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Impact Of Microclimatic Data Measured Above Maize And Grass Canopies On Penman-Monteith Reference Evapotranspiration Calculations

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Impact of Microclimatic Data Measured above Maize and Grass Canopies on Penman-Monteith Reference Evapotranspiration Calculations

S. Irmak, L. O. Odhiambo

Abstract. *Estimation of reference evapotranspiration (ET_{ref}) using measured microclimatic data and the Penman-Monteith (PM) method provides a powerful means of quantifying actual plant evapotranspiration (ET_a) needed for use in various disciplines. When applying the PM method to estimate ET_{ref}, it is desirable to measure the required microclimatic data over a reference grass or alfalfa surface rather than above non-reference surfaces. However, in reality, establishing and maintaining a reference surface for long periods of time is a difficult task. Other surface energy balance systems, such as the Bowen ratio energy balance system (BREBS), eddy covariance system, and surface renewal, are increasingly used to measure surface energy fluxes along with the microclimatic data above various plant canopies. These systems could be another source of data for ET_{ref} estimations when reference weather station data are not available due to logistical difficulties associated with establishing and maintaining a separate reference weather station. In many cases, data measured above other vegetation surfaces using the surface energy balance systems are the only source of data for ET_{ref} and ET_a estimations due to the absence of reference weather stations. There is little information on how microclimatic data measured above different plant canopies impact the calculated ET_{ref} if used in the PM method in place of data collected from a reference surface. This study compares data measured above grass and maize (Zea mays L.) canopies and assesses how the variables measured above two canopies impact ET_{ref} calculated using the ASCE standardized Penman-Monteith (ASCE-EWRI PM) equation. Two years (2005 and 2006) of hourly microclimatic data measured above a grass surface using an automated weather station and above a maize canopy using BREBS installed on a well-watered maize field were used. The results obtained indicate very good agreements between the microclimatic variables measured above grass and maize, and between ET_{ref} calculated with data measured above the two surfaces. The measured rainfall was the same for both sites (316 and 323 mm in 2005 for the weather station and BREBS, respectively, and 368 and 366 mm in 2006). The main difference between the two surfaces was in wind speed (u_2) and aerodynamic resistance (r_a). On a seasonal average basis, u_2 was 15% and 20% higher over the grass canopy than the maize canopy for 2005 and 2006, respectively. The maximum difference in r_a between the two surfaces occurred when the maize was at its maximum height (2.45 m). On a seasonal average, the r_a above the maize canopy was 37 s m^{-1} higher than the r_a above the grass surface. However, the impact of u_2 and r_a on ET_{ref} was insignificant. The grass and alfalfa-reference ET (ET_o and ET_r) estimated using the data measured above maize ($ET_{o\text{-}maize}$ and $ET_{r\text{-}maize}$) and above grass ($ET_{o\text{-}grass}$ and $ET_{r\text{-}grass}$) were very similar in both years. In 2005, $ET_{o\text{-}maize}$ (816 mm) and $ET_{o\text{-}grass}$ (824 mm) were within 1%, and $ET_{r\text{-}maize}$ (1,033 mm) and $ET_{r\text{-}grass}$ (1,070 mm) were within 3%. The same percentages were obtained in 2006 ($ET_{o\text{-}maize}$ = 671 mm, $ET_{o\text{-}grass}$ = 675 mm, $ET_{r\text{-}maize}$ = 838 mm, $ET_{r\text{-}grass}$ = 868 mm). Thus, in practice, data measured above a well-watered maize canopy can be a substitute for the microclimatic data measured above a reference surface in ET_{ref} estimations when "reference" weather station data are not available to solve the PM equation in areas with similar rainfall (>300 mm) during the growing season, as observed in this study.*

***Keywords**. Bowen ratio energy balance, Evapotranspiration, Microclimate, Penman-Monteith, Plant canopy, Reference surface.*

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Estimating reference evapotranspiration (ET_{ref}) from measured microclimatic data and the Penman-Monteith (PM) method provides a means of quantifying plant evapotranspiration (ET_a) needed for studies related to water resources planning and assessment, hydrologic studies, surface energy balance, soil-plant-atmosphere interactions, and plant physiology research. In addition to direct measurement techniques, the ET_a of a given vegetation surface under specific sets of conditions is commonly calculated from the "two step" approach, which consists of multiplying ET_{ref} with plant-specific coefficients (k) to obtain ET_a (i.e., $ET_a = ET_{ref} \times k$) (Doorenbos and Pruitt 1977; Wright 1982). ET_{ref} is estimated from a uniform grass or alfalfa-reference surface using fixed surface and aerodynamic resistance values (r_s and r_a, respectively) in the PM equation. Besides the "two step" approach, the PM method can also be used to estimate ET_a in a "one step" approach by using plant-specific r_s and r_a. The r_s term describes the leaf resistance to water vapor flow through the leaf stomata openings. The r_a term describes the resistance from vegetation upward and involves friction from air flowing over vegetative surfaces.

Over the last decades, numerous derivations of the PM method have been developed to estimate ET_{ref}. However, using different ET_{ref} methods can results in different ET_{ref} and k values for the same vegetation surface, even in the same location, causing confusion as to which method to use to determine ET_{ref} and k. Three widely used derivations of the PM method are: the full form of the ASCE Penman-Monteith (ASCE-PM) equation (Jensen et al., 1990), the FAO-56 Penman-Monteith (FAO-56 PM) equation (Allen et al., 1998), and the standardized ASCE-EWRI Penman-Monteith (ASCE-EWRI PM) equation (ASCE-EWRI, 2005). These three equations are essentially similar in structure, but differ in some equation coefficients. The ASCE-EWRI PM equation has been recommended for use by the ASCE Evapotranspiration in Irrigation and Hydrology Committee in order to standardize the ET_{ref} calculation procedures to improve transferability of k values for different plant species between regions (Walter et al., 2000; ASCE-EWRI 2005).

The ET_{ref} computed by the PM method is a representation of the evapotranspiration rate at which water will be evaporated from a "reference" surface, if water is readily available within the plant root zone. The use of the ET_{ref} concept permits a physically realistic characterization of the effect of the microclimate of a field on the evaporative transfer of water from the soil-plant system to the atmospheric air layers overlying the field (Wright, 1996). Ideally, ET_{ref} characterizes the magnitude of the evaporative demand of the surrounding atmosphere of a vegetation surface. The demand is determined by meteorological conditions, and k indicates the relative ability of a specific plant-soil surface to meet that demand. In addition to the microclimatic drivers such as incoming shortwave or net radiation (R_s or R_n), air temperature (T_a), relative humidity (RH), and wind speed at 2 m height (u_2), ET_{ref} is a function of numerous other controlling variables such as leaf area, soil water status, and morphological and physiological properties of the surface through their influence on the governing energy exchange and aerodynamic diffusion processes within the boundary layer of the surface. Thus, k and ET_{ref} collectively indicate the actual evaporative demand that needs to be met by the vegetation-soil surface.

When applying the PM method to estimate ET_{ref}, it is desirable to measure the required microclimatic data, including R_s or R_n, u_2, RH, T_a, and dewpoint temperature (T_d), over a "reference" grass or alfalfa surface with adequate fetch so that the air passing over the surface saturates with the aerodynamic and vapor conditions of the boundary layer of the vegetation surface representing the reference surface characteristics. The two reference surfaces commonly used for ET_{ref} computations are: (1) a grass surface, which is generally a cool season variety such as tall fescue (*Festuca arundinacea* L.) or perennial ryegrass (*Lolium perenne* L.) clipped to maintain about 0.12 m height throughout the season, actively growing, disease and water stress free, well-fertilized, completely shading the ground, and transpiring at a potential rate (Doorenbos and Pruitt, 1977; Jensen et al., 1990); and (2) an alfalfa (*Medicago sativa* L.) surface, which is mainly applied to varieties typically grown in the U.S. and maintained at about 0.50 m plant height with similar management conditions as described for grass (Wright 1982, Jensen et al., 1990). Both references require a sufficient fetch distance of about 1 to 100 ratio in all directions (i.e., if the wind speed is measured at 2 m, the fetch distance in all directions should be at least 200 m).

The primary objective for a reference surface is to have common microclimatic and aerodynamic characteristics of the surface in which the microclimatic data are collected so that the k values can be more readily transferable between regions for different vegetation. Thus, it can be assumed that when calculating k values as the ratio of ET_a to ET_{ref} (i.e., $k = ET_a/ET_{ref}$), the data gathered from reference surfaces would result in more robust and transferable k values when the same ET_{ref} equation is used. This is because, although the data are from different regions, they are measured above surfaces that have the same or very similar aerodynamic, plant morphological and physiological, and soil water characteristics. However, the challenge is that there are very few weather stations sited over such ideal reference surfaces because of the difficulties associated with the cost and logistics of establishing and, more importantly, maintaining an extensive, actively growing, uniform, well-watered grass or alfalfa surface for long periods of time. Thus, inexorably, a large number of automated weather stations are located on non-reference surfaces. A survey of automated weather station sites in the U.S. indicated that 55% of the sites have a natural vegetation cover, only 25% have grass cover, 1% percent has alfalfa cover, and 19% have no vegetative cover (Hubbard and Brusberg, 1999). Information is not available

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on the prevalence of irrigation and maintenance at the surveyed weather station sites with which to make any assessment of the water stress conditions, plant height, ground cover, and other characteristics of the vegetation in the automated weather station sites.

