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# Free-air $CO_2$ enrichment effects on the energy balance and evapotranspiration of sorghum

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**Abstract**

Increasing atmospheric carbon dioxide ($CO_2$) likely will affect future water requirements of most plants, including agricultural crops. This research quantifies such effects on the energy balance and evapotranspiration (ET) of sorghum (*Sorghum bicolor* (L.) Möench, a $C_4$ grain crop) using a residual energy balance approach. During the summer and autumn of 1998 and 1999, sorghum was grown under free-air $CO_2$ enrichment (FACE) conditions near Maricopa, Arizona.

Latent heat flux ($\lambda$ET) was determined by subtracting soil heat flux ($G_0$) and sensible heat flux ($H$) from net radiation ($R_n$) values in both Control $CO_2$ plots (about 370 $\mu$mol mol$^{-1}$) and FACE plots (Control + 200 $\mu$mol mol$^{-1}$). $R_n$ was observed using net radiometers. $G_0$ was measured with soil heat flux plates at a depth of 10 mm, then corrected for heat storage above the plates. $H$ was determined using measurements of air temperature from aspirated psychrometers, leaf temperature from infrared thermometers, and wind data from a three-cup anemometer. Both FACE and Control plots were divided into semicircular halves to allow a well-watered (Wet) treatment and a drought-stressed (Dry) treatment. This allowed comparisons of the FACE effect on ET in normal and water-stressed conditions. Under Wet conditions, FACE decreased $\lambda$ET by 13.8 ± 1.8% in 1998, and 11.8 ± 1.9% in 1999. Drought-stress resulted in a reduction in $\lambda$ET of 8.5 ± 3.7% for the FACE treatments in 1998, but

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an increase in λET of 10.5 ± 5.1% in 1999. When soil water was readily available, midday canopy temperatures in the FACE plots were increased by 1.47 ± 0.09 °C in 1998, and 1.85 ± 0.20 °C in 1999, indicative of increased stomatal resistance due to $CO_2$ enrichment. These data suggest that soil water availability is a determining factor for the FACE effect.

Water use efficiency (WUE) increased about 28% due to elevated $CO_2$ under Wet conditions due to a savings of water for about the same growth, whereas under Dry conditions it increased about 16% due to much greater relative growth on only a slightly higher amount of water.
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## 1. Introduction

Global atmospheric carbon dioxide ($CO_2$) concentrations are increasing rapidly. A doubling of the current atmospheric $CO_2$ concentration (∼370 μmol mol$^{-1}$) is quite possible during this century (IPCC, 2001). The atmospheric $CO_2$ concentration has been shown to have a direct impact on the growth and productivity of plants (e.g., Kimball, 1983; Conroy, 1992; Street-Perrott et al., 1997). Because of the importance of $CO_2$ to plants, there have been several hundred studies on how $CO_2$ change can affect agriculture (summarized by Kimball, 1983; Idso and Idso, 1994; Kimball et al., 2002).

Most $CO_2$ studies in agriculture have focused on how plants respond to higher $CO_2$ concentrations (Conroy, 1992; Idso and Idso, 1994; Morse and Bazzaz, 1994; Sage, 1994; Siebke et al., 2002), which have shown that with more abundant $CO_2$, plants are generally larger and more productive. Other studies have shown that lower $CO_2$ concentrations result in decreased plant productivity (Kimball, 1983) and altered plant distribution (Street-Perrott et al., 1997; Huang et al., 2001). These studies suggest that plants do not all respond exactly the same way to $CO_2$ availability, especially due to differences in plant photosynthetic pathways (Monteith, 1978; Kimball, 1983; Ghannoum et al., 2000).

Most plants utilize one of two photosynthetic pathways ($C_3$ or $C_4$) to sequester carbon from the atmosphere. The $C_3$ pathway accounts for about 85% of plant species globally, and approximately 95% of all plants (Idso and Idso, 1994). Therefore, most scientific attention has been given to the effects of rising $CO_2$ on $C_3$ plants (Conroy, 1992; Idso and Idso, 1994). However, the importance of $C_4$ plants, which include corn, sorghum, and sugarcane, cannot be ignored. Globally, $C_4$-type plants account for about a fifth of the total primary productivity (Ghannoum et al., 2000). Because they tend to be better adapted to warmer temperatures and drought conditions, $C_4$ plants are primarily suited for tropical and subtropical (Ottman et al., 2001), arid, and semi-arid warm regions such as grasslands and desert (Ghannoum et al., 2000).

