are coefficients taken as 0.0234° C^{-1} and −8.76° C, respectively, following Steiner et al. (1991) for Bushland conditions. In addition, the "potential" or "maximum" winter wheat ET was computed using the algorithms from CERES-Wheat (DSSAT, 1989; Jones and Kiniry, 1986) as:

$$ET_{eeq} = R_s(4.872 \times 10^{-3} + 4.371 \times 10^{-3}\alpha)(T_c + 29) \quad (7)$$

$$ET_{ceres} = \begin{cases} 1.1\,ET_{seq} & \text{for } 5 \le T_{max} \le 24 \\ ET_{eeq}\{0.01\,\mathrm{Exp}[0.18(T_{max} + 20)]\} & \text{for } T_{max} < 5 \\ ET_{eeq}[0.05(T_{max} - 24) + 1.1] & \text{for } T_{max} > 24 \end{cases} \quad (8)$$

where $T_c = [(0.6\ T_{max}) + (0.4\ T_{min})]$ and albedo (α) was as assumed to be 0.23. These equations were coded in a FORTRAN program to compute the daily ET values. The code was verified against REF-ET, version 2.1 (Allen, 1990), although REF-ET computed R_n according to Wright (1982) using different functions for α and different coefficients for net long-wave radiation (eq. 12 in Appendix I). Linear regressions were computed among ET estimates for all these models (eqs. 2 through 8) and ET_r (reference ET for 0.5-m-tall alfalfa) and ET_o (reference ET for 0.12-m-tall grass).

Daily crop coefficients (K_c) were computed for each day of the three seasons as:

$$K_c = ET_l/ET_r \quad (9)$$

where ET_l is lysimeter measured ET in mm d^{-1}. Basal crop ET days were selected based on a criterion of $\Sigma(ET_r) \ge$ 10 mm after a rain or irrigation event. This criterion was arbitrarily selected.

Because sprinkler irrigation methods were used and maximum irrigation amounts seldom exceeded 35 mm (table 1), if the criterion was increased above 10 mm very few actual days of data would meet a "basal" definition. Certainly, this criterion did not insure "basal" conditions, but soil surface wetness should have a much reduced effect on ET at this time. It would take a single day during warm spring conditions but up to seven days under winter conditions with very low ET rates. On the basal ET days, the crop coefficient was defined to be the basal crop coefficient, K_{cb}. Basal crop coefficients were fit to time (days of year) and to cumulative growing degree day scales. The K_c and K_{cb} curves were fit with four-term Fourier series models using PROC REG of SAS (SAS/STAT, 1987). Growing degree days (Ritchie and NeSmith, 1991) were computed as follows:

$$GDD = \begin{cases} [(T_u + T_{min})/2] - T_b & \text{for } T_{max} \geq T_u \text{ and } T_{min} \geq T_b \\ T - T_b & \text{for } T_b \leq T_{max} \leq T_u \text{ and } T_{min} \geq T_b \\ [(T_{max} + T_b)/2] - T_b & \text{for } T_b \leq T_{max} \leq T_u \text{ and } T_{min} \leq T_b \\ 0 & \text{for } T_{max} \leq T_b \text{ and } T_{min} \leq T_b \end{cases} \quad (10)$$

where

GDD = daily growing degree days in ° C-d
T_u = upper temperature threshold in ° C taken as 26° C
T_b = base temperature in ° C taken as 0° C
T = mean of T_{max} and T_{min}

Results and Discussion

Winter wheat is subjected to extremes in cold temperatures during winter and to potentially high temperatures and evaporative demand conditions in the spring and early summer at Bushland. The spring season also can be windy (2 m height mean daily wind speeds exceeding 5 m s^{-1}) and dry (relative humidities below 10%). Table 2 summarizes the climatic conditions for each of the months in the three growing seasons, and figures 1 through 3 show the daily climatic patterns for the 1989-1990, 1991-1992, and 1992-1993 seasons, respectively. Of particular note is the wide range in the climatic parameters for the winter wheat seasons. Maximum daily air temperature ranged from –12 to over 42° C; daily mean dew point temperatures ranged from –21.5 to over 16° C; daily mean wind speeds at a 2-m elevation ranged from near 0 (0 mean daily wind speeds never occur, but anemometers can ice up in the winter and indicate erroneous wind speeds of 0 m s^{-1}) to nearly 12 m s^{-1}; and daily rainfall averaged only 1.1 mm d^{-1}, which is far below the ET demand for wheat in this climate. The low rainfall for the winter wheat season (54-year mean at Bushland is 341 mm from 1 September to 30 June or 1.13 mm d^{-1}) emphasizes the importance of irrigation and soil water conservation practices in this region to provide the necessary water for optimum crop growth and yield of winter wheat. In general, these seasons typified the climatic variations of the Southern High Plains. The range between T_{max} and T_{min} was usually about 20° C, and the difference between T_{min} and T_{dew} was about 5° C but was somewhat larger with warmer air temperatures.

Winter wheat LAI and DM development are shown in figure 4 for the three seasons. Crop growth measurements were not begun until early spring of 1990, so the parameter values shown during the fall and winter (dashed curves) are estimated based on past experiences and data from the later years. The wheat cultivar used in 1989-1990 (TAM-200) is susceptible to winter kill, but did not affect the stand density in that year. The wheat cultivar was changed to TAM-107 in 1991-1992 to reduce this risk of winter kill and was again changed in 1992-1993 to Mesa because of lodging problems with the taller TAM-107. The 1991-1992 wheat crop grew exceptionally tall (in excess of 1.5 m), and areas in the field lodged after heading including areas in and around the northeast weighing lysimeter. For that reason, ET data after heading in 1991-1992 are presented for information only and should not be taken as representative. The maximum LAI in the 1989-1990, 1991-1992, and 1992-1993 seasons, respectively, was 3.6, 7.0, and 4.2, and the maximum total dry matter was 1.6, 2.2, and 1.9 kg m^{-2} for the samples from the field (fig. 4). All of these values are indicative of good irrigated winter wheat crops under commercial production; however, LAI values for the 1989-1990 and 1992-1993 seasons were somewhat lower than we expected for the nonwater stressed conditions. No significant weed, insect, or disease problems developed in these cropping seasons, but the fields were aerially sprayed for control of aphids in the 1989-1990 and 1991-1992 seasons, and weeds were sprayed in the 1991-1992 and 1992-1993 seasons (table 1).

Table 2. Summary of average monthly climatic parameters and daily maximum, minimum, and averages during the winter wheat growing seasons