The requirements for microclimatic data measurements over a reference surface that has well-watered and well-maintained agronomical conditions can be extremely critical, especially in arid and semi-arid regions. The reasons are described in detail by Allen (1996) as: "The rates of ET_{ref} and sensible heat from vegetation surface affect the shape and magnitude of vapor and air temperature profiles. Similarly, the roughness of an evaporating vegetation surface affects the shape and magnitude of wind pattern and velocities above the surface. As ET_{ref} from the surrounding weather station decreases, sensible heat transfer increases, resulting in increased air temperature and reduction in humidity and increase in vapor pressure deficit above the surface." However, while meeting the reference surface requirements can be critical in arid or semi-arid regions, where lack of precipitation can result in advection and/or an increase in sensible heat and cause non-reference conditions, it can be argued that these requirements can be less critical in areas with adequate rainfall (i.e., humid and sub-humid regions). It can also be argued that in areas with adequate rainfall, the atmospheric demand in the surrounding air of the weather station can be close to that at the reference surface, provided that adequate fetch and proper calibration and maintenance of instrumentation exist. Thus, in humid and sub-humid regions, the ET_{ref} is primarily impacted by adequate fetch and instrumentation maintenance/calibration rather than by the aerodynamic and air vapor (well-watered) characteristics of the reference surface. The hypothesis tested in this study is that, in the absence of a reference weather station, the microclimatic data measured above other well-watered vegetation surfaces (i.e., maize canopy) could be an alternative source of data for ET_{ref} estimations.

Recent trends in evapotranspiration studies show that surface energy flux measurement methods, such as the Bowen ratio energy balance system (BREBS), eddy covariance system, surface renewal, and other methods, are periodically used to evaluate latent and sensible heat flux densities above various vegetation canopies, primarily for research purposes. A review of literature shows that BREBS measurements have been used: (1) to quantify evapotranspiration rates above plant canopies (Tanner, 1960; Denmead and McIlory, 1970; Fuchs, 1973; Lang, 1973; Blad and Rosenberg, 1974; Gutierrez and Meinzer, 1994; Cargnel et al., 1996; Todd et al., 2000; Yrisarry and Naveso, 2000; Marin et al., 2005; Hanson and May, 2006; Silva et al., 2007; Zhang et al., 2007; Ito et al., 2008; Irmak and Mutiibwa, 2009a), (2) as a standard to evaluate alternative evapotranspiration measurements or model estimates (Malek and Bingham, 1993; Ortega-Farias et al., 1993; Xing et al., 2008; Zhang et al., 2008; Irmak et al., 2008a), (3) for partitioning ET data into transpiration from plants and evaporation from soil surface components (Massman, 1992; Ashktorab and Pruitt, 1994; Zeggaf et al., 2008); and (4) to calculate crop coefficients (Malek and Bingham, 1993) and surface resistance (Kjelgaard and Stockle, 2001; Irmak et al., 2008b), among many other uses. Several others studies show that eddy correlation system (Swinbank, 1951; Tanner, 1960; Anderson et al., 1984; Kizer and Elliot, 1991; Soegaard and Boegh, 1995; Anthoni et al., 1999; Kordova-Biezuner et al., 2000; Wilson et al., 2001; Paco et al., 2006; Li et al., 2008; Sun et al., 2008) and the surface renewal method (Paw et al., 1995; Snyder et al., 1996; Spano et al., 2000; Zapata and Martinez-Cob, 2001; Castellvi et al., 2006; Castellvi et al., 2008) have also been used for evapotranspiration measurements over a variety of surfaces and for calibration of empirical evapotranspiration models.

In the aforementioned applications of the surface energy balance systems, the microclimatic data are mostly measured above various vegetation canopies and not above a reference grass or alfalfa surface. Although ET_a of vegetation under surface energy systems is directly determined by one of the surface energy balance methods, ET_{ref} is still required for calculating ET_a for other vegetation in the nearby area that is not measured by the surface energy balance systems. Furthermore, at many sites, there are no nearby reference weather stations, and data measured above other vegetation surfaces using the surface energy balance systems are the only source of data for ET_{ref} and ET_a estimations. However, there is a lack of studies that have been conducted to evaluate how such data may impact the calculated ET_{ref} if used in the PM method in place of data collected by a reference weather station sited over a reference grass or alfalfa surface. This article reports the results of a study conducted to: (1) compare the microclimatic data measured above grass and maize (*Zea mays* L.) canopies, and (2) determine the potential impact of the data measured above the maize canopy on ET_{ref} calculations relative to the data measured over the grass surface when the ASCE standardized PM equation is used. Key variables considered in the study were incoming shortwave solar radiation (R_s), air temperature (T_a), wind speed (u_2), relative humidity (RH), calculated dewpoint temperature and aerodynamic resistance (T_d and r_a, respectively), grass and alfalfa-reference evapotranspiration (ET_o and ET_r, respectively), and rainfall.

Materials and Methods

Study Area and Data Collection

The microclimatic data used in this study were measured at the University of Nebraska-Lincoln South Central Agricultural Laboratory (SCAL) near Clay Center, in the south-central part of Nebraska. The site is located at an elevation of 552 m above MSL and lies at 40° 34′ N and 98° 08′ W. The weather in the south-central part of Nebraska is influenced by cold dry continental air masses from Canada during winter and warm moist air from the Gulf of Mexico during summer. The long-term average (1983-2008) annual rainfall is 680 mm, with the majority of the rainfall occurring in the early spring from late April to late June. A summary of long-term monthly average weather variables at the site is presented in table 1. The highest wind speed usually occurs from January to late May and early June, with daily average wind speed showing significant fluctuation ranging from 2 m s^{-1} to over 8 m s^{-1}. The lowest wind speeds usually occur in the summer months. Long-term average air temperature ranges from -5°C in January and December to 25°C in July.

Measurements of the microclimatic data were made during the 2005 and 2006 growing seasons (April-October) at two sites approximately 2 km apart. A grass-reference automated weather station (AWS) operated by the High

Table 1. Summary of long-term average weather variables measured at the automated reference weather station (AWS), Clay Center, Nebraska.

Microclimatic Variable	May	June	July	Aug.	Sept.
Wind speed (m s^{-1})	4.0	3.5	2.9	2.6	3.1
Maximum air temp. (°C)	22.5	28.1	30.3	29.2	25.3
Minimum air temp. (°C)	9.3	14.6	17.3	16.3	10.7
Relative humidity (%)	71.3	70.2	73.2	74.5	68.8
Solar radiation (W m^{-2})	225.0	259.8	259.8	228.5	184.4
Rainfall (mm)	112.0	110.0	93.0	83.0	63.0

Plains Regional Climate Center (HPRCC, http://hprcc1.unl.edu/cgi-hpcc/home.cgi) was used at the first site. The AWS consisted of standard instruments used for measuring climatic variables and was maintained on a natural grass cover that somewhat met the reference conditions criteria. The site was not irrigated. The fetch condition was adequate in all directions of the weather station. The quality and integrity of the measured microclimatic data were assessed using the procedures and guidelines given in Allen (1996) and in the ASCE ET Task Committee Report (ASCE-EWRI, 2005). At the second site, the microclimatic variables, including actual evapotranspiration and other surface energy balance components, were measured using a deluxe version of a Bowen ratio energy balance system (BREBS) (Radiation and Energy Balance Systems, REBS, Inc., Bellevue, Wash.), which was installed in the middle of a 13 ha well-watered maize field. The fetch distance was 520 m in the north-south direction and 280 m in the east-west direction. Rainfall was recorded using a rainfall sensor (model TR-525, Texas Electronics, Inc., Dallas, Tex.). All variables were sampled every 30 s and were averaged and recorded every hour using a data logger and relay multiplexer (models CR10X and AM416, Campbell Scientific, Inc., Logan, Utah). A complete description of all the components, measurements, and operation of the deluxe BREBS is given in Irmak et al. (2008a, 2008b), Irmak and Mutiibwa (2008, 2009b, 2009c). Table 2 provides a summary of the specifications and installation heights of the sensors used to measure the microclimatic variables at the AWS and BREBS.

In 2005, the maize field was planted on April 22 with hybrid Pioneer 33B51 seeds at a rate of 73,000 plants ha^{-1}. The plants emerged on May 12 [20 days after planting (DAP)], reaching full canopy closure on July 2 (71 DAP) and silking growth stage on July 12 (81 DAP). Plant reached physiological maturity stage on September 7 (138 DAP) and was harvested on October 17. In 2006, the field was planted with hybrid Pioneer 33B54 seeds at a rate of 74,130 plants ha^{-1} on May 12. The plants emerged on May 20 (8 DAP), reached full canopy closure on July 8 (57 DAP) and silking growth stage on July 15 (64 DAP). Plant reached maturity stage on September 13 (124 DAP) and was harvested on October 5. In both 2005 and 2006, the planting depth, row spacing, and irrigation treatments were kept the same. The planting depth was 0.05 m and row spacing was 0.76 m with an east-west row direction. The maize field was irrigated using a subsurface drip irrigation system with the drip laterals placed in the middle of every other row (1.52 m) and at a depth of approximately 0.40 m below the soil surface. Irrigation was applied two to three times a week to replenish the soil water content to approximately 90% of the field capacity (FC) in the effective root zone depth (0.90 m). The available soil water in the effective root zone fluctuated between FC and a maximum allowable depletion of 40% to 45% of FC throughout the growing season to avoid crop water stress (Irmak and Mutiibwa, 2008, 2009a, 2009b).