$C_4$ plants utilize a $CO_2$-concentrating mechanism that allows leaves to maintain fairly consistent and relatively high internal $CO_2$ levels (Kanai and Edwards, 1999). Therefore, $C_4$ plants most likely will not experience the same photosynthetic enhancements under higher $CO_2$ as will the $C_3$ type. This concentrating factor could cause $C_4$ plants to respond less favorably in terms of their size and productivity, since they are already naturally adapted to higher internal $CO_2$ concentrations (Morse and Bazzaz, 1994; Farquhar, 1997).

On the other hand, most $C_3$ plants exhibit significant increases in production under $CO_2$-enriched conditions. Accompanying this increase, plants tend to experience a decrease in stomatal conductance (Morison, 1987), which in turn reduces their rates of transpiration per unit of leaf area. However, increased productivity often leads to larger leaf areas from which more water may be transpired and evaporated (Kimball et al., 1999). These competing factors create uncertainty regarding how evapotranspiration (ET) will be affected by increasing $CO_2$.

Because of the different processes, it is unlikely that $C_3$ plants and $C_4$ plants will respond the same way to the increasing $CO_2$ concentration. If a change in $CO_2$ causes adaptations in plant structure, physiology, and productivity, it is likely that agriculture will experience variations in ET. Thus, an important question considered herein is: how will a $CO_2$-enriched environment affect ET in a $C_4$ agricultural crop?

The effects of elevated $CO_2$ on the growth of $C_3$-type plants are becoming fairly well proven (e.g., Kimball et al., 2002). Free-air $CO_2$ enrichment (FACE) studies on $C_3$ crops such as cotton (Mauney et al., 1994), wheat (Kimball et al., 1995, 2002), clover (Hebeisen et al., 1997), ryegrass (Daepp et al., 2000), rice (Kim et al., 2001) and potato (Magliulo et al., 2003) have shown significant increases in both biomass and yield for plants exposed to $CO_2$ concentrations of about 200 $\mu$mol mol$^{-1}$ above ambient. Cotton grown under FACE conditions at Maricopa, Arizona, exhibited a large increase in productivity (+40%) relative to Control plots (Mauney et al., 1994), but there was no distinguishable change in overall ET (Hunsaker et al., 1994; Dugas et al., 1994; Kimball et al., 1994). Wheat, on the other hand, showed a less positive growth response (+13%; Kimball et al., 2002), and a relative decrease in ET (−7%) for well-watered conditions (Hunsaker et al., 1996, 2000; Kimball et al., 1999). As reviewed by Kimball et al. (2002), potato showed a strong stimulation in yield (+27.5%), but a decrease in above-ground biomass (−20.8%). However, the reductions in biomass and stomatal conductance appeared to not be additive because Magliulo et al. (2003) observed a relatively modest 12% decrease in water use of their FACE plots compared to the controls at ambient $CO_2$.

Studies on $C_4$ plants have been fewer, but most have shown a smaller growth response to $CO_2$ (Ghannoum et al., 2000). However, one effect of $CO_2$ that is consistent among all $C_3$ and $C_4$ plants is a partial closing of stomata in response to higher $CO_2$ (Morison, 1987, 1998; Idso and Idso, 1994; Field et al., 1995; Siebke et al., 2002; Kimball et al., 2002). This partial stomatal closure reduces transpiration, resulting in the plant losing less water to the atmosphere per unit of leaf area (Field et al., 1995).

An additional effect of increased stomatal resistance is a warming of the leaves (Siebke et al., 2002). Idso et al. (1993) report that leaf temperature is inversely proportional to stomatal conductance. Plants exposed to higher $CO_2$ have consistently warmer surfaces, leading to an increase in sensible heat (Field et al., 1995).

Also, as a result of decreased transpiration, water use efficiency (WUE; biomass production/total ET) typically rises (Siebke et al., 2002). Considering transpirational decreases alone, a plant grown at a higher rate of $CO_2$ could produce the same amount of biomass using less water per unit of biomass, thus increasing water use efficiency. The decrease in transpiration, however, combined with different growth responses, leads to uncertainty with regard to plant water usage per unit of land area in a future high-$CO_2$ environment (Wullschleger et al., 2002).

In 1998 and 1999, sorghum was grown under FACE conditions at Maricopa, Arizona. This $C_4$-plant species had a minimal growth response to $CO_2$ enrichment (Ottman et al., 2001). Thus, our hypothesis is that ET will decrease under $CO_2$-enriched conditions in a $C_4$ crop with ample soil water because there will be little change in the growth of leaf area, while the stomatal conductance will decrease. Consequently, WUE will be increased by $CO_2$ enrichment.