Season Month	R_s (MJ m^{-2} d^{-1})	T_{max} (° C)	T_{min} (° C)	T_{avg} (° C)	T_{dew} (° C)	U_{2g} (m s^{-1})	P_b (kPa)	Prec. (mm)
1989-1990								
October*	16.2	23.0	5.1	13.0	0.9	2.98	88.6	0.8
November	12.8	17.8	–1.8	7.2	–6.2	3.59	88.4	1.0
December	10.3	6.9	–8.5	–1.9	–8.2	3.57	88.6	6.4
January	12.5	10.7	–4.9	2.3	–6.6	4.66	88.3	8.9
February	13.6	12.9	–3.7	3.7	–4.8	4.93	88.3	30.7
March	16.5	15.0	0.7	7.5	–0.9	4.40	88.3	31.2
April	21.8	20.3	5.2	12.5	2.8	5.15	88.2	17.8
May	25.2	25.3	8.8	17.1	3.8	5.19	88.2	80.8
June	28.8	36.2	17.4	26.	9.5	5.45	88.3	5.1
1991-1992								
September*	19.6	26.1	9.1	17.5	5.5	4.92	89.4	0.0
October	16.1	22.1	5.3	13.4	0.5	4.15	88.9	26.3
November	9.9	10.7	–1.9	3.8	–3.3	4.87	89.1	23.9
December	8.5	9.2	–2.6	2.6	–4.8	4.19	89.2	76.9
January	10.0	8.9	–3.2	2.0	–5.6	4.29	89.0	20.8
February	13.2	13.5	–0.7	5.9	–4.2	4.20	88.9	13.2
March	18.7	17.3	1.0	8.9	–1.3	4.27	88.7	48.8
April	21.9	22.0	6.0	13.7	2.9	3.88	88.8	14.7
May	20.7	23.5	9.8	16.5	6.1	4.05	89.0	80.5
June	24.9	28.1	13.9	20.6	10.4	3.71	88.7	164.9
July*	26.5	34.1	16.7	25.3	11.5	4.58	88.8	0.0
1992-1993								
September*	19.9	28.2	6.2	16.9	1.4	3.18	89.8	0.0
October	14.9	23.5	6.1	14.2	1.5	4.12	89.1	7.4
November	10.8	10.3	–3.2	3.1	–5.7	4.64	88.9	42.1
December	9.0	6.7	–4.9	0.2	–6.0	4.31	88.9	14.4
January	8.5	7.1	–5.3	0.2	–5.6	3.45	88.9	22.9
February	12.0	9.5	–4.3	2.0	–5.8	4.73	88.9	5.6
March	17.7	15.9	–0.4	7.3	–3.1	4.77	88.9	25.1
April	22.0	21.0	3.4	12.0	–1.4	5.16	88.6	14.0
May	23.5	25.0	9.9	17.2	5.2	5.10	88.8	55.9
June*	24.7	29.9	15.0	22.2	9.4	5.34	88.8	58.4
Daily Statistics								
Maximum	32.1	42.5	22.2	30.8	16.7	11.95	90.3	59.7
Minimum	1.7	–12.0	–20.6	–18.1	–21.5	0.00	87.2	0.0
Average	16.5	17.5	2.3	9.4	–0.7	4.42	88.7	1.1

* Partial months.

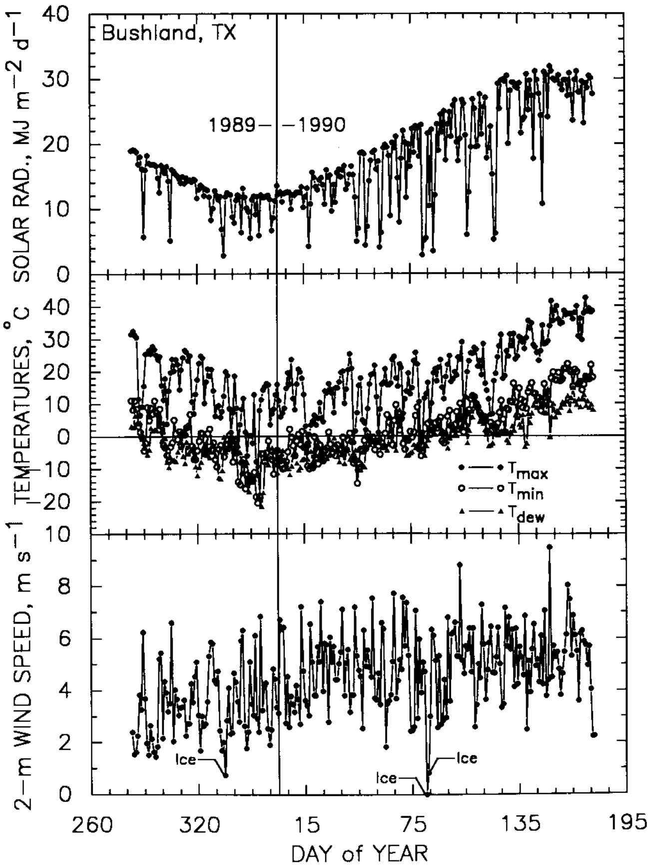

Figure 1–Daily climatic parameters for the 1989-1990 winter wheat growing season at Bushland, Tex.

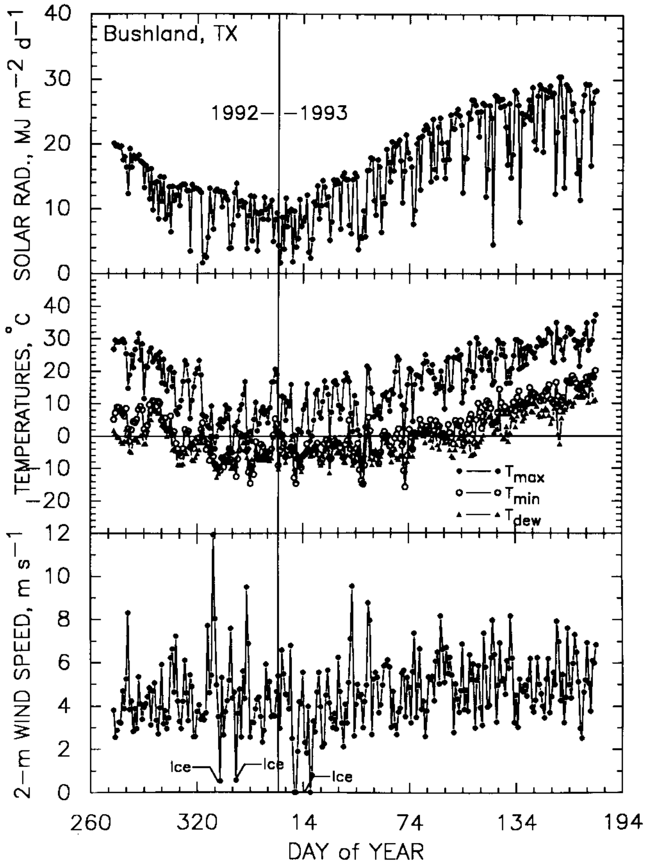

Figure 3–Daily climatic parameters for the 1992-1993 winter wheat growing season at Bushland, Tex.

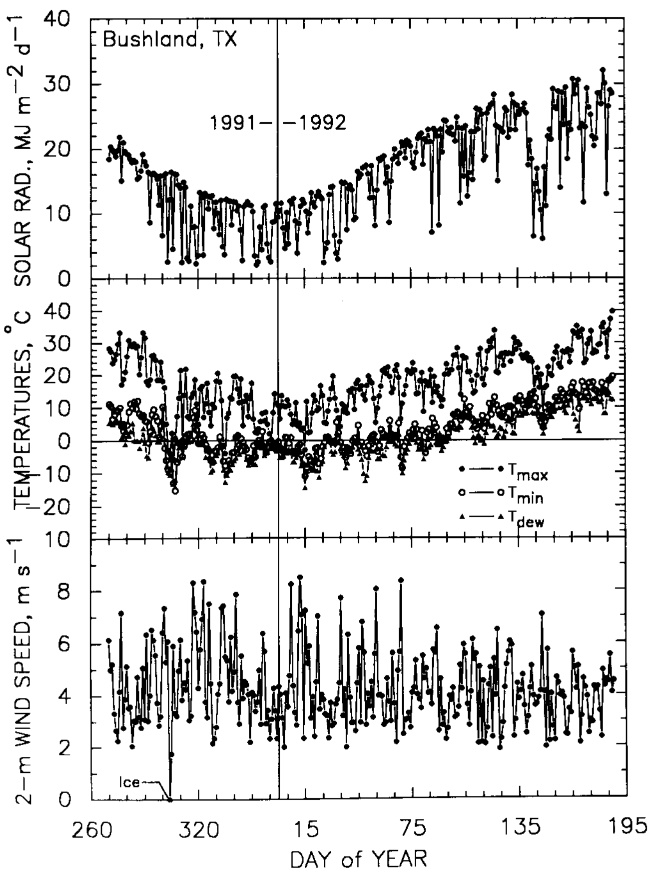

Figure 2–Daily climatic parameters for the 1991-1992 winter wheat growing season at Bushland, Tex.