The Standardized ASCE-EWRI Penman-Monteith Equation

The computation of parameters in the standardized ASCE-EWRI-PM equation incorporates procedures for calculating net radiation, soil heat flux, vapor pressure deficit, and air density. In the equation, a constant latent heat of vaporization (2.45 MJ kg^{-1}) and a fixed value for surface albedo (0.23) are used. The coefficients of the ASCE-EWRI-PM equation presume that the microclimatic data are measured over a grass or alfalfa-reference canopy at the weather station and is expressed as:

$$\mathrm{ET}_{ref} = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{C_n}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \quad (1)$$

where ET_{ref} is standardized reference evapotranspiration (mm d^{-1} for daily time step or mm h^{-1} for hourly time step), R_n is net radiation at the grass or alfalfa surface (MJ m^{-2} d^{-1}

Table 2. Summary of specifications and installation heights of the sensors used to measure microclimatic variables at the automated weather station (AWS) above the grass canopy and the Bowen ratio energy balance system (BREBS) installed on a well-watered maize canopy.

	Variable	Instruments[a]	Specified Accuracy	Sensor Height	Sampling Interval	Averaging Interval
AWS	Air temperature	Probe (model HMP35C)	±0.2°C	1.5 m	60 s	1 h
	Relative humidity	Probe (model HMP35C)	±2%	1.5 m	60 s	1 h
	Wind speed	Cup anemometer (model 034B)	0.12 m s^{-1} for WS <10.1 m s^{-1} ±1.1% for WS >10.1 m s^{-1}	3.0 m	60 s	1 h
	Solar radiation	Pyranometer (model LI200X)	±3%	1.5 m	60s	1 h
BREBS	Air temperature	Chromel-constantan thermocouple probe (model TH04015)	±0.0055°C	Avg. of 0.75 m above canopy	30 s	1 h
	Relative humidity	Chromel-constantan thermocouple probe (model TH04016)	±0.033%	Avg. of 0.75 m above canopy	30 s	1 h
	Wind speed	Cup anemometer (model 034B)	0.12 m s^{-1} for WS <10.1 m s^{-1} ±1.1% for WS >10.1 m s^{-1}	3.0 m	30 s	1 h
	Solar radiation	Double-sided total hemispherical radiometer (model THRDS7.1)	±3%	4.5 m	30 s	1 h

[a] Model HMP35C probe from Vaisala Corp., Handar Business Unit, Sunnyvale, Cal.;
Model 034B cup anemometer from Met-One, Grants Pass, Ore.;
Model LI200X pyranometer from LiCor Corp., Lincoln, Neb., and
Models TH04015, TH04016, and THRDS7.1 from Radiation and Energy Balance Systems, Inc., Seattle, Wash.

or MJ m^{-2} h^{-1} for hourly time steps), G is soil heat flux density (MJ m^{-2} h^{-1} for hourly time step and $G = 0$ for daily time step), T is mean daily or hourly air temperature at 1.5 to 2.5 m height (°C), u_2 is mean daily or hourly wind speed at 2 m height (m s^{-1}), e_s is saturation vapor pressure (kPa), e_a is actual vapor pressure (kPa), (e_s - e_a) represents vapor pressure deficit (kPa), Δ is the slope of the saturation vapor pressure-temperature curve (kPa °C^{-1}), γ is the psychometric constant (kPa °C^{-1}), C_n is the numerator constant that changes with reference surface type (grass or alfalfa) and calculation time step (°C mm s^3 Mg^{-1} d^{-1} or °C mm s^3 Mg^{-1} h^{-1}), and C_d is the denominator constant that changes with reference surface type and calculation time step. The unit for the 0.408 coefficient is m^2 mm MJ^{-1}.

The recommended values of reference grass and alfalfa characteristics and coefficients for the ASCE-EWRI-PM equation are given in table 3. Both C_n and C_d are functions of time step and aerodynamic resistance (i.e., reference vegetation type). The value of C_d depends on bulk surface resistance and daytime/nighttime periods. Daytime is defined as occurring when the average R_n during an hourly period is positive. As part of the standardization, the associated equations for calculating r_a and bulk surface resistance have been incorporated into the equation. However, in this study, to investigate the impact of different wind speeds on r_a, within the ASCE-EWRI PM equation r_a was calculated independently from measured plant height following Monteith et al. (1965), Plate (1971), and Brutsaert (1982):

$$r_a = \frac{\ln\left[\frac{z_w - d}{z_{om}}\right]\ln\left[\frac{z_h - d}{z_{oh}}\right]}{k^2 u_2} \quad (2)$$

where z_w is height of wind measurements (2 m), z_h is height of humidity measurements (2 m), h is mean height of reference grass surface (0.12 m and varied for maize canopy), d is zero plane displacement height (0.67h, m), z_{om} is roughness length governing momentum transfer (0.123h, m), z_{oh} is roughness length for transfer of heat and vapor (0.0123h, m), and k is von Karman's constant (0.41). Substituting the above values into equation 2, r_a as a function of u_2 is calculated as:

$$r_a = \frac{208}{u_2} \quad (3)$$

The ASCE-EWRI equation requires wind speed at 2 m, but wind speed at both the weather station and the BREBS site was measured at 3 m. The 3 m wind speed was converted to 2 m using the following logarithmic function:

$$u_2 = u_z \frac{4.87}{\ln(67.8 z_w - 5.42)} \quad (4)$$

where u_z is measured wind speed at z height (m s^{-1}), and z_w is the height of wind speed measurements.

Calculation of Dewpoint Temperature

The T_d reflects the absolute amount of water vapor present in the air and is independent of air temperature, unlike RH. It represents the temperature to which a given parcel of air must be cooled at constant pressure and constant water vapor content in order for saturation to occur. To compare the absolute amounts of air moisture present above the grass and maize canopies, T_d was computed above both surfaces at 7:00 a.m. Central Standard Time (CST) using the following equation (Murray, 1967):

$$T_{d(i)} = \frac{237.3}{\dfrac{1}{\left[\dfrac{\ln\left(\dfrac{RH_i}{100}\right)}{17.27}\right] + \left[\dfrac{T_{a(i)}}{237.3 + T_{a(i)}}\right]} - 1} \quad (5)$$

where $T_{d(i)}$ is dewpoint temperature (°C) for period i, RH_i is average relative humidity (%) for period i, and $T_{a(i)}$ is average air temperature (°C) for period i.

Table 3. Recommended values of reference crop characteristics and coefficients for the ASCE-EWRI Penman-Monteith equation.

Variable	Grass-Reference Surface (ET_o)	Alfalfa-Reference Surface (ET_r)
Vegetation height	0.12 m	0.5 m
Height of measurement		
Wind speed, z_w	3 m	3 m
Air temp. and RH, z_r	1.5 to 2.5 m	1.5 to 2.5 m
Zero-plane displacement height, d	0.08 m	0.08 m[a]
Latent heat of vaporization, λ	2.45 MJ kg^{-1}	2.45 MJ kg^{-1}
Surface resistance, r_s		
Daily	70 s m^{-1}	45 s m^{-1}
Daytime	50 s m^{-1}	30 s m^{-1}
Nighttime	200 s m^{-1}	200 s m^{-1}
R_n cutoff for daytime	>0 MJ m^{-2} h^{-1}	>0 MJ m^{-2} h^{-1}
R_n cutoff for nighttime	≤0 MJ m^{-2} h^{-1}	≤0 MJ m^{-2} h^{-1}
Daily time step value for C_n	900 mm d^{-1}	1600 mm d^{-1}
Hourly time step value for C_n		
Daytime	37 mm h^{-1}	66 mm h^{-1}
Nighttime	37 mm h^{-1}	66 mm h^{-1}
Daily time step value for C_d	0.34 mm h^{-1}	0.38 mm h^{-1}
Hourly time step value for C_d		
Daytime	0.24 mm h^{-1}	0.25 mm h^{-1}
Nighttime	0.96 mm h^{-1}	1.7 mm h^{-1}

[a] Zero-plane displacement height for ET_{ref} assumes that u_2 is measured over clipped grass.

Analyses and Statistics

With appropriate values of the constants C_n and C_d, equation 1 was used to calculate standardized ET_{ref} for both grass (ET_o) and alfalfa (ET_r). All ET_{ref} calculations were made on an hourly time step using microclimatic data measured from both the weather station and the BREBS. In addition, we computed daily ET_{ref} from sum-of-hourly values for daily comparisons. Pairwise comparisons were made for the ET_{ref} calculated with the microclimatic data collected above both surfaces using equation 1. The goodness-of-fit between the data series was evaluated using the coefficient of determination (r^2) and the index of agreement (D) proposed by Legates and McCabe (1999). The r^2 value is insensitive to additive and proportional differences between data sets. Because of these limitations, the index of agreement (D), which is sensitive to additive and proportional differences between datasets, was used as an additional measure to verify the agreements between the data

series. The index of agreement (D) is expressed as (Legates and McCabe, 1999):

$$D = 1.0 - \frac{\sum_{i=1}^{n} \left(X_i - Y_i\right)^2}{\sum_{i=1}^{n} \left(\left|Y_i - \overline{X}\right| + \left|X_i - \overline{X}\right|\right)^2} \tag{6}$$

The index of agreement gives a measure of the degree of agreement between two data series (X and Y) and represents an improvement over r^2. The value of D varies between 0 and 1, where 0 indicates no agreement and 1 indicates a perfect agreement of all data pairs. Both r^2 and D are oversensitive to extreme values (outliers). For error analysis, the root mean square difference (RMSD) and mean bias error (MBE) were used. Both RMSD and MBE represent the average difference between a pair of data values. The RMSD measures the non-systematic variation between the data sets, and the MBE measures the systematic variation between the data sets. The RMSD and MBE are expressed as follows:

$$\text{RMSD} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left(X_i - Y_i\right)^2} \tag{7}$$

$$\text{MBE} = \frac{1}{n} \sum_{i=1}^{n} \left(X_i - Y_i\right) \tag{8}$$

Results and Discussion

Comparison of Microclimatic Data Measured above Grass and Maize Canopies

Microclimatic variables, including R_s, T_a, u_2, and RH measured above the grass and maize canopies were compared using plots of 5-day running averages. The 5-day