## 2. Materials and methods

Micrometeorological data were collected and processed from a two-season free-air carbon dioxide ($CO_2$) enrichment (FACE) study conducted at the University of Arizona, Maricopa Agricultural Center (33.1°N, 112.0°W, 361 m above sea level), Maricopa, Arizona, in order to determine the effects of elevated $CO_2$ and water supply on the energy balance and evapotranspiration (ET) of grain sorghum (*Sorghum bicolor* (L.) Möench). A plot plan and experimental details have previously been presented by Ottman et al. (2001). The data collected during this experiment were analyzed using a residual energy balance approach (Kimball et al., 1994, 1995, 1999).

### 2.1. Carbon dioxide enrichment

Lacking walls, FACE is the best approach for determining the effects of elevated $CO_2$ on crop responses under conditions representative of future fields (Hendrey, 1993). The FACE system consisted of four toroidal plenum rings of 25 m-diameter, constructed from 0.305 m-diameter irrigation pipe (Lewin et al., 1992). The rings were placed in the sorghum field shortly after planting. The rings had 2.5 m-high vertical pipes with individual valves spaced every two meters around the periphery. Air enriched with $CO_2$ was blown into the rings, and it exited through holes at various elevations on the vertical pipes.

$CO_2$ enrichment was achieved using a computer Control system connected to an anemometer and wind vane. The $CO_2$ concentration was continuously measured at the center of each ring. The computer used wind direction information to turn on only those vertical vent pipes upwind of the plots, so that $CO_2$-enriched air flowed across the plots no matter which way the wind blew. During calm conditions, every other vent pipe was opened. The system used wind speed and $CO_2$ concentration data to adjust $CO_2$ flow rates thus maintaining the desired $CO_2$ concentration at the center of each enriched ring. The FACE $CO_2$ concentration was elevated 200 $\mu$mol mol$^{-1}$ above the ambient concentration (about 360 $\mu$mol mol$^{-1}$ in the daytime) 24 h per day, all season long, except for a few brief periods when there were various mechanical problems. Four matching Control rings with blowers were installed in each replicate. The Control rings provided airflow similar to the FACE rings, but did not provide additional $CO_2$, thereby assuring nearly identical microclimatic effects due to the FACE apparatus (Pinter et al., 2000).

### 2.2. Water treatment

In addition to $CO_2$ enrichment, the experiment utilized a strip-split-plot design to allow two separate water treatments (Ottman et al., 2001; Conley et al., 2001). Each FACE and Control ring was split into two semicircular plots. This enabled one half of each ring to receive ample irrigation (Wet), while the other half was allowed to experience drought stress (Dry). The Wet sides received irrigation to compensate for potential ET according to a schedule produced by Fox et al. (1992). The Dry treatments received only two irrigations each season, amounting to less than half the total water received by the Wet sides through irrigation and rainfall.

Total irrigation in the Wet treatments amounted to 1198 and 894 mm for the 1998 and 1999 seasons, respectively. For the Dry treatments, 454 mm was applied in 1998, while only 338 mm was applied through flood irrigation in 1999. Rainfall during the 1998 season (29 mm) was much lower than in 1999 (126 mm). However, before the late-season major storms in 1999, the Maricopa Agricultural Center Arizona Meteorological Network (AZMET) station (Brown, 1987) received 76 mm of rain. The result was that total water availability during the main parts of the growing season was reduced in 1999 compared with 1998. Total irrigation-plus-rain in 1998 was 1218 and 474 mm for the Wet and Dry treatments, respectively. Prior to the storms of 1999, total irrigation-plus-rain was 970 mm (Wet) and 414 mm (Dry). Thus the Dry plots in 1999 had about 13% less soil water than 1998.

### 2.3. Field layout

The FACE sorghum field consisted of four replicates of four separate treatments. Each replicate contained a FACE ring and a Control ring, and each ring was divided into a Wet side and a Dry side (for a detailed field layout diagram, see Ottman et al., 2001). The resulting treatments for each replicate were as follows: Control–Wet (CW), Control–Dry (CD), FACE–Wet (FW), and FACE–Dry (FD). The replicates were numbered 1–4; however, the number of instruments available to determine the energy balance was sufficient for only Replicates 3 and 4. Thus, the following eight treatment–rep plots were used: CW3, CW4, CD3, CD4, FW3, FW4, FD3, and FD4. Micrometeorological instrumentation described later was placed in each of the eight plots. Additionally, two ambient mini-stations were placed between the FACE and Control rings in Replicates 3 and 4 on the Wet side of the field (plots AW3 and AW4) to provide additional monitoring of foliage temperature and dewfall.