Combine field grain yields (table 1) for the 1989-1990, 1991-1992, and 1992-1993 seasons were 520, 680, and 538 g m^{-2}, which are similar to the irrigated wheat yield range shown by Musick and Porter (1990) for Bushland. Wheat grain yields from the lysimeter (9 m^2) were 103, 56, and 112% of the field combine yields in 1989-1990, 1991-1992, and 1992-1993 seasons. The low grain yield in 1991-1992 resulted from lodging inside the lysimeter crop, and its effect on grain filling. Wheat growth in the lysimeters and the surrounding field was typical for irrigated wheat crops in all years, except the lodging in 1991-1992. Other irrigated plots with TAM-107 at Bushland also lodged that year.

Linear regressions between ET estimates from the various equations are given in table 3. The combination equations all had much higher coefficients of determination than the temperature-radiation-based equations. Standard errors of the estimate for the combination equations averaged 0.52 mm d^{-1} compared with the average of 1.06 mm d^{-1} for the radiation-temperature equations. All regressions had significant Y-axis intercepts and therefore, significant biases, some approaching 1.0 mm d^{-1}. However, this bias was smaller for the ET_0 (reference ET for grass). The lack of consistent simple ratios between the various ET models implies that conversion of crop coefficients computed with a specific reference ET method may not be simply translated for other ET equations. Of particular note is the large difference between the computed ET for alfalfa and grass using the ASCE equations. Alfalfa ET would be approximately 39% larger

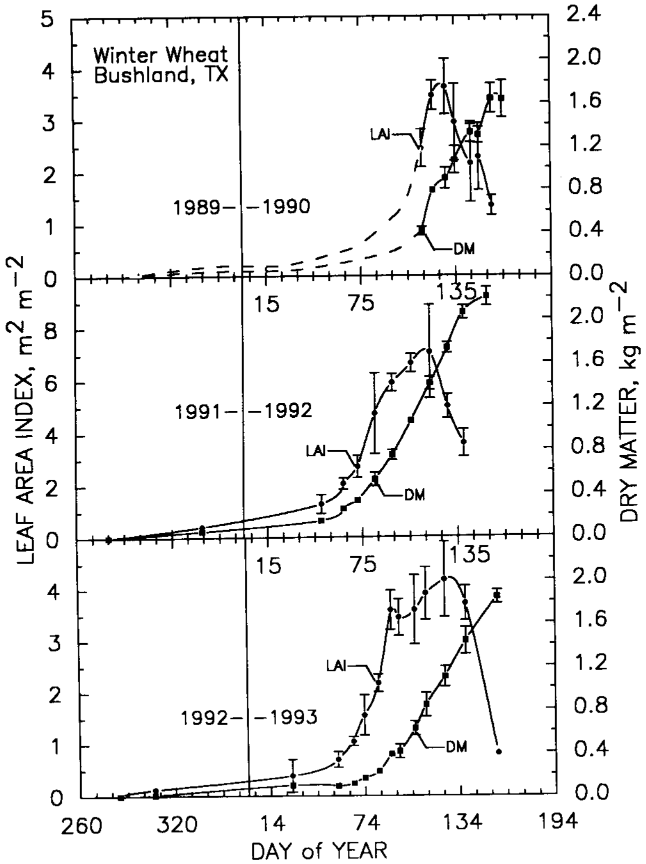

Figure 4–Leaf area index and dry matter for sprinkler irrigated winter wheat at Bushland, Tex., for 1989-1990 (top), 1991-1992 (middle), and 1992-1993 (bottom) growing seasons. Error bars are standard deviations.

than grass ET. Similar computed results were found by Allen et al. (1989) and Jensen et al. (1990) for windy sites (Bushland should be considered a windy site), although little published ET data are available (to the authors' knowledge) to verify these computed results. ET_r was similar in magnitude to the ET_{fao} and ET_{kim} equations, although about 5% higher and 11% lower, respectively. The relation between reference ET equations permit comparisons of crop coefficients among ET equations as presented later.

The ET_r values for 0.5-m-tall alfalfa is shown in figure 5 for the three seasons. Peak ET_r values exceeded 18 mm d^{-1} during an advective heat wave in late May and early June of 1990; two days exceeded 14 mm d^{-1} in the spring of 1992; and one day exceeded 16 mm d^{-1} in the spring of 1993. These computed alfalfa ET rates are considerably greater than maximum reported ET rates measured with weighing lysimeters for alfalfa in Nebraska of 14.2 mm d^{-1} (Rosenberg and Verma, 1978) or in Idaho of 11.0 mm d^{-1} (Wright, 1988). Measured ET values are shown in figure 6 for the three seasons. Peak ET rates for the wheat exceeded 10 mm d^{-1} for 19 days in the spring of 1990, for 4 days in 1992, and for 13 days in 1993. Winter ET rates were generally between 1 and 2 mm d^{-1} in all years; however, in the 1989-1990 winter ET rates were often less than 1 mm d^{-1} due to the limited crop growth during the fall. Wind and vapor pressure deficit affect the

Table 3. Summary of linear regressions between various reference ET methods (dependent variable) and ET_r [0.5-m-tall alfalfa (Allen et al., 1989; Jensen et al., 1990); independent variable] for the 1989-1990, 1991-1992, and 1992-1993 winter wheat growing seasons (planting to harvest; N = 817) at Bushland, Tex.

Reference ET Model	Mean (mm d^{-1})	Standard Deviation (mm d^{-1})	Intercept (mm d^{-1})	Slope	r^2	$S_{y/x}$* (mm d^{-1})	Mean Ratio†
ET_r	6.10	3.39	——	——	——	——	——
ET_o	4.33	2.34	0.14	0.69	0.992	0.21	0.722
ET_{p48}	4.43	2.10	0.82	0.59	0.916	0.61	0.788
ET_{fao}	5.44	2.67	0.79	0.76	0.939	0.66	0.951
ET_{kim}	6.52	3.26	0.77	0.94	0.965	0.61	1.123
ET_{pt}	2.63	1.33	0.91	0.28	0.510	0.93	0.506
ET_{jh}	3.36	2.66	–0.98	0.71	0.825	1.11	0.484
ET_{ceres}	3.39	2.68	–0.97	0.72	0.824	1.13	0.502

* Standard error of the estimate.
† Mean of the daily ratios of the model ET to the ET_r value (i.e., ET_{oi} / ET_{ri} for day i).

magnitude of computed reference ET in this environment. This is particularly true on days with both high vapor pressure deficits and high wind speeds. The measured wheat ET rates that exceeded 13 mm d^{-1} in the spring of