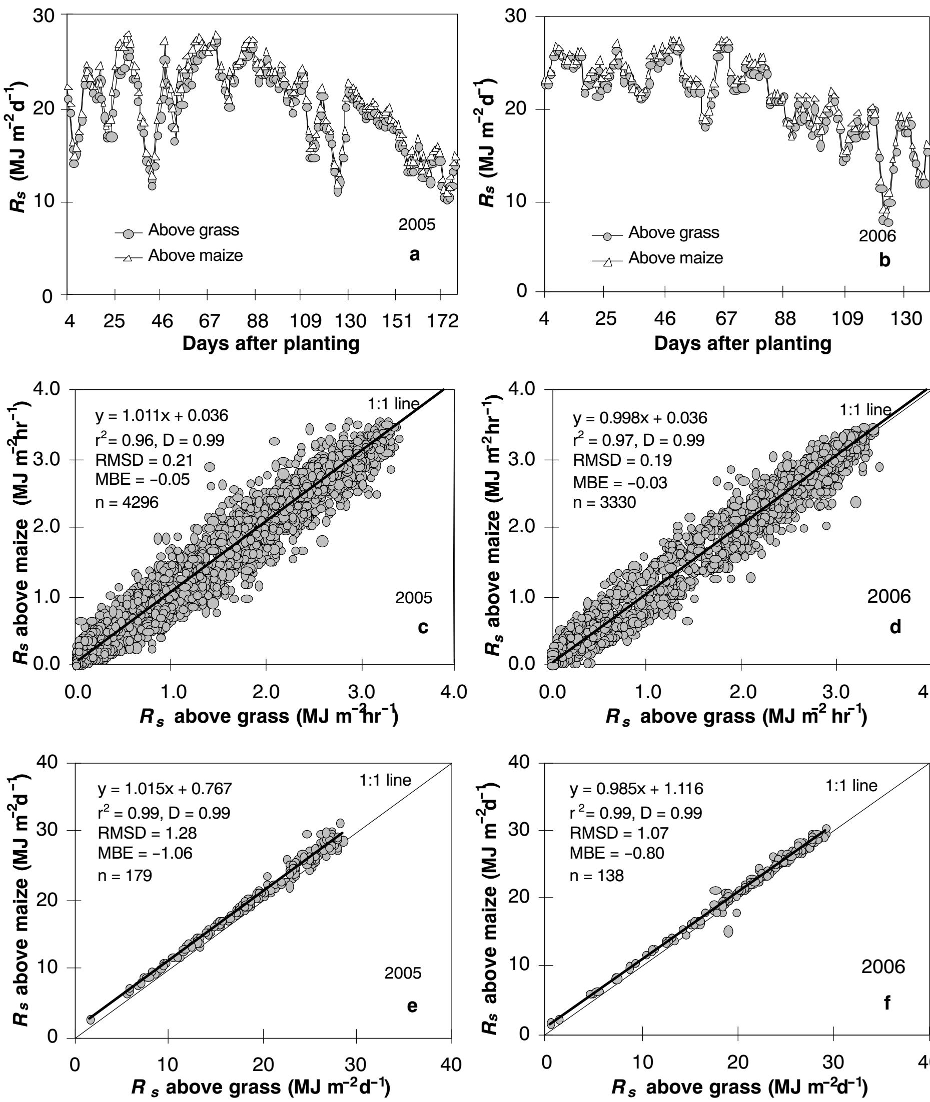

Figure 1. (a-b) Five-day running average of seasonal distribution of incoming shortwave solar radiation (R_s) measured above grass and maize canopies, (c-d) regression plots of hourly solar radiation measured above a grass vs. maize canopy, and (e-f) regression plots of daily solar radiation measured above a grass vs. maize canopy.

running averages dampen the daily fluctuations within the variables and allow differences between the data sets to be observed more clearly. The comparison for each variable is discussed separately.

Solar Radiation

Incoming shortwave radiation above a surface is not influenced by the underlying surface conditions, but by time of the year, longitude and latitude of the location, time of the day, and turbidity and cloudiness of the atmosphere. Since the weather station and the BREBS were in close proximity to each other, the same factors influenced the amount of R_s received on both surfaces. Consequently, the amounts of R_s received above the grass and maize canopies were expected to be similar. However, since the ET_{ref} is impacted significantly by R_s, it is important to demonstrate that both surfaces receive the same R_s and that the potential differences in ET_{ref} between the surfaces are not due to R_s. Figures 1a and 1b shows that R_s measured above both canopies followed the same trend throughout the growing season in 2005 and 2006 and that the two data sets were in very good agreement. Measured R_s values above the maize surface was slightly higher than those measured above grass surface across the range of data. On an hourly basis, the R_s measured above the maize and grass surfaces were within 2.7% and 1.4% in 2005 and 2006, respectively. On a daily basis, they were within 5.0% and 3.4% in 2005 and 2006, respectively. These slight variations of R_s between the two surfaces may be attributed to differences in sensitivity of the radiometers used and/or leveling or differences in maintenance procedures of the radiometers. The BREBS was closely supervised and maintained on a weekly basis by the authors, whereas the weather station instrumentation was maintained by HPRCC personnel and the details of the maintenance for the weather station are not known. An LI200X pyranometer (LiCor Corp., Lincoln, Neb.; table 2) was used above the grass surface, and a double-sided total hemispherical radiometer was used above the maize canopy. Although both sensors have a manufacturer specified accuracy of ±3%, the total hemispherical radiation sensor has better sensitivity. The r^2 (figs. 1c and 1d) and the D values between hourly R_s data were 0.96 and 0.99, respectively, for the 2005 data, and 0.97 and 0.99 for the 2006 data. The RMSD and MBE were 0.21 MJ m^2 h^{-1} and -0.05 MJ m^2 h^{-1}, respectively, for the 2005 data, and 0.19 MJ m^{-2} h^{-1} and -0.03 MJ m^{-2} h^{-1}, respectively, for the 2006 data. A better agreement between the values was obtained when the R_s data were summed to daily time periods, as shown in figures 1e and 1f. These results indicate that the difference in R_s data measured above the grass surface and maize canopy were insignificant, and for all practical purposes they can be considered equal.

Air Temperature

Past studies indicate that T_a and RH above vegetation surfaces can be impacted by surface and subsurface factors that influence the partitioning of R_n into latent heat of evaporation and sensible heating of the air, soil, and vegetation. Under moist surface conditions, most of the R_n is used to evaporate water and a relatively smaller amount is used for sensible heat, increasing RH and usually reducing T_a due to evaporative cooling. On the other hand, in situations where surface moisture is limiting, a considerable portion of R_n can be used for sensible heat in the surrounding air, soil, and vegetation, resulting in higher T_a and lower RH relative to moist surface conditions. Allen and Pruitt (1986) reported T_a values measured above irrigated areas that were 2°C to 5°C lower than T_a measured over non-irrigated areas with corresponding increases in RH. In this study, the soil surface in the subsurface-irrigated maize field was mostly dry since no surface wetting occurs due to irrigation, and this type of irrigation method appears not to have had a significant impact on modification of the local microclimate by heating, cooling, or humidifying of the air above the maize canopy relative to the grass surface. The minimum and maximum air temperatures measured above the grass and maize canopies followed the same trend and were in very good agreement throughout the growing seasons in both years, as shown in figures 2a and 2b. Figures 2c and 2d represent the relationship between T_a measured above the grass and maize canopies. The r^2 and D values for hourly temperature data were 0.99 and 1.00, respectively, for both 2005 and 2006 data. The RMSD and MBE values were 0.615°C and 0.096°C, respectively, for the 2005 data, and 0.648°C and -0.158°C, respectively, for the 2006 data. Agreements between the T_a values were better when air temperature was averaged for daily time periods, as shown in figures 2e and 2f. These results indicate that T_a data measured above the grassed surface and maize canopy are the same and would not have any impact on the ET_{ref} computations above both surfaces.

Other studies conducted in arid and semi-arid regions show that T_a and RH measurements may misrepresent ET_{ref} environments if a fully vegetated, well-watered, and fully transpiring vegetation surface is not present. ET humidifies and cools the equilibrium boundary layer due to evaporative cooling process. The absence of ET_{ref} conditions therefore results in a drier and warmer equilibrium boundary layer and subsequent T_a and RH measurements (Allen, 1996). The likelihood of the occurrence of a warmer and drier boundary layer conditions in humid and sub-humid regions is, however, less than in arid and semi-arid regions because the reference surface and other surfaces will have similar RH and T_a and similar evaporative demand, and thus similar ET_{ref} and evaporative cooling.