### 2.4. Residual energy balance approach

Determining differences in evapotranspiration in the FACE experiment involved measuring the energy balance in both the FACE and Control plots of the same sorghum field. Besides canopy temperature, net radiation, and other environmental factors, the ultimate goal was to determine ET rates using a residual energy balance approach:

$$R_n = G_0 + H + \lambda \mathrm{ET} \quad (1)$$

where $R_n$ is the net radiation (W m$^{-2}$, positive downward); $G_0$ the soil surface heat flux (W m$^{-2}$, positive downward); $H$ the sensible heat flux (W m$^{-2}$, positive upward); and $\lambda$ET the latent heat flux (W m$^{-2}$, positive upward) where $\lambda$ is the latent heat of vaporization (2.501 MJ kg$^{-1}$)

Upon rearranging the terms in Eq. (1), λET is modeled as the residual when all other terms are measured or calculated:

$$\lambda \mathrm{ET} = R_{\mathrm{n}} - G_0 - H \quad (2)$$

The residual energy balance method was chosen because of its ability to effectively reveal relative differences in ET (e.g., Kimball et al., 1999). Other meteorological methods were determined to be ineffective within the context of a FACE experiment. Methods such as eddy–flux correlation and Bowen ratio techniques are nearly impossible given the limited fetch within an individual FACE plot.

Each factor in Eq. (2) was calculated using measurements from several micrometeorological instruments strategically placed within FACE and Control plots. Then, comparisons of ET for both current ambient $CO_2$ (Control, about 360 μmol mol$^{-1}$) and future $CO_2$ (FACE, about 550 μmol mol$^{-1}$) concentrations were made.

### 2.4.1. Net radiation, $R_n$

Because of its large daytime magnitude, net radiation ($R_{\mathrm{n}}$) is perhaps the most important part of the energy flux equation (Eq. (1)). Measuring $R_{\mathrm{n}}$ is relatively simple when net radiometers are used, provided accurate calibrations are done. The net radiometers (Model Q*6 with ventilators; Radiation and Energy Balance Systems, Seattle, WA) were mounted at a relative height of 1 m above the crop surface in each of the eight plots. Top and bottom sensors were covered by clear plastic domes, which were continuously ventilated to prevent condensation, as well as to obviate the need for wind correction.

In order to remove instrument biases from season-long averages of the comparisons between FACE and Control, the net radiometers were switched weekly between the FACE and Control plots in each replicate and water treatment, according to the following pattern: the FW net radiometer was moved to CW; CW was moved to FW; FD was moved to CD; and CD was moved to FD.

Before the first season started, in between seasons, and after the second season, the radiometers were calibrated against a standard at the US Water Conservation Laboratory. The standard used was a Schulze–Lange ventilated net radiometer (Model LXV 055; DR Lange, Germany) that was never used for routine measurements in the field, being held back only for calibrations. The Schulze–Lange was determined to be one of the most accurate net radiometers by Halldin and Lindroth (1992). During each calibration run, the radiometers were all mounted at 1 m above bare soil, whose surface had been uniformly roughened using a garden rake. Their outputs were recorded for approximately two clear days and nights. Each Q*6 net radiometer output was plotted against the output of the Schulze–Lange standard. Linear regressions were computed for each radiometer and used to convert raw data output (mV) to energy fluxes (W m$^{-2}$).

### 2.4.2. Soil heat flux, $G_0$

A total of 16 heat flux plates were used to measure soil heat transfer. Within each treatment of Replicate 4, four heat flux plates (Model HFT-3, Radiation and Energy Balance Systems, Seattle, WA) were buried at 10 mm and spaced evenly between two rows of sorghum, perpendicular to the orientation of the crop rows. By placing them in this fashion, a more representative soil heat flux could be determined. During the morning, the two sensors nearest the west row received the highest fluxes, while the plates nearest the east row were shaded by plants. In the afternoon and evening, this relationship reversed.