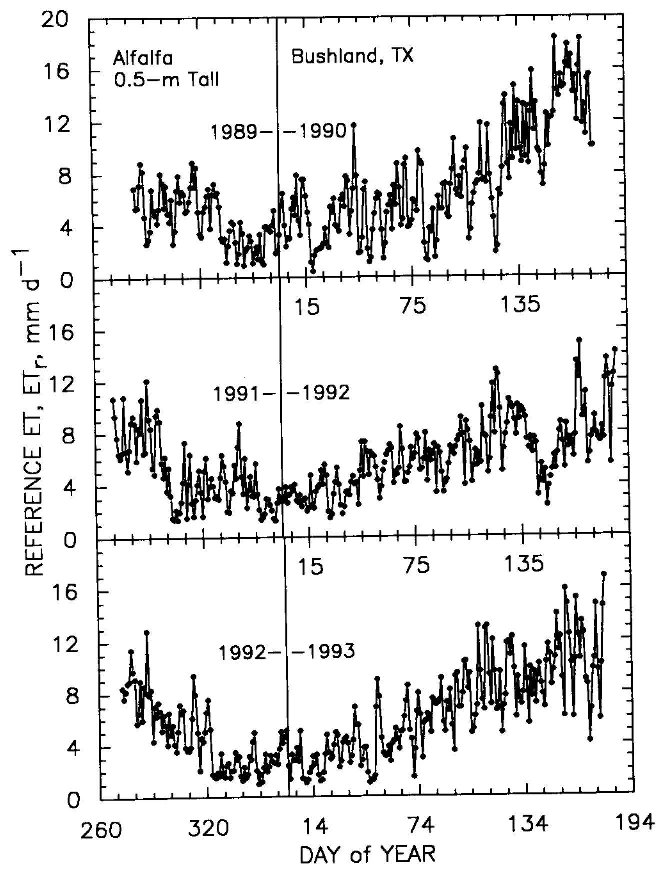

Figure 5–Computed daily reference ET for 0.5-m-tall alfalfa with a Penman-Monteith combination equation [Allen et al. (1989) for 1989-1990 (top), 1991-1992 (middle), and 1992-1993 (bottom) growing seasons].

1992 (see middle graph in fig. 6) are reasonable considering the strong regional advection at this time.

Seasonal ET values were 791, 957, and 931 mm for the 1989-1990, 1991-1992, and 1992-1993 seasons, respectively (table 1). These seasonal ET values are considerably higher than the mean reported for previous Bushland surface irrigated studies of 710 mm using soil water balance methods (Musick and Porter, 1990). Although it is reasonable to expect slightly greater ET for crops that are sprinkler irrigated more frequently than surface irrigated crops, this should not be a major factor in the apparent disagreement of the seasonal ET values for winter wheat at Bushland. Part of the difference can be attributed to snow capture and measurement by the lysimeter compared with less accurate precipitation gauges. The specific seasonal weather and plant growth patterns could have caused greater ET in these years. For example, the warmer winter conditions and rather mild late spring and early summer conditions in the 1991-1992 season resulted in high ET early and a long season with 53 days between heading and physiological maturity.

Both K_{cb} and K_c crop coefficient values are presented in tables 4 and 5, respectively, and the K_{cb} curves for the day and GDD time scales are shown in figures 7 and 8, respectively. The statistics for the K_c and K_{cb} curve fits to the Fourier series are shown below:

	K_{cb} – d		K_{cb} – GDD		K_c – d		K_c – GDD	
Season	r^2	MSE	r^2	MSE	r^2	MSE	r^2	MSE
1989-1990	0.739	0.132	0.930	0.005	0.533	0.185	0.561	0.032
1991-1992	0.918	0.080	0.942	0.004	0.658	0.167	0.328	0.103
1992-1993	0.848	0.090	0.916	0.005	0.635	0.154	0.669	0.022

where MSE is the mean square error. In general, the GDD time scale improved the coefficient of determination (r^2) and reduced the MSE compared with the day time scale, particularly for the K_{cb} data. In 1991-1992, the GDD time scale reduced the r^2 value for the K_c data. The K_{cb} data for the GDD scale peaked before heading in 1991-1992 and 1992-1993 seasons with values of 1.00 and 0.90, respectively (fig. 8). In the 1989-1990 season the peak K_{cb}, 0.86, for the GDD scale did not occur until well after heading (fig. 8). The GDD scale did extend and smooth the temporal period of peak K_{cb} values almost symmetrically around the heading date (fig. 8). The K_{cb} curves for the day time scale showed wide variation for the individual years and rather large differences compared with the winter wheat K_{cb} curve from Idaho (Wright, 1982). The K_{cb} curve fits for the two time scales affected the K_{cb} values as well. The K_{cb} values for the GDD time scale were slightly lower for the peak time periods (table 4). Mean peak K_{cb} values were 0.94 for the day scale and 0.90 for the GDD scale. For the day scale, peak K_{cb} values occurred near heading in 1991-1992 and in 1992-1993, but they occurred about 10 days after heading in 1989-1990 (fig. 7). Wright (1982) presented K_{cb} values (table 4 and fig. 7) which differ from values presented here. Part of this disagreement can be due to the differing winter wheat development periods at Bushland, Texas, compared with those at Kimberly, Idaho. The Bushland harvest dates were about 40 days earlier than at Kimberly, and heading and rapid growth were about 32 days earlier at Bushland, while seeding dates were about 8 days earlier at Bushland. In addition, Wright (1982) presented K_{cb} values for a single winter wheat season. Peak K_{cb} from this study reached 1.00 only in the 1991-1992 season, and peak K_c values (table 5) reported here are less than peak K_c values of 1.00 reported by Wright (1982) and of 1.10 reported by Meyer and Green (1981) using a different reference ET equation. Our peak K_c and K_{cb} values would be even lower after converting the ET_r value to ET_{kim} (table 3; mean $ET_{kim}/ET_r = 1.123$). With full ground cover (LAI ≥ 3) and well-watered conditions, Meyer et al. (1987) reported that lysimeter-measured wheat ET exceeded potential ET computed with ET_{p48} (Penman, 1948) (eq. 2) by about 18% at Griffith, New South Wales, Australia (CSIRO), and ET_{fao} also underpredicted measured ET as did the combination equation using the Wright and Jensen (1978) wind function. They derived a local wind function that reduced the underprediction to 1.5%.

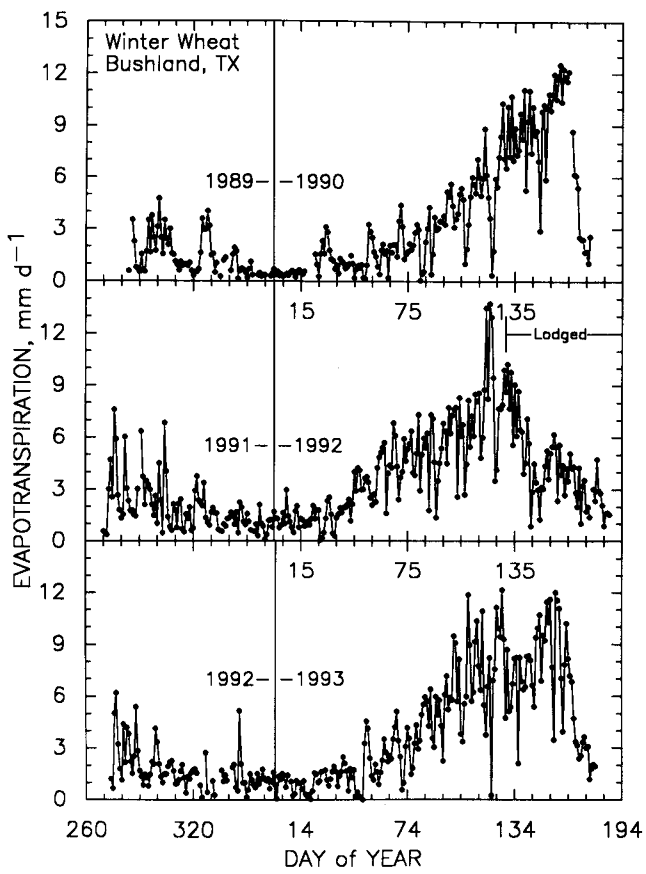

Figure 6–Measured daily ET for sprinkler irrigated winter wheat at Bushland, Tex., for 1989-1990 (top), 1991-1992 (middle), and 1992-1993 (bottom) growing seasons.