Relative Humidity and Dewpoint Temperature

Figures 3a and 3b presents the trend and variation of RH measured above both canopies. The RH measured above the maize canopy was approximately 2% higher than above the grass canopy from a few days after plant emergence to harvest. Slightly higher values of RH above the maize canopy may be attributed to higher rates of plant transpiration of the maize canopy. Figures 3c and 3d show the regressions of the hourly RH measured above both surfaces. The r^2 and D values for the hourly RH data were 0.98 and 0.99, respectively, for 2005 data, and 0.97 and 0.99, respectively, for 2006 data. The RMSD and MBE values were: 3.43% and -1.21%, respectively, for 2005 data, and 3.95% and -1.81%, respectively, for 2006 data. Similar values were obtained for the daily time periods, as shown in figures 3e and 3f. Although RH is often used as a measure of the amount of water vapor present in the air, it is dependent on T_a. A change in T_a can result in a change in RH without necessarily a change in the absolute amount of water vapor present in the air. Because of this ambiguity in RH values, the calculated dewpoint temperature, which is a better measure of the absolute amount of water vapor present in the air, was also used to compare air moisture above the grass and maize

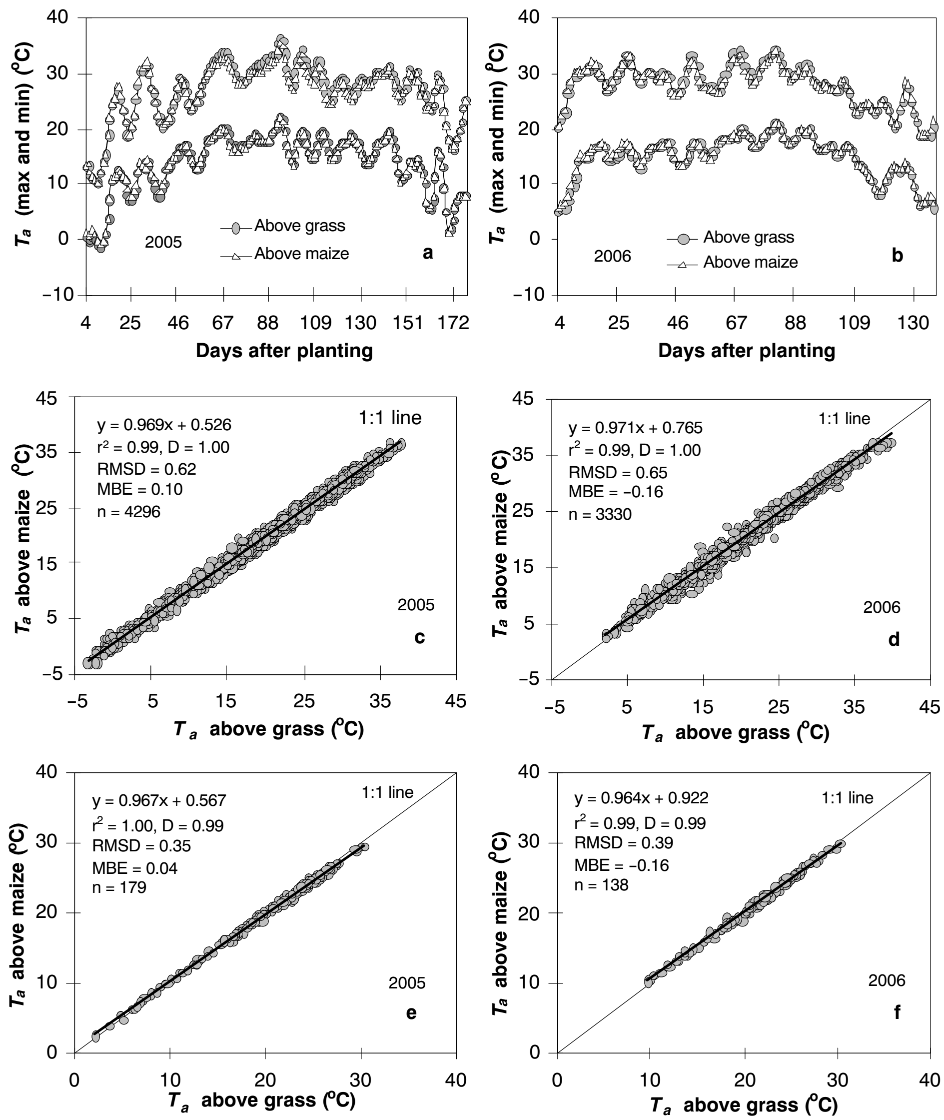

Figure 2. (a-b) Five-day running average of maximum and minimum air temperature (T_a) measured above grass and maize canopies, (c-d) regression plots of hourly air temperature measured above a grass vs. maize canopy, and (e-f) regression plots of daily air temperature measured above a grass vs. maize canopy.

canopies. Figures 4a and 4b shows very close agreement between the T_d values for both surfaces. The r^2 and D values for T_d calculated above the grass and maize canopies were both 1.00 for 2005, and 0.99 and 1.00, respectively, for 2006. The RMSD and MBE were 0.36°C and -0.003°C, respectively, for 2005, and 0.43°C and 0.32°C for 2006.

Wind Speed

In discussing the difference in wind speed above grass and maize surfaces, it is important to take into account the fact that wind speed passing over a surface is modified by the drag force (resistance) exerted by the underlying surface. For a vegetated surface, the magnitude of the resistance is determined by factors such as plant height, the structure and flexibility of individual plants, the size and arrangement of plant parts, and the plant density. Differences in plant height and roughness between a grass surface and taller agronomical plants can reduce wind speed over taller plants by as much as 50% in the lower atmospheric layer above the plant (Allen and Wright, 1997). Figures 5a and 5b shows that u_2 was initially slightly higher above the maize canopy than the grass surface before emergence, but gradually decreased as the plant height increased. At 47 DAP in 2005 and 32 DAP in 2006, the wind speed measured above the grass surface exceeded that measured above maize canopy and continued to be greater for the rest of the growth period, with increasing differences towards the end of the season. In 2005, the daily maximum difference in wind speed between the two surfaces was observed on April 22 as 2.1 m s^{-1}. In 2006, the maximum difference was also early in the season on May 17 as 2.2 m s^{-1}. The seasonal average u_2 for the grass and maize canopies, respectively, was 3.3 and 2.8 m s^{-1} for 2005, and 3.0 and 2.4 m s^{-1} for 2006. On a seasonal average, the u_2 was 15% and 20% higher over the grass canopy than the maize canopy for 2005 and 2006, respectively. The differences in u_2 were particularly large from about full canopy closure until harvest. Figures 5c and 5d present the regressions of the hourly wind data. The r^2 and D values for the hourly measured u_2 data were 0.84 and 0.94, respectively, for 2005, and 0.78 and 0.91, respectively, for 2006. The RMSD and

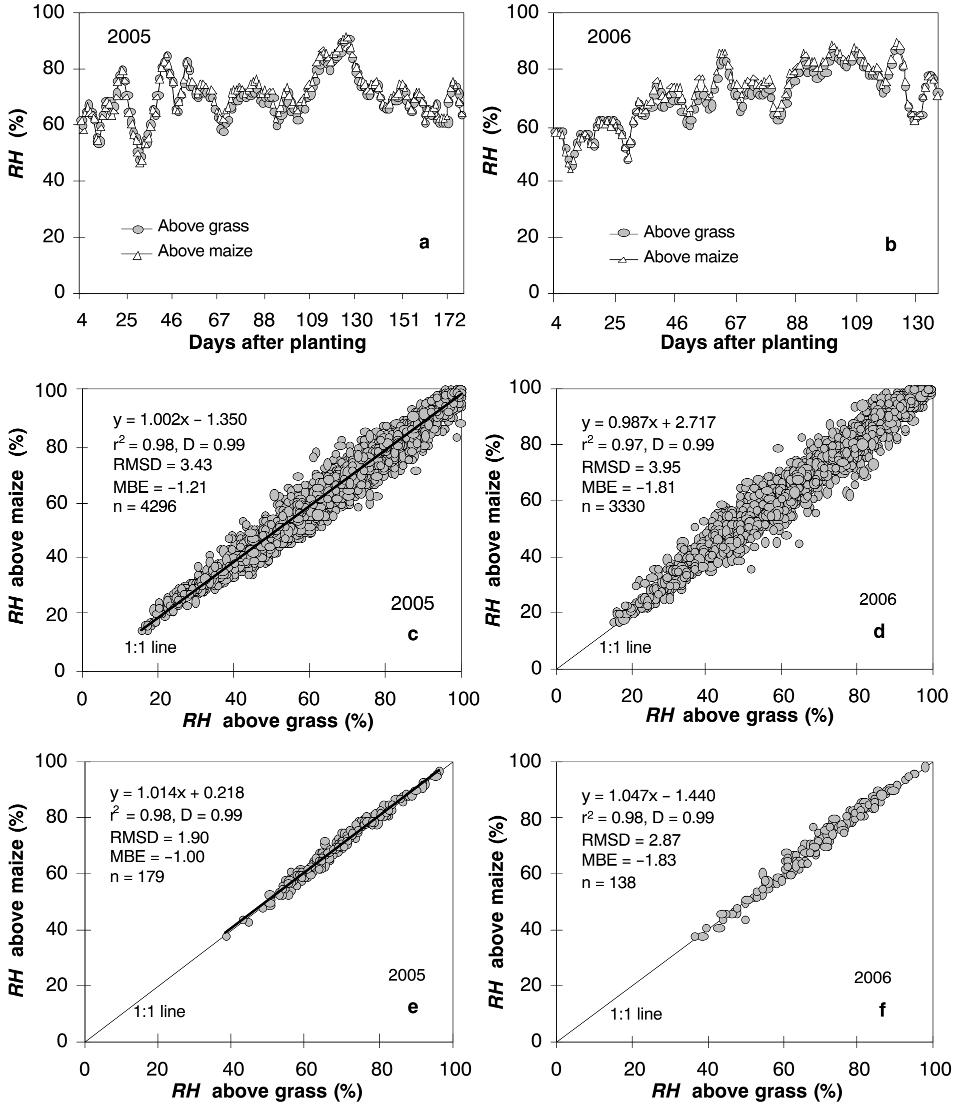

Figure 3. (a-b) Five-day running average of relative humidity (*RH*) measured above grass and maize canopies, (a-b) regression plots of hourly relative humidity measured above a grass vs. maize canopy, and (e-f) regression plots of daily relative humidity measured above a grass vs. maize canopy.