One potential source of error lay in the heat storage of the soil above the plates. To account for this, thermocouples were installed above each plate at a depth of 5 mm. These thermocouples allowed an accurate determination of the heat flux through the soil surface regime by accounting for changes in energy storage below the surface and above the heat flux plates (Kimball et al., 1994). Soil heat flux was determined using the following equation:

$$G_0 = G_{10} + C\,\Delta z\,\frac{\Delta T}{\Delta t} \quad (3)$$

where $G_0$ is the soil surface heat flux (W m$^{-2}$); $G_{10}$ the soil heat flux at 10 mm depth (W m$^{-2}$); $C$ the volumetric heat capacity of upper 10 mm soil layer (MJ m$^{-3}$ °C$^{-1}$); $\Delta z$ the soil depth increment (10 mm); $\Delta T$ the change in soil temperature above the soil heat flux plate (°C); and $\Delta t$ is the time between temperature observations (900 s).

$C$ was calculated following Kimball et al. (1994), who used the individual volumetric heat capacities of

soil minerals, organic matter, and water to determine a combined value of 1.9 MJ $m^{-3}$ °$C^{-1}$. An average water volume fraction of 0.20 was used because calculations showed varying water content from air dry to saturation caused errors in $G_0$ to be less than 2 W $m^{-2}$.

*2.4.3. Sensible heat flux, H*

Determining the final component of the residual energy balance equation, sensible heat flux ($H$), required several meteorological instruments. $H$ was calculated using the following equation:

$$H = \rho_a c_p \frac{T_s - T_a}{r_a} \quad (4)$$

where $\rho_a$ is the air density (kg $m^{-3}$); $c_p$ the heat capacity of air (J $kg^{-1}$ °$C^{-1}$); $T_s$ the "surface" temperature (°C); $T_a$ the air temperature (2 m dry bulb, °C); $r_a$ is the aerodynamic resistance (s $m^{-1}$).

Air density ($\rho_a$) was calculated from the ideal gas law using air temperature and pressure data. An average station pressure of 97.0 kPa was determined from the Arizona Meteorological Network (AZMET) station (Brown, 1987) at the Maricopa Agricultural Center. The heat capacity of air ($c_p$) was considered a constant equal to 1020 J $kg^{-1}$ $K^{-1}$. The other terms in the sensible heat equation ($T_s$, $T_a$, and $r_a$) are discussed in the following sections.

*2.4.3.1. Air temperature, $T_a$.* Air temperature ($T_a$) was measured using aspirated psychrometers installed at a height of 2 m in FW4 and CW4. Each psychrometer was constructed using 0.025 m PVC pipe, reflective coating tape, thermocouple wiring, a 12 V fan, and a ceramic wick (Peresta et al., 1991). Fans were installed in one end of each psychrometer to circulate air through the PVC pipes containing the thermocouple junctions. The fans were wired to 12 V car batteries housed in shelters. The batteries were connected to 110 V chargers that were plugged into ac circuits at the FACE and Control system control boxes.

Thermocouple wiring offered an easy source for temperature measurement, with very little error. In each psychrometer, one thermocouple was mounted inside the PVC pipe to represent dry-bulb temperature ($T_a$). Another thermocouple was mounted inside the ceramic wick, which was kept constantly wet via a vertical PVC reservoir filled with distilled water. This thermocouple was used to measure a wet-bulb temperature for the calculation of vapor pressure. Vapor pressure was then used to correct infrared thermometer readings, as described in the next section. The entire outer surface of each psychrometer was coated with metallic tape to reflect incoming solar radiation, thus keeping the psychrometer body temperatures closer to ambient air temperature. The psychrometers were refilled and serviced several times per week throughout both growing seasons.

*2.4.3.2. Canopy surface temperature, $T_s$.* Canopy surface temperatures ($T_s$) were measured using infrared thermometers (IRTs; Model 4000a, Everest Interscience, Tucson, AZ). A total of 10 IRTs were deployed: 8 for the instrumented plots, plus 1 in each replicate in the open field midway between the FACE and Control rings on the Wet side. The IRTs were mounted about 1 m above the sorghum canopy and adjusted weekly to maintain this relative height. The IRTs were aimed north at a 45° angle below horizontal, downward toward the canopy centered over a row. To minimize solar radiative effects, the IRTs were mounted inside white metal shields. Also, because the IRTs are sensitive to their own body temperature, thermocouples were taped to each body within the sun shield to measure instrument temperature.

Like the net radiometers, all IRTs were calibrated before and after the 1998 season, and again after the 1999 season. The calibrations were done in a temperature-controlled environment using an extended-area blackbody source (Model EABB-250, Advanced Kinetics, Huntington Beach, CA). The calibrations encompassed a wide range of body (0 to 45 °C) and target (−5 to 70 °C) temperatures. These temperature ranges exceed those experienced in the field. Non-linear calibration equations provided corrections for each field sensor based on body temperature and target temperature.