The K_{cb} curves for each season responded to the differing crop growth patterns (fig. 4) that characterized each growing season. The seasonal K_{cb} curves from Wright (1982) used an effective planting date of 15 February and an effective emergence date of 1 March with an actual planting date of 10 October and an actual emergence date of 25 October. This was simply a method to fit a curve to the K_{cb} values to a day time scale for the spring growth and summer seasons. The GDD time scale permitted the

Table 4. Basal crop coefficients, K_{cb}, for winter wheat at Bushland, Tex.

Planting Date Month/Day	Season	Basal Crop Coefficient, K_{cb} (fraction)										
		Time from Planting to Heading (%)										
		0	10	20	30	40	50	60	70	80	90	100
10/10 (02/20)*	1989-1990	0.26	0.29	0.32	0.37	0.40	0.46	0.52	0.59	0.67	0.77	0.84
09/27 (01/01)	1991-1992	0.26	0.29	0.36	0.44	0.59	0.69	0.82	0.91	0.96	0.99	0.99
09/29 (01/01)	1992-1993	0.34	0.34	0.34	0.37	0.44	0.54	0.62	0.70	0.80	0.91	1.00
	Mean	0.29	0.31	0.34	0.39	0.48	0.56	0.65	0.73	0.81	0.89	0.94
10/10 (02/15)	Wright (1982)	0.15	0.15	0.15	0.30	0.55	0.80	0.95	1.00	1.00	1.00	1.00
		Time after Heading (d)										
		0	10	20	30	40	50	60	70	80		
	1989-1990	0.84	0.88	0.84	0.69	0.47	0.24	—	—			
	1991-1992†	0.99	0.95	0.87	0.75	0.58	0.39	0.21	0.06			
	1992-1992	1.00	0.99	0.90	0.71	0.48	0.26	—	—			
	Mean	0.94	0.94	0.87	0.72	0.51	0.30	—	—			
	Wright (1982)	1.00	1.00	1.00	1.00	0.95	0.50	0.20	0.10	0.05		
		Growing Degree Days (° C–d)										
		0	200	400	600	800	1,000	1,200	1,400	1,600	1,800	2,000
	1989-1990	0.10	0.13	0.17	0.17	0.14	0.15	0.31	0.55	0.71	0.77	0.83
	1991-1992	0.08	0.10	0.23	0.33	0.30	0.33	0.54	0.81	0.95	0.96	0.97
	1992-1993	0.15	0.17	0.23	0.28	0.33	0.47	0.69	0.86	0.89	0.88	0.92
	Mean	0.11	0.13	0.21	0.26	0.26	0.32	0.51	0.74	0.85	0.87	0.91
		Growing Degree Days (° C–d)										
		2,000	2,200	2,400	2,600	2,800	3,000					
	1989-1990	0.83	0.89	0.78	0.45	—	—					
	1991-1992†	0.97	0.98	0.87	0.61	0.38	0.24					
	1992-1993	0.92	0.88	0.63	0.29	—	—					
	Mean	0.91	0.92	0.76	0.45	0.38	0.24					

	Planting to Heading		Heading to Harvest		Planting	Heading
	Days	GDD (° C–d)	Days	GDD (° C–d)	Date	Date
1989-1990	211 (78)*	1,799 (796)	48	957	10/10/89	05/09/90
1991-1992	213 (118)	1,821 (999)	70	1,271	09/27/91	04/27/92
1992-1993	218 (125)	1,716 (957)	54	1,016	09/29/92	05/05/93

* Effective dates in parenthesis.
† Crop was lodged after heading.

complete seasonal K_{cb} curve to be presented on one graph and a single X-axis scale (fig. 8). No previous studies of K_{cb} curves for winter wheat have presented data for the fall and winter periods. Winter dormancy is not continuous in the Southern High Plains, and winter wheat continues to grow and extract soil water to meet the evaporative demand during winter. During this period, leaf growth cycles between new leaf growth and leaf die back. We used an effective planting date of 20 February for the 1989-1990 season and 1 January for the other seasons. The 1989-1990 wheat crop was planted later than the other crops, grew less in the fall, and consequently took longer to achieve full-ground cover in the spring. In 1989-1990, the LAI was only 2.5 in late April compared with LAIs above 6 in 1991-1992 and above 3.5 in 1992-1993 at the same time (fig. 4).

Winter wheat also matures during a highly variable thermal regime in the Southern High Plains. Mean temperatures during winter wheat grain filling directly affect the length of the grain filling period (Wiegand and Cuellar, 1981), and the subsequent senescence of the crop. The period between heading and harvest can vary by as much as 20 days (see the 1991-1992 growing season compared with the 1989-1990 and 1991-1992 growing seasons shown in fig. 7 or table 4). Clearly, both LAI and the phenology of winter wheat (Ritchie, 1991) are difficult to characterize in this environment, and both affect the K_{cb} values.

The GDD time scale compared to the day scale had inflection points near winter solstice of each year. The GDD time scale reduced the variability between the 1991-1992 and 1992-1993 growing seasons substantially (fig. 8), but these two seasons still differed from the 1989-1990 season as discussed above. The GDD accumulations from planting (P) to winter solstice (WS), WS to heading (HD), emergence (E) to beginning grain fill (five days after anthesis) (BGF), BGF to physiological maturity (PM), and emergence to harvest (HV) are given below for each growing season:

Season	P to WS	WS to HD	E to BGF	BGF to PM	P to HV
1989-1990	652	1,147	1,883	488	2,756
1991-1992	780	1,042	1,926	642	3,092
1992-1993	697	1,019	1,758	656	2,732

The GDD accumulation between emergence and terminal spikelet formation depends on several genetic factors that affect vernalization, photoperiod response, and phyllochron period (Ritchie, 1991). Therefore, the prediction of ΣGDD required for heading, physiological maturity, etc. depends on several factors in addition to simple climatic indices. Length of the grain filling period (see BGF to PM above)

Table 5. Mean crop coefficients, K_c, for sprinkler irrigated winter wheat at Bushland, Texas

Planting Date Mo/Day	Season	Basal Crop Coefficient, K_{cb} (fraction) — Time from Planting to Heading (%): 0	10	20	30	40	50	60	70	80	90	100
10/10 (02/20)*	1989-90	0.31	0.35	0.38	0.42	0.45	0.49	0.54	0.60	0.66	0.74	0.80
09/27 (01/01)	1991-92	0.34	0.35	0.38	0.44	0.54	0.66	0.79	0.88	0.92	0.94	0.94
09/29 (01/01)	1992-93	0.38	0.35	0.32	0.33	0.41	0.52	0.60	0.68	0.74	0.81	0.88
	Mean	0.34	0.35	0.36	0.40	0.47	0.56	0.64	0.72	0.77	0.83	0.87
10/10 (02/15)	Wright (1982)	0.30	0.30	0.30	0.50	0.75	0.90	0.98	1.00	1.00	1.00	1.00
	Meyer and Green (1981)	0.24	0.20	0.20	0.20	0.30	0.44	0.59	0.76	0.91	1.04	1.10