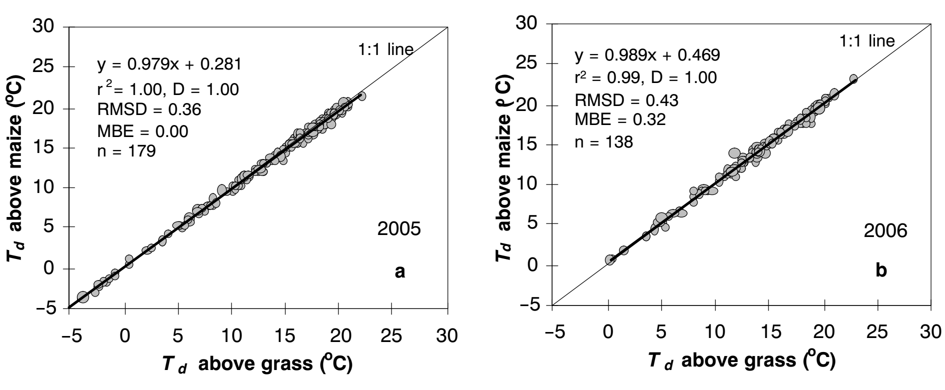

Figure 4. Scatter plots of calculated dewpoint temperature (T_d) above grass vs. maize canopies.

MBE values for hourly measured u_2 data were 0.93 m s^{-1} and 0.43 m s^{-1} respectively, for 2005, and 1.06 m s^{-1} and 0.56 m s^{-1} respectively for 2006. Unlike the other microclimatic variables, the agreement between u_2 values measured above grass and maize decreased when u_2 data were averaged to daily time periods, as shown in figures 5e and 5f.

The differences in wind speed affected the calculated r_a for the 2006 data (only 2006 data are shown), as shown in figures 6a and 6b. The r_a values were very similar early in the season until 45 to 50 DAP, after which the r_a above the maize canopy exceeded the r_a above the grass canopy as the height of the maize increased. The value of r_a ranged from 22 to

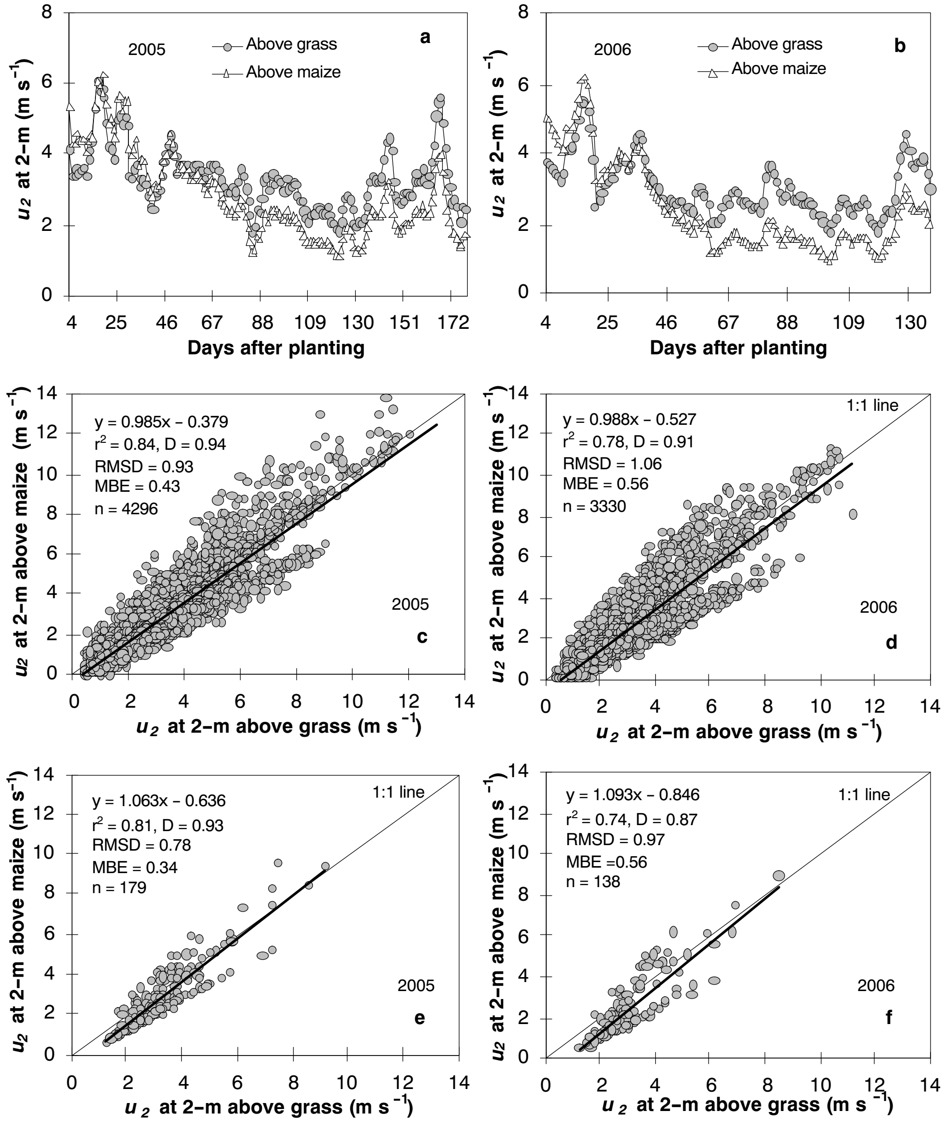

Figure 5. (a-b) Five-day running average of wind speed (u_2) measured above grass and maize canopies, (c-d) regression plots of hourly wind speed at 2 m measured above a grass vs. maize canopy, and (e-f) regression plots of daily wind speed at 2 m measured above a grass vs. maize canopy.

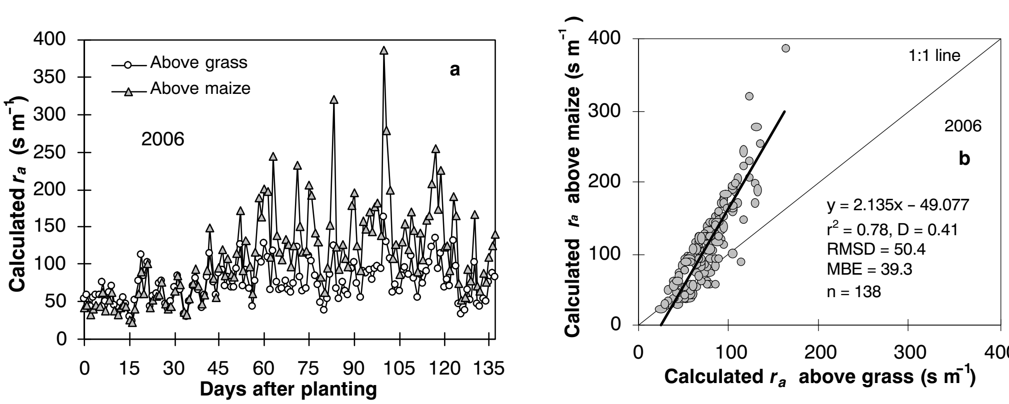

Figure 6. (a) Seasonal distribution (5-day average) of calculated daily aerodynamic resistance (r_a) above grass and maize canopies and (b) regression plot of aerodynamic resistance above a grass vs. maize canopy.

387 s m^{-1} for maize and from 20 to 163 s m^{-1} for the grass canopy. The seasonal average r_a values for the grass and maize canopies were 75 and 112 s m^{-1}, respectively. The maximum difference between the two r_a values occurred between 80 and 100 DAP when the maize was at its maximum height. The difference in r_a between the two

canopies showed a decreasing trend towards the end of the season due to leaf aging and senescence of the maize canopy, while the grass remained green and active for a longer period. On a seasonal average, the r_a above the maize canopy was higher by 37 s m^{-1} than the r_a above the grass surface.

Impact of Grass vs. Maize Canopy Microclimatic Data on Calculated Reference Evapotranspiration

The ET_o and ET_r values calculated using microclimatic data measured above the maize canopy (i.e., $ET_{o\text{-}maize}$ and $ET_{r\text{-}maize}$) were compared with ET_o and ET_r values calculated using data measured above the grass surface (i.e. $ET_{o\text{-}grass}$ and $ET_{r\text{-}grass}$). Figures 7a through 7d shows that $ET_{o\text{-}maize}$ followed the same daily trend as $ET_{o\text{-}grass}$, and $ET_{r\text{-}maize}$ also followed the same daily trend as $ET_{r\text{-}grass}$. However, $ET_{o\text{-}maize}$ and $ET_{r\text{-}maize}$ were slightly higher than $ET_{o\text{-}grass}$ and $ET_{r\text{-}grass}$, respectively, from planting to a few days after emergence. At 48 DAP in 2005 and 32 DAP in 2006 (average crop height = 0.85 m), $ET_{o\text{-}grass}$ and $ET_{r\text{-}grass}$ began to be equal or exceed $ET_{o\text{-}maize}$ and $ET_{r\text{-}maize}$, respectively. The largest differences in ET (1.0 to 1.5 mm d^{-1}) between the grass and maize canopies occurred between full canopy closure and harvest for maize. However, the differences in ET_{ref} values between the two surfaces were very small. It is worth noting that this is the same period during which the difference in wind speed measured above both surfaces was the greatest. We also compared diurnal variations of microclimate variables for typical days when ET_o values calculated using data measured above the maize canopy was less than, equal to, and greater than those calculated using data measured above the grass surface. The results presented in figures 8a through 8d show the diurnal variation of climatic variables on a typical day (May 19, 2006) when $ET_{o\text{-}maize} > ET_{o\text{-}grass}$ and $ET_{r\text{-}maize} > ET_{r\text{-}grass}$, and the results in figures 8e through 8h show the diurnal variation of climatic variables on a typical day (June 31, 2006) when $ET_{o\text{-}maize} = ET_{o\text{-}grass}$ and $ET_{r\text{-}maize} = ET_{r\text{-}grass}$. Similarly, the results in figures 8i through 8l show the diurnal variation of climatic variables on a typical day (June 19, 2006) when $ET_{o\text{-}maize} < ET_{o\text{-}grass}$ and $ET_{r\text{-}maize} < ET_{r\text{-}grass}$. These results indicate that the most significant difference in microclimate variables was in wind speed, as shown in figures 8d, 8h, and 8l, and can be summarized as follows: (1) $ET_{o\text{-}maize}$ was greater than $ET_{o\text{-}grass}$ when wind speed above the maize canopy was greater than wind speed above the grass surface (fig. 8d), (2) $ET_{o\text{-}maize}$ was equal to $ET_{o\text{-}grass}$ when wind speed above the grass surface was equal to wind speed above the maize canopy (fig. 8h), and (3) $ET_{o\text{-}maize}$ was less than $ET_{o\text{-}grass}$ when measured wind speed above the maize canopy was less than wind speed above the grass surface (fig. 8l). Thus, among all climatic variables analyzed, u_2 was largely responsible for the small difference in ET_o and ET_r calculated using data measured over grass and maize canopies.