Besides the calibration formulas, IRT data were corrected for reflected sky radiation (Kimball et al., 1995), which was calculated from the 8–14 μm equation of Idso (1981) using air dry bulb and vapor pressure data from the psychrometers. Canopy emittance was assumed to be 0.98.

Similar to the net radiometer rotations, in order to remove instrument biases from season-long averages of the comparisons between FACE and Control, IRTs were switched weekly between the FACE and Control

plots within each replicate and water treatment. In addition, the IRTs from the Wet treatments were also interchanged among the IRTs at the Ambient stations within each replicate according to the following pattern: the CW IRTs were moved to the AW plots; the AW IRTs were moved to the FW plots; and the FW IRTs were moved to the CW plots.

*2.4.3.3. Aerodynamic resistance, $r_a$.* Aerodynamic resistance ($r_a$) was calculated using the methods of Jackson et al. (1987) and Kimball et al. (1994, 1995, 1999). The primary instrument used for this determination was a three-cup anemometer (Model 12102D, R.M. Young Co., Traverse City, MI) mounted at 2 m above the ground near the FACE weather station, which was inside the experimental field between the FACE and Control rings of REP3. When the wind speed was higher than 0.1 m s$^{-1}$, $r_a$ was calculated according to the following equation:

$$r_a = \frac{1}{u}\left(\frac{1}{k}\ln\left(\frac{z-d+z_0}{z_0}\right)\right)^2\phi \tag{5}$$

where $u$ is the 2 m wind speed (m s$^{-1}$); $k$ the von Karman's constant (0.40); $z$ the wind speed height (2 m); $d$ the zero-plane displacement (m); $z_0$ the roughness length (m); and $\phi$ the stability correction.

Roughness length ($z_0$) and zero-plane displacement ($d$) were estimated based on plant height ($h$), according to relationships presented by Azevedo and Verma (1986) for grain sorghum. Three-step regressions were calculated, yielding the following empirical equations to calculate $z_0$ and $d$:

$$z_0 = 0.207h - 0.057; \tag{6}$$

when 0.300 m $< h \leq$ 0.695 m

$$z_0 = 0.094h + 0.022; \tag{7}$$

when 0.695 m $< h \leq$ 0.868 m

$$z_0 = 0.036h + 0.072; \tag{8}$$

when $h >$ 0.868 m (8)

$$d = 0.821h - 0.095; \tag{9}$$

when 0.300 m $< h \leq$ 0.898 m

$$d = 0.481h + 0.211; \tag{10}$$

when 0.898 m $< h \leq$ 1.204 m

$$d = 0.798; \quad \text{when } h > 1.204\,\text{m} \tag{11}$$

When $h$ was less than 0.3 m, the FACE and Control air supply rings were assumed to be disturbing the wind flow over the treatments (Kimball et al., 1999). Therefore, calculations of $z_0$ and $d$ were set to their corresponding values at a minimum height of 0.3 m.

The stability correction term, $\phi$, was calculated using the following equations: Following Mahrt and Ek (1984) for stable conditions, when the crop surface temperature was lower than air temperature ($T_s < T_a$):

$$\phi = (1 + 15Ri)(1 + 5Ri)^{1/2} \tag{12}$$

where

$$Ri \text{ is the Richardson number} = \frac{g(T_a - T_s)(z-d)}{(T_a + 273.16)u^2} \tag{13}$$

where $g$ is the acceleration of gravity (9.81 m s$^{-2}$)

For unstable conditions ($T_s > T_a$):

$$\phi = \left(\frac{1 - 15Ri}{[1 + K(-Ri)^{1/2}]}\right)^{-1} \tag{14}$$

where

$$K = 75k^2\frac{[(z-d+z_0)/z_0]^{1/2}}{\{\ln[(z-d+z_0)/z_0]\}^2} \tag{15}$$

For neutral stability (when $|T_s - T_a| < 0.1\,°C$), and when the wind speed was negligible ($u < 0.1$ m s$^{-1}$), $r_a$ was set to a maximum value of 1720 s m$^{-1}$. Otherwise, during calm conditions, when the temperature gradient between $T_s$ and $T_a$ was greater than 0.1 °C, the following formula from the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE, 1972, p. 40) was substituted to compute $r_a$:

$$r_a = \frac{\rho_a c_p}{1.52|T_s - T_a|^{1/3}} \tag{16}$$

*2.4.3.4. Fetch considerations.* As discussed previously by Kimball et al. (1999), the semicircular plots had a useable radius of only about 10 m, so the fetch was rather short to evaluate the effects of $CO_2$ on ET using micrometeorological methods that rely on measurement of profiles of windspeed, temperature, and water vapor above the crop. However, the residual energy balance technique (Eq. (1)) was reasoned to be less sensitive to the fetch constraints and could be used to determine the relative differences between the FACE and Control plots. The first reason is that all of

the plots were in fields of sorghum where, to a first approximation, the structural elements were close to the same size and geometry everywhere. Therefore, the aerodynamic resistance used in the calculation of *H* and determined from wind speed at a single mast would not be expected to vary much among plots. A second reason is that turbulent transfer processes are a logarithmic function of height above the surface, so that the gradients close to the crop are largest and most important in determining the rates of transfer. In this case, actual crop surface temperatures were measured with infrared thermometers, thereby minimizing fetch requirements.

In their recent paper using the same residual energy balance approach to determine ET in a FACE potato experiment, Magliulo et al. (2003) utilized the work of Brunet et al. (1994) to adjust their surface temperature measurements to a semi-infinite fetch condition. They used the surface temperatures of the Control plots as the upwind condition, and then they divided the differences between FACE and Control plots by a factor from Fig. 8 of Brunet et al. to arrive at "corrected" FACE surface temperatures. In a re-analysis of our data, we followed the approach of Magliulo et al. to estimate surface temperatures for semi-infinite fetch of the FACE treatment. However, because the method introduced another subtraction into the computation, we found that the resultant FACE temperatures and sensible heat fluxes had double the noise (as one should expect from a theoretical error analysis), which greatly reduced confidence about treatment effects.

Magliulo et al. (2003) also introduced corrections into their air temperature measurements based on the work of Itier et al. (1994). However, close examination of their air correction method reveals that they were using this correction to estimate the air temperature over the middle of their small FACE plots from measurements of air temperature from a single weather mast point in their field. In magnitude, their air temperature correction was trivial. What is more important is that their air temperature corrections did not adjust to the semi-infinite fetch condition, and such an adjustment is difficult because of profile adjustments, as addressed in the next paragraph. Therefore, both because of the additional noise introduced with the surface temperature adjustments and because of the profile adjustment concerns with air temperature adjustments to infinite fetch, we have not adjusted the results presented herein. Thus, our measurements represent processes at the plot scale.

Ideally, it is desirable to determine the likely effects of elevated $CO_2$ on ET and the other fluxes for field and regional scales from plot-scale measurements. Moreover, the "semi-infinite" correction introduced by Magliulo et al. (2003) to their surface temperatures is a reasonable approach. However, the question of how to adjust air temperature measurements to make them representative of infinite fetch is profound, and it bears on the whole issue of how profiles of temperature and water vapor adjust to changes in stomatal conductance within the planetary boundary layer as the scale changes from plant to plot to field to region. As addressed in more detail by Kimball et al. (1999), Jarvis and McNaughton (1986) postulated that changes in stomatal conductance would have little effect at regional scales because of such profile adjustments. On the other hand, several more recent papers whose authors used general circulation models (e.g., Sellers et al., 1996) suggest that changes in stomatal conductance are likely to be important at regional scales. Therefore, the reader should probably regard the plot-scale measurements presented herein as indicative of the likely upper range of the effects of a 200 $\mu$mol mol$^{-1}$ increase in $CO_2$ concentration on sensible and latent energy fluxes, recognizing that profile-adjustment feedbacks may cause the ultimate future changes at larger scales to be somewhat smaller. We emphasize, however, that these plot-scale measurements of ET using the residual energy balance approach agree fairly well with those of Conley et al. (2001) made in the same field using an independent soil water balance approach, thereby adding credence to both methods.

## 3. Results and discussion

### 3.1. Foliage temperature differences

For the well-watered Wet irrigation treatment, season-long average FACE foliage temperatures were much warmer than Control during the middle of the day (Fig. 1). At night, when the stomata were closed, this temperature difference was not evident. The maximum midday temperature differences were $1.47 \pm 0.09\,^{\circ}$C in 1998 and $1.85 \pm 0.20\,^{\circ}$C in 1999.