Season	Time after Heading (d): 0	10	20	30	40	50	60	70	80
1989-90	0.80	0.83	0.79	0.66	0.47	0.28	——	——	
1991-92†	0.94	0.90	0.84	0.72	0.57	0.41	0.26	0.27	
1992-92	0.88	0.88	0.83	0.69	0.52	0.36	——	——	
Mean	0.87	0.87	0.82	0.69	0.52	0.35	——	——	
Wright (1982)	1.00	1.00	1.00	1.00	0.95	0.55	0.25	0.15	0.10

Season	Growing Degree Days (° C–d): 0	200	400	600	800	1,000	1,200	1,400	1,600	1,800	2,000
1989-90	0.11	0.36	0.35	0.26	0.23	0.28	0.38	0.53	0.67	0.75	0.76
1991-92	0.12	0.26	0.54	0.59	0.43	0.36	0.52	0.78	0.90	0.92	0.93
1992-93	0.37	0.34	0.34	0.34	0.34	0.44	0.64	0.79	0.81	0.79	0.84
Mean	0.20	0.32	0.41	0.40	0.33	0.36	0.51	0.70	0.79	0.82	0.84

Season	Growing Degree Days (° C–d): 2,000	2,200	2,400	2,600	2,800	3,000
1989-90	0.76	0.78	0.75	0.48	——	——
1991-92†	0.93	0.91	0.78	0.58	0.44	0.32
1992-93	0.84	0.85	0.64	0.30	——	——
Mean	0.84	0.85	0.72	0.45	0.44	0.32

Season	Planting to Heading: Days	Planting to Heading: GDD (° C–d)	Heading to Harvest: Days	Heading to Harvest: GDD (° C–d)	Planting Date	Heading Date
1989-90	211 (78)*	1,799 (796)	48	957	10/10/89	05/09/90
1991-92	213 (118)	1,821 (999)	70	1,271	09/27/91	04/27/92
1992-93	218 (125)	1,716 (858)	54	1,016	09/29/92	05/05/93

* Effective dates in parenthesis.
† Crop was lodged after heading.

depends largely on temperature during the grain-fill stage (Wiegand and Cuellar, 1981). The grain-fill duration (GFD) for these three seasons was linearly related to mean air temperature during the grain-fill period GFD (d) = 79.5 – 2.32 T_{gf}, r^2 = 0.948, $S_{y/x}$ = 2.2 d, where T_{gf} is the mean air temperature in ° C during the grain-fill period. This

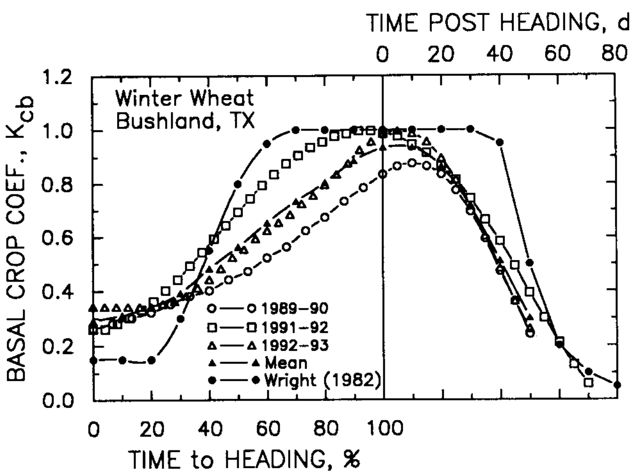

Figure 7–Basal crop coefficient, K_{cb}, curves for the 1989-1990, 1991-1992, and 1992-1993 winter wheat growing season in relation to percent time from planting to heading and time in d post heading.

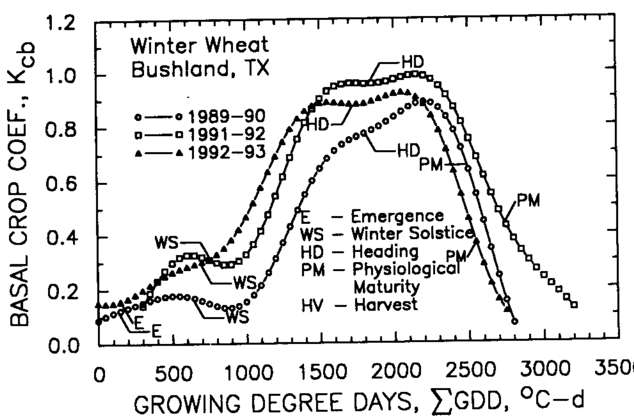

Figure 8–Basal crop coefficient, K_{cb}, curves for the 1989-1990, 1991-1992, and 1992-1993 winter wheat growing season in relation to growing degree days. The symbols E, WS, HD, and PM represent dates of emergence, winter solstice, heading, and physiological maturity, respectively.

relationship is similar to ones reported by Wiegand and Cuellar (1981) with slopes of –3.65 d ° C^{-1} and –2.6 d° C^{-1} and intercepts of 110 and 68 days for two growing seasons.

Combination ET equations (eqs. 2 through 4) and the Penman-Monteith ET equation (eq. 1) should be strictly applied to instantaneous energy balance and weather parameters and not daily time-averaged parameters (Van Bavel, 1966). However, in most cases time-averaged daily data have produced acceptable results using various combination equations or the PM equation. The apparent discrepancy between the peak K_{cb} values at Bushland and other locations is attributed largely to the much stronger winds and the high vapor pressure deficits at Bushland, but could also be due to other crop factors such as canopy surface resistance (r_c) and LAI. An example of the impact of these variables on ET of winter wheat and predictions of ET_r with daily climatic data is given below. In 1992, a windy day preceded a calm day (for Bushland) on 28 and 29 April when most other climatic parameters were similar with near maximum LAI and ground-cover and six and seven days after a 30-mm, irrigation but with a profile soil water content still above 85% of field capacity:

Day	R_s MJ m^{-2}	T_{max} ° C	T_{min} ° C	T_{avg} ° C	T_{dew} ° C	U_{2g} m s^{-1}	ET_r mm d^{-1}
28 April (119)	26.1	30.3	11.1	20.1	4.7	5.01	11.7
29 April (120)	26.7	28.4	7.8	18.3	4.1	2.34	7.9

Crop height was 0.76 m, and the LAI was 7.0. The wheat was at heading but no lodging had occurred yet.

On 28 April (DOY 119), 2-m wind speeds over the grass weather station averaged over 4 m s^{-1} until 0600, then declined to 2.5 m s^{-1} at 0815, increased to 8.4 m s^{-1} at 1215, and remained over 3.5 m s^{-1} until 2215. On 29 April (120), 2-m wind speeds were below 3.0 m s^{-1} until after 1700, except for the 30-min periods at 0800 to 0830 and 1400 to 1430. An instantaneous Penman-Monteith ET equation (same as eq. 1) for 30-min periods was compared with 30-min ET rates (fig. 9). Both R_n (REBS Q*6 net radiometer) and G (REBS TH-1 heat flux plates at 50 mm

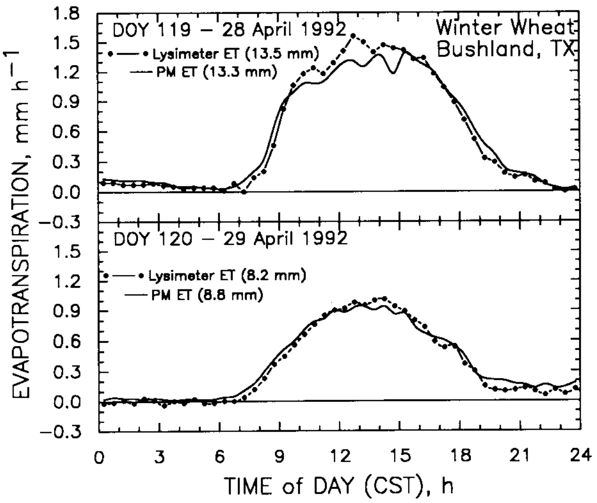

Figure 9–Half-hour measured ET for irrigated winter wheat (crop height was 0.76 m and LAI was 7.0) on 28 April 1990 (DOY 119) and 29 April (DOY 120) and computed ET using the Penman-Monteith equation with r_a and r_c calculated following Allen et al. (1989).

and calorimetric corrections for heat storage changes in the 0- to 50-mm layer of soil with thermocouples at 20- and 40 mm depths) were measured at the lysimeter (see Dusek et al., 1987, for details) for the 30-min periods. The instantaneous Penman-Monteith ET calculation used 30-min measured R_n and G, wet- and dry-bulb temperatures (ventilated psychrometer; Dusek et al., 1993), and wind speed (Met-One 014A cup anemometer) for the northeast lysimeter. Air temperatures and wind speeds were measured at 2.97 m above the ground (2.2 m above the wheat crop) at the lysimeter.