Wind speed impacts ET_o and ET_r through its influence primarily on the r_a in the ASCE-EWRI PM equation. The r_a was calculated separately using equation 3. The r_a calculated using u_2 measured over grass and maize canopies showed poor agreement, as shown in figure 6b. The r^2 and D values on a daily time scale were 0.78 and 0.41, respectively, and the RMSD and MBE values were 50.4 s m^{-1} and 39.3 s m^{-1}, respectively. Thus, the maize canopy impacts r_a through its

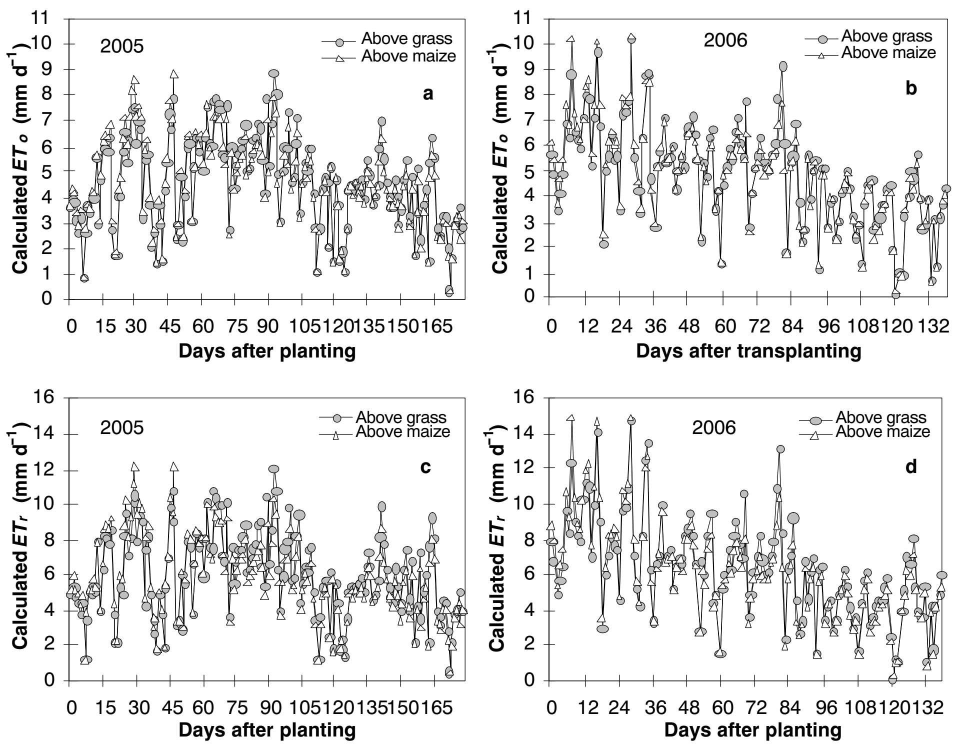

Figure 7. (a-b) Seasonal variation of estimated grass-reference evapotranspiration (ET_o), and (c-d) alfalfa-reference evapotranspiration (ET_r) with data measured above grass and maize canopies.

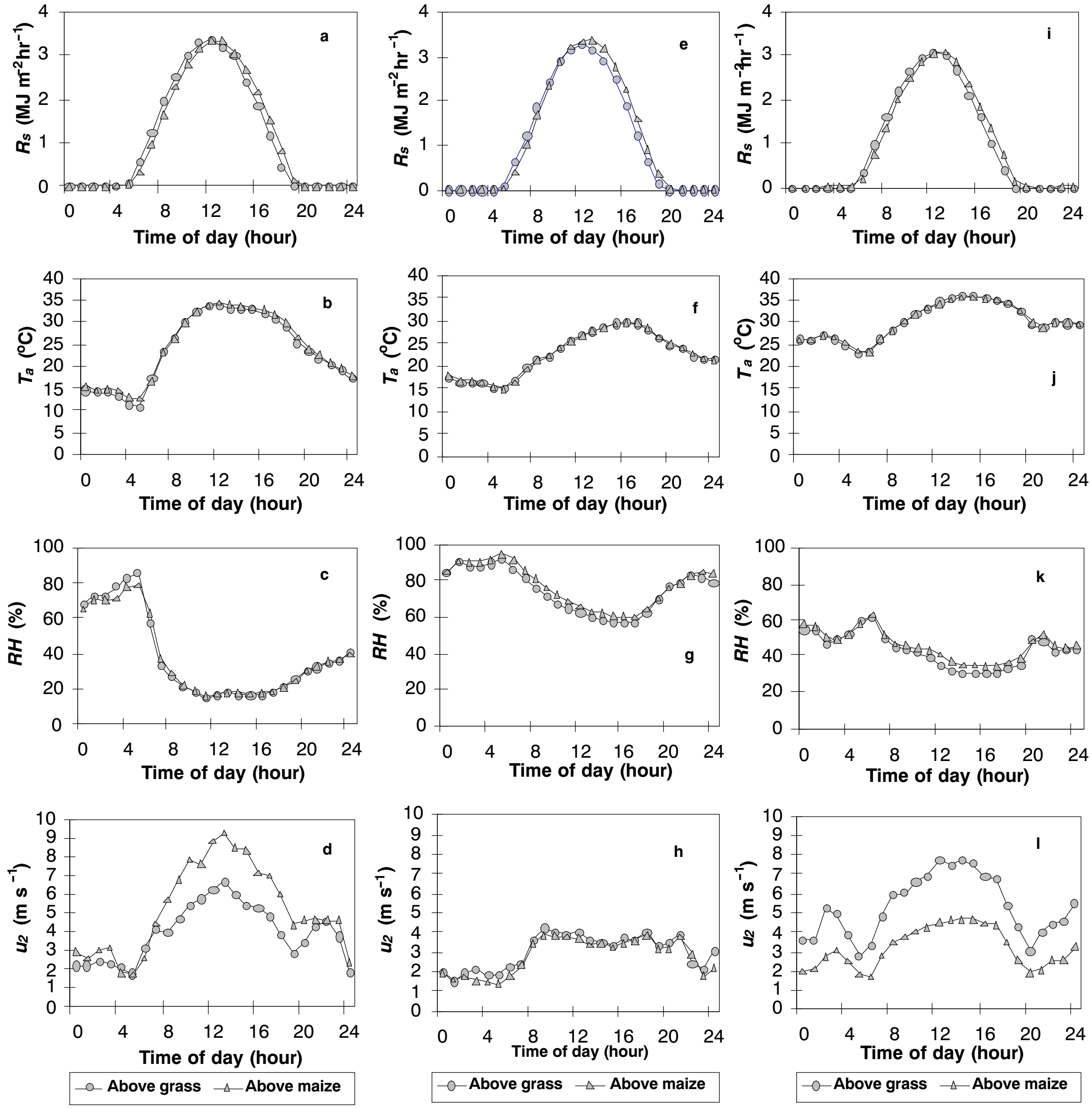

Figure 8. Typical microclimatic conditions influencing the relationship between grass-reference evapotranspiration (ET_o) and alfalfa-reference evapotranspiration (ET_r) calculated with data measured above a grass vs. maize canopy: (a) through (d) represent conditions on a day when ET_o and ET_r above maize > ET_o and ET_r above grass (May 19, 2006), (e) through (h) represents conditions on a day when ET_o and ET_r above maize = ET_o and ET_r above grass (June 31, 2006), and (i) through (l) represent conditions when ET_o and ET_r above maize < ET_o and ET_r above grass (June 19, 2006).

effect on wind speed. However, the impact on r_a did not translate into a significant difference between ET_o and ET_r calculated using data measured over both surfaces (figs. 9a through 9h). Figures 10a and 10b show the cumulative ET_o and ET_r values calculated using data measured above grass and maize canopies for both the 2005 and 2006 growing seasons. The seasonal cumulative $ET_{o\text{-}maize}$ and cumulative $ET_{o\text{-}grass}$ were 816 mm and 824 mm, respectively, for 2005, and 671 mm and 675 mm, respectively, for 2006. The seasonal cumulative $ET_{r\text{-}maize}$ and cumulative $ET_{r\text{-}grass}$ were 1033 mm and 1070 mm, respectively, for 2005, and 838 mm and 868 mm, respectively, for 2006, with no significant differences between cumulative ET_o and ET_r values calculated using the microclimatic data measured above grass and maize canopies.