Actual LAI was used to estimate r_c following Allen et al. (1989) (eq. 27 in Appendix I), and r_a was computed using the wheat crop height and the methods described in Appendix I. The instantaneous Penman-Monteith ET equation accurately predicted total ET for both days [within 0.2 mm (< 1% under) on DOY 119 and 0.6 mm (7% over) on DOY 120]; however, it tended to overestimate nighttime ET on DOY 119 with the strong winds before dawn and likewise on DOY 120 with moderate evening winds (after 1815 2-m winds exceeded 2.0 m s^{-1} for most of the evening and night). The large difference in nighttime ET rates with windy conditions (0000 to 0600 and 2000 to 2200 on DOY 119 and 2000 to 2400 on DOY 120) with values approaching 0.10 mm h^{-1} for these periods or higher in contrast with the ET rates less than 0.05 mm h^{-1} under the calm nighttime conditions (0000 to 0600 on DOY 120). The instantaneous Penman-Monteith ET equation underestimated peak ET rates on DOY 120, but even more so on DOY 119 under the stronger daytime winds. The daily 0.5-m-tall alfalfa reference ET_r was 12% and 5% lower than E_l on DOY 119 and DOY 120, respectively. The instantaneous Penman-Monteith ET equation performed much better on the windy day (DOY 119), even using the same simplified expression for r_c (a diurnal constant as used here), in estimating the wheat ET than the daily ET_r computed from daily climate data. The difference between the instantaneous and daily Penman-Monteith ET equation was 0.9 mm on the calm day (DOY 120), but was 1.6 mm on the windy day (DOY 119).

A sensitivity analysis was conducted using data from DOY 120 to examine how changes in LAI and leaf diffusion resistance (r_l) (eq. 29 in Appendix I) would affect the Penman-Monteith ET equation (called ET_{pm}). This showed that $\partial ET_{pm}/\partial LAI$ was 0.15 mm d^{-1} per unit LAI, and $\partial ET_{pm}/\partial r_l$ was 0.011 mm d^{-1} per s m^{-1}. The ET_{pm} value was relatively insensitive to these parameters although errors in either one would cause some bias. On DOY 120 in 1992, an r_l value of 150 s m^{-1} for a LAI of 7.0 and a LAI value of 5 for an r_l of 100 s m^{-1} provided the closest agreement between ET_{pm} and ET_l. Steiner et al. (1991) reported an r_l value of 162 s m^{-1} provided good agreement between ET_l for sorghum using a daily Penman-Monteith ET equation like ET_r. Clearly, estimates of r_l and LAI and diurnal patterns of wind and vapor pressure deficit affect estimated ET using the daily Penman-Monteith ET equation. These results certainly demonstrate a potential for instantaneous ET models to more correctly estimate ET if R_n, G, and r_l can be accurately modeled. However, r_l should be affected by solar irradiance (Idso, 1983) and soil surface wetness would necessitate a multilayer Penman-Monteith model (Shuttleworth and Wallace, 1985;

Shuttleworth and Gurney, 1990) although Raupach and Finnigan (1988) argued that both types of models need to be examined.

The above results indicate that the crop coefficient concept may need additional validation, particularly as it may apply to winter wheat. In particular, individual season growth conditions and perhaps even environmental and management factors can affect the crop coefficients (Neale et al., 1989; Jagtap and Jones, 1989). It appears that the ground cover, LAI, and/or crop height could be used to *normalize* the time scale in some manner. This is beyond the scope of this article but may be the subject of future applications of the crop coefficient approach for irrigation scheduling models.

Summary and Conclusions

Evapotranspiration from sprinkler irrigated winter wheat is affected by the high spring winds and associated high vapor pressure deficits that result in large energy advection in the Southern High Plains. Daily ET rates for winter wheat exceeded 12 mm d^{-1} on a few days, and several weeks had ET rates exceeding 60 mm wk^{-1}. Seasonal ET amounts varied from 791 to 950 mm for sprinkler irrigated winter wheat managed for high grain yields in this environment.

Reference ET methods each responded differently to the climatic variables in this region. In particular, the alfalfa reference ET equations (Allen et al., 1989; Jensen et al., 1990) predicted high daily ET rates exceeding 16 mm d^{-1} in a few cases. Empirical correction factors (multipliers times reference ET) to account for low day/night wind ratios, high daytime wind speeds, and low maximum relative humidity (Doorenbos and Pruitt, 1977) could be less than 0.7 in certain situations that occur periodically in this environment. Daily reference ET models are not well adapted for the Southern High Plains. In particular, several widely used radiation-temperature-based models (Priestley-Taylor, Jensen-Haise, and CERES-Wheat) severely underpredicted daily alfalfa "reference" ET rates and daily maximum winter wheat ET rates at Bushland. The reference ET method clearly must be evaluated and compared with existing "standard" ET methods when this type of climatic variability is routine. All reference ET equations evaluated contained significant bias when applied at Bushland for these winter wheat seasons.

Basal and mean crop coefficient values were computed and summarized for three growing seasons at Bushland. The K_{cb} curves on a daytime scale were more variable than those presented on a GDD time scale. Leaf area index and mean temperature during grain filling (anthesis to maturity) were shown to affect these K_{cb} curves. The GDD time scale reduced the postheading variation in the K_{cb} curves for the three seasons. Peak K_{cb} was less than reported from other locations, and the differences are attributed to specific cultivars, seasonal climatic patterns, and seasonal differences in crop growth patterns. These differences certainly emphasize the difficulty in extrapolating crop coefficients to other environments, and in applying crop coefficients in individual years with differing crop development patterns.

The instantaneous Penman-Monteith ET equation accurately predicted winter wheat ET on two consecutive days (one with high wind and one with low wind) when used with instantaneous (half-hour) climatic parameters. However, both LAI and r_l affected the ET predictions. In particular, r_l may be difficult to properly characterize for diurnal conditions because the single-layer Penman-Monteith model is affected by both plant and soil properties.

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APPENDIX I

The constants required to compute ET_r and ET_o are:

h_a = 0.50 alfalfa crop height (m)
h_g = 0.12 grass crop height (m)
α = 0.23 albedo (fraction)
ε_c = 0.98 emissivity (fraction)
C_s = 2.1 soil specific heat (MJ $m^{-3}\,°C^{-1}$)
d_s = 0.18 soil depth in m for computing soil heat flux
r_l = 100.0 leaf diffusion resistance (s m^{-1})

The equations used to compute the parameters in the Penman-Monteith ET equation are taken from Allen et al. (1989) and Jensen et al. (1990) mainly and are provided here to document the methods used in this work.

$$R_n = (1 - \alpha)\, R_s - R_{nl} \qquad (11)$$

$$R_{nl} = [a_c(R_s/R_{so}) + b_c]\,(a_1 + b_1\sqrt{e_d})\,\sigma\,(T^4_{kmax} + T^4_{kmin})/2 \qquad (12)$$

where

α	= albedo (decimal fraction)
R_{nl}	= net long-wave radiation in MJ m^{-2} d^{-1}
a_c and b_c	= cloud factors (a_c = 1.35; b_c = –0.35) (Jensen et al., 1990)
R_s	= solar radiation in MJ m^{-2} d^{-1}
R_{so}	= clear day solar radiation in MJ m^{-2} d^{-1}
a_1 and b_2	= emissivity factors (a_1 = 0.35; b_1 = –0.14) (Jensen et al., 1990)
σ	= Stefan Boltzman constant (4.90×10^{-9} MJ m^{-2} d^{-1} K^{-4})
T_{kmax}	= daily maximum air temperature in K and T_{kmin} is daily minimum air temperature in K

Clear day solar radiation was computed as:

$$R_{so} = 0.75\,(37.6\,d_r)\,[\omega_s \,\mathrm{Sin}(\varphi)\,\mathrm{Sin}(\delta) + \mathrm{Cos}(\varphi)\,\mathrm{Cos}(\delta)\,\mathrm{Sin}(\omega_s)] \qquad (13)$$

where

d_r = relative distance from Earth to Sun (decimal fraction)
ω_s = sunset hour angle
δ = solar declination angle
φ = latitude angle (0.614 for Bushland, Tex.)

All angles are in radians, and these parameters were computed from:

$$\omega_s = \mathrm{Arcos}\,[-\mathrm{Tan}(\varphi)\,\mathrm{Tan}(\delta)] \qquad (14)$$

$$d_r = 1 + \left[0.033\,\mathrm{Cos}\left(\frac{2\,\pi\,\mathrm{DOY}}{365}\right)\right] \qquad (15)$$

$$\delta = 0.4093\,\mathrm{Sin}\left(\frac{2\,\pi\,\mathrm{DOY}}{365} - 1.39\right) \qquad (16)$$

where DOY is the integer day of the year following Jensen et al. (1990) and Allen et al. (1989).

Daily soil heat flux was computed as:

$$G = C_s\,d_s\,(T_i - \overline{T_3}) \qquad (17)$$

where T_i is mean daily air temperature in ° C [(T_{max} + T_{min})/2] for DOY i, and $\overline{T_3}$ is the mean air temperature in ° C for the three previous days following Wright (1982).

Other parameters for the Penman-Monteith ET equation were computed from:

$$T = (T_{max} + T_{min})/2 \qquad (18)$$

$$e_o = 0.611\,\mathrm{Exp}\left[\frac{17.27\,T}{(T + 237.3)}\right] \qquad (19)$$

$$e_d = 0.611\,\mathrm{Exp}\left[\frac{17.27\,T_{dew}}{(T_{dew} + 237.3)}\right] \qquad (20)$$

$$e_a = \frac{0.611\,\mathrm{Exp}\left[\frac{17.27\,T_{max}}{(T_{max} + 237.3)}\right] + 0.611\,\mathrm{Exp}\left[\frac{17.27\,T_{min}}{(T_{min} + 237.3)}\right]}{2} \qquad (21)$$

$$\lambda = 2.501 - \frac{T}{423.5} \qquad (22)$$

$$\Delta = \frac{4\,098\,e_o}{(T + 237.3)^2} \qquad (23)$$

$$T_{kv} = \frac{T_k}{\left(1 - \frac{0.378\,e_d}{P_b}\right)} \qquad (24)$$

$$\rho = \frac{1000\,P_b}{T_{kv}\,R} \qquad (25)$$

where

T	= mean daily air temperature in ° C
T_{min}, T_{max}, T_{dew}	= daily minimum and maximum air temperatures and mean daily dew point temperature in ° C
e_o	= saturated vapor pressure in kPa at T
e_a	= mean saturated vapor pressure in kPa at T_{max} and T_{min}
e_d	= saturated vapor pressure at T_{dew}
P_b	= barometric pressure in kPa
T_{kv}	= virtual air temperature in K for T
R	= universal gas constant (287 J kg^{-1} K^{-1})

Alfalfa and grass canopy resistance parameters for the Penman-Monteith ET equations were computed as follows:

$$LAI_a = 5.5 + 1.5\,\ln(h_a) \qquad (26)$$

$$LAI_g = 24\,h_g \qquad (27)$$

$$r_{ca} = \frac{r_l}{0.5\,LAI_a} \qquad (28)$$

$$r_{cg} = \frac{r_l}{0.5\,LAI_g} \qquad (29)$$

$$r_{aa} = \frac{\ln\left(\frac{Z_m - d_a}{Z_{oma}}\right)\ln\left(\frac{Z_h - d_g}{Z_{oha}}\right)}{k^2\,U_{2a}} \qquad (30)$$

$$r_{ag} = \frac{\ln\left(\frac{Z_m - d_g}{Z_{omg}}\right) \ln\left(\frac{Z_h - d_g}{Z_{oha}}\right)}{k^2 U_{2g}} \quad (31)$$

where

- r_{ca}, r_{aa} = alfalfa reference canopy surface resistance and aerodynamic resistances (s m^{-1})
- r_{cg}, r_{ag} = grass reference canopy surface resistance and aerodynamic resistance (s m^{-1})
- LAI_a, LAI_g = leaf area index (fraction) for alfalfa and grass
- r_l = leaf resistance in s m^{-1} [taken as 100 s m^{-1} following Allen (1986), Allen et al. (1989), and Jensen et al. (1990)]
- Z_m = wind speed measurement height in m (2.0 m)
- Z_h = air temperature/relative measurement height in m (1.50 m)
- d_a, d_g = zero plane displacement heights in m for alfalfa and grass
- Z_{oma}, Z_{omg} = roughness lengths in m for momentum for alfalfa and grass
- Z_{oha}, Z_{ohg} = roughness lengths in m for heat and water vapor for alfalfa and grass
- k = von Karman's constant (0.41)
- U_{2a}, U_{2g} = 2-m elevation wind speeds in m s^{-1} over alfalfa and grass

The alfalfa and grass aerodynamic parameters were estimated as follows:

$$d_a = 0.667\ h_a \quad (32)$$

$$d_g = 0.667\ h_g \quad (33)$$

$$Z_{oma} = 0.123\ h_a \quad (34)$$

$$Z_{omg} = 0.123\ h_g \quad (35)$$

$$Z_{oha} = 0.1\ Z_{oma} \quad (36)$$

$$Z_{ohg} = 0.1\ Z_{omg} \quad (37)$$

Wind speed over the grass at the weather station was extrapolated to the same height (2.0 m) over the reference alfalfa following Allen et al. (1989) as follows:

$$U_{2a} = U_{2g} \frac{\ln\left(\frac{Z_{elb} - d_g}{Z_{omg}}\right) \ln\left(\frac{Z_m - d_a}{Z_{oma}}\right)}{\ln\left(\frac{Z_{elb} - d_a}{Z_{oma}}\right) \ln\left(\frac{Z_m - d_g}{Z_{omg}}\right)} \quad (38)$$

where Z_{elb} was taken as 10 m following Steiner et al. (1991). Equation 38 simplifies to $U_{2a} = 0.873\ U_{2g}$ when the appropriate constants are substituted.