One of the primary reasons for having very similar values of microclimatic variables between the two sites is the amount of rainfall. The rainfall measured at both sites was almost identical in both years. The rainfall from planting (April 22) to harvest (October 17) in 2005 was 316 and 323 mm for the weather station and BREBS, respectively. In 2006, the rainfall from planting (May 12) to harvest (October 5) was 368 and 366 mm, respectively. Thus, in areas where enough rainfall occurs (i.e., at least 316 mm) during the growing season, the data measured from an automated weather station that is sited over a grass surface can represent "reference" conditions, and microclimatic data are comparable to measurements made over a well-watered maize canopy for ET_{ref} estimations when reference weather station data are not available.

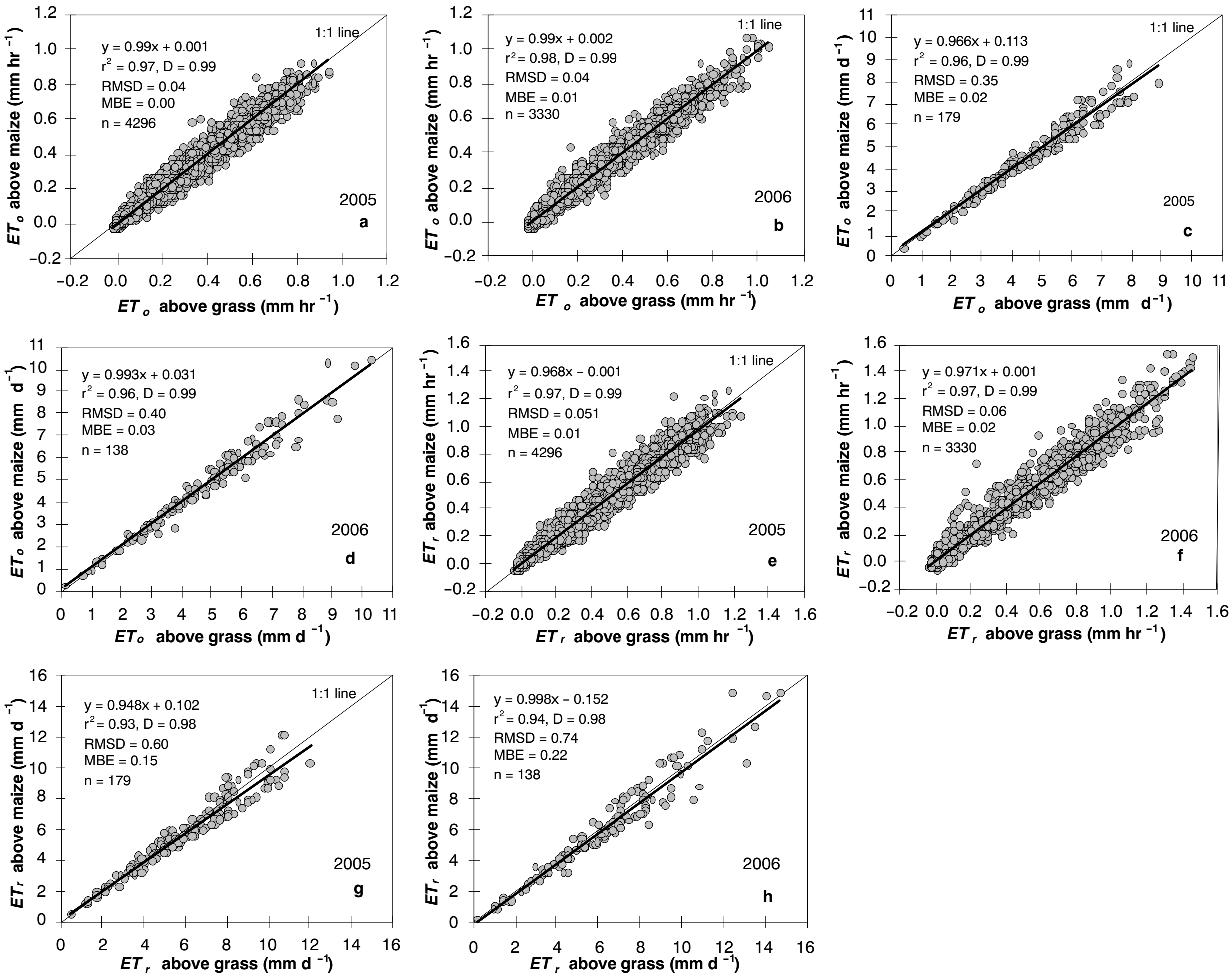

Figure 9. (a-d) Regression of estimated grass-reference evapotranspiration (ET_o) above a grass vs. maize canopy, and (e-h) regression of estimated alfalfa-reference evapotranspiration (ET_r) above a grass vs. maize canopy.

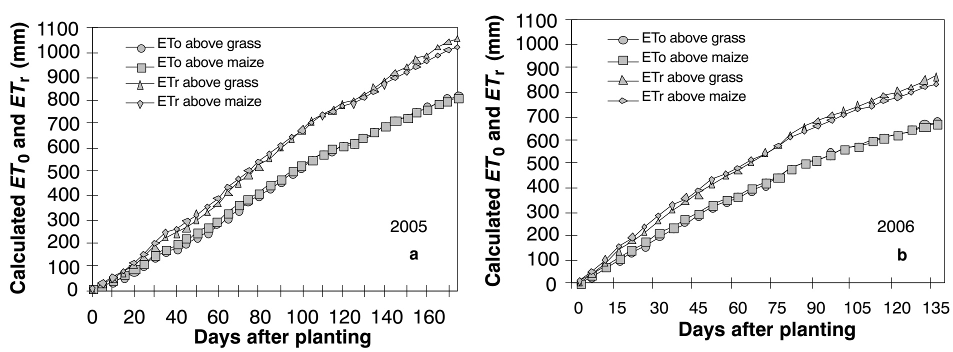

Figure 10. Seasonal cumulative grass-reference evapotranspiration (ET_o) and alfalfa-reference evapotranspiration (ET_r) above grass and maize canopies.

Summary and Conclusions

It is recommended that reference evapotranspiration (ET_{ref}) calculations be made using microclimatic data measured over either a grass or alfalfa-reference surface when using the Penman-Monteith (PM) method. This aids in transferability of plant-specific coefficients between locations. However, it is a very difficult task to establish and maintain such reference surfaces for long periods. Significant numbers of other energy flux measurement systems, such as the Bowen ratio energy balance system (BREBS), eddy covariance system, and surface renewal system, are increasingly used to measure microclimatic and flux data over various plant canopies. These systems could be another source of microclimatic data for ET_{ref} estimations when reference weather stations are not present. However, there is little information on the potential impact of two data sources (reference weather station-measured vs.

microclimatic data measured above other well-watered other vegetation surfaces) on the estimated ET_{ref}. This study compared microclimatic data measured above grass and maize canopies and assessed how the variables measured above a maize canopy impact the ET_{ref} calculated using the standardized ASCE Penman-Monteith (ASCE-EWRI PM) equation relative to the ET_{ref} values estimated using the data measured above a reference grass canopy. The following conclusions were drawn from the study:

- The results indicate a very strong relationships between not only weather station-measured and BREBS-measured microclimatic variables (wind speed, air temperature, dewpoint temperature, relative humidity, and incoming shortwave radiation), but also the grass and alfalfa-reference evapotranspiration (ET_o and ET_r, respectively) estimated from the two data sources using the PM method.
- The main differences between the two surfaces were in wind speed (u_2) and aerodynamic resistance (r_a). On a seasonal average basis, the u_2 was 15% and 20% higher over the grass canopy than the maize canopy for 2005 and 2006, respectively. The maximum difference in r_a between the two surfaces occurred when the maize was at its maximum height (2.45 m). On a seasonal average, the r_a above the maize canopy was 37 s m^{-1} higher than the r_a above the grass surface. However, the impact of u_2 and r_a on ET_{ref} was subsidiary.
- The grass and alfalfa-reference ET (ET_o and ET_r) estimated using the data measured above maize ($ET_{o\text{-}maize}$ and $ET_{r\text{-}maize}$) and above the grass canopy ($ET_{o\text{-}grass}$ and $ET_{r\text{-}grass}$) were very similar in both years. In 2005, $ET_{o\text{-}maize}$ (816 mm) and $ET_{o\text{-}grass}$ (824 mm) were within 1%, and $ET_{r\text{-}maize}$ (1,033 mm) and $ET_{r\text{-}grass}$ (1,070 mm) were within 3%. The same percentages were obtained in 2006 ($ET_{o\text{-}maize}$ = 671 mm, $ET_{o\text{-}grass}$ = 675 mm, $ET_{r\text{-}maize}$ = 838 mm, $ET_{r\text{-}grass}$ = 868 mm).
- Our results indicate that the microclimatic variables measured above a well-watered maize canopy can be an alternative source of data for ET_{ref} estimations when "reference" weather station-measured data are not available to solve the PM equation in areas that receive similar rainfall (316 mm) observed during the growing season of this study. However, the results presented in this article are specific for a non-stressed maize canopy irrigated with a subsurface drip irrigation system and may not be applicable in general to other plant surfaces. Thus, further validation of these analyses for other surfaces is needed to fully understand the impact and dynamics involved with using microclimatic data measured above different vegetation surfaces, relative to the grass or alfalfa-reference surfaces for ET_{ref} estimations when using the Penman-Monteith model.

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