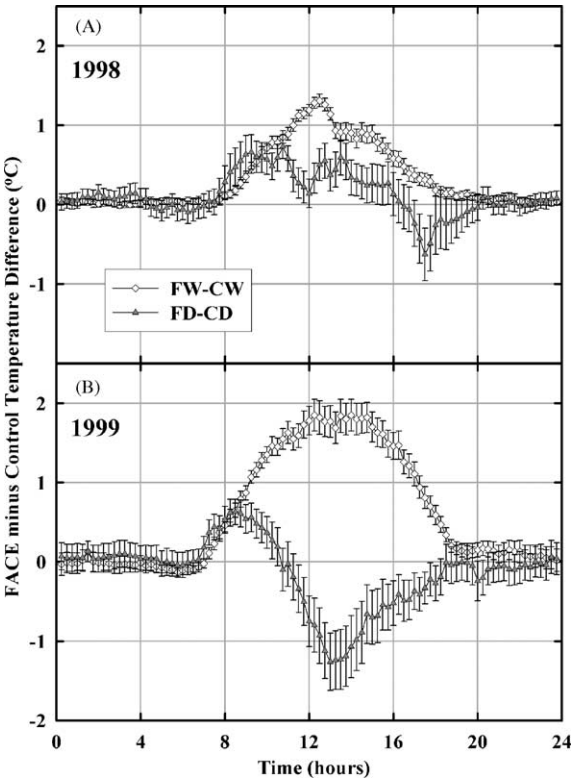


Fig. 1. (A) 1998 and (B) 1999 average diurnal sorghum canopy temperature differences and standard errors vs. time of day between FACE and Control in the Wet (FW–CW; open diamonds) and Dry (FD–CD; filled triangles) treatments. Each data point is an average for that time of day for all the days for which there were good data for complete days from 3 September to 8 November 1998 (A) or 2 July to 16 October 1999 (B).

In the Dry treatments, the diurnal relationship was different. Around sunrise (approximately 7 a.m.), FACE–Dry (FD) plants were warmer than Control–Dry (CD) plants. This difference was consistent through mid-morning. However, during the midday, while the available soil water in the Control Dry treatments began to be depleted, the FACE plants experienced additional transpirational cooling. In 1999 (Fig. 1B), the average midday FD foliage temperatures were actually cooler than those of the CD plants. This demonstrates the $CO_2$ effect on soil moisture. Because the FACE plants used less water relative to the Control plants in the Dry treatments, the $CO_2$-enriched plants were able to conserve water in the soil, even after the Control plants stopped transpiring. Because of this water savings, the FACE plants were able to cool transpirationally throughout the day. The result was that on average FD plants were cooler in the midday and late afternoon than CD plants in 1999. This is consistent with the midday cuvette leaf temperature readings presented by Wall et al. (2001).

In 1998 (Fig. 1A), the midday reversal was not as evident. One possible explanation for this is that the Dry treatments in 1998 received more irrigation water than was planned due to cracked soil (Ottman et al., 2001). Therefore, the plants had more soil water available during that season. The result was that both FACE and Control plants had access to water for transpirational cooling, longer into the day. Since the FACE stomata were less open, the transpirational cooling was decreased, resulting in warmer plants in the $CO_2$-enriched treatments. Similar to 1999, the 1998 foliage temperature differences were slightly negative later in the day, before sunset. This is most likely the result of having the Control plants the most water-stressed, creating warmer leaf temperatures.

### 3.2. Net radiation, $R_n$

Seasonal trends of net radiation ($R_n$, Figs. 2A and B, and 3A and B) declined with day-of-year (DOY) through the growing season as solar radiation decreased due to lowering solar angles. The downward spikes indicate days that were partly cloudy or overcast such that the downward flux of radiation was abruptly decreased. Another factor affecting $R_n$ was the amount of soil exposed. Because the growth response varied depending on treatment, some plots had relatively more soil "visible" to the net radiometer. Because Dry soil has a higher albedo and is warmer than green plant material during the daytime, the upward fluxes of both short- and long-wave radiation were increased in the Dry and Control treatments. Thus, the Dry treatments had slightly lower net radiation than the Wet treatments, since there was more reflected solar radiation from the exposed soil.

The slopes of the regression lines in Figs. 4A and B, and 5A and B indicate reductions in $R_n$ due to FACE of $1.9 \pm 0.3$, $1.7 \pm 0.4$, $2.6 \pm 0.2$, and $0.3 \pm 0.6\%$ for the Wet–1998, Wet–1999, Dry–1998, and Dry–1999 treatment–years, respectively. The FACE–Wet treatments had relatively lower $R_n$ than Control–Wet (Fig. 4A and B) because of the increased thermal radiation from the relatively warmer leaves (Fig. 1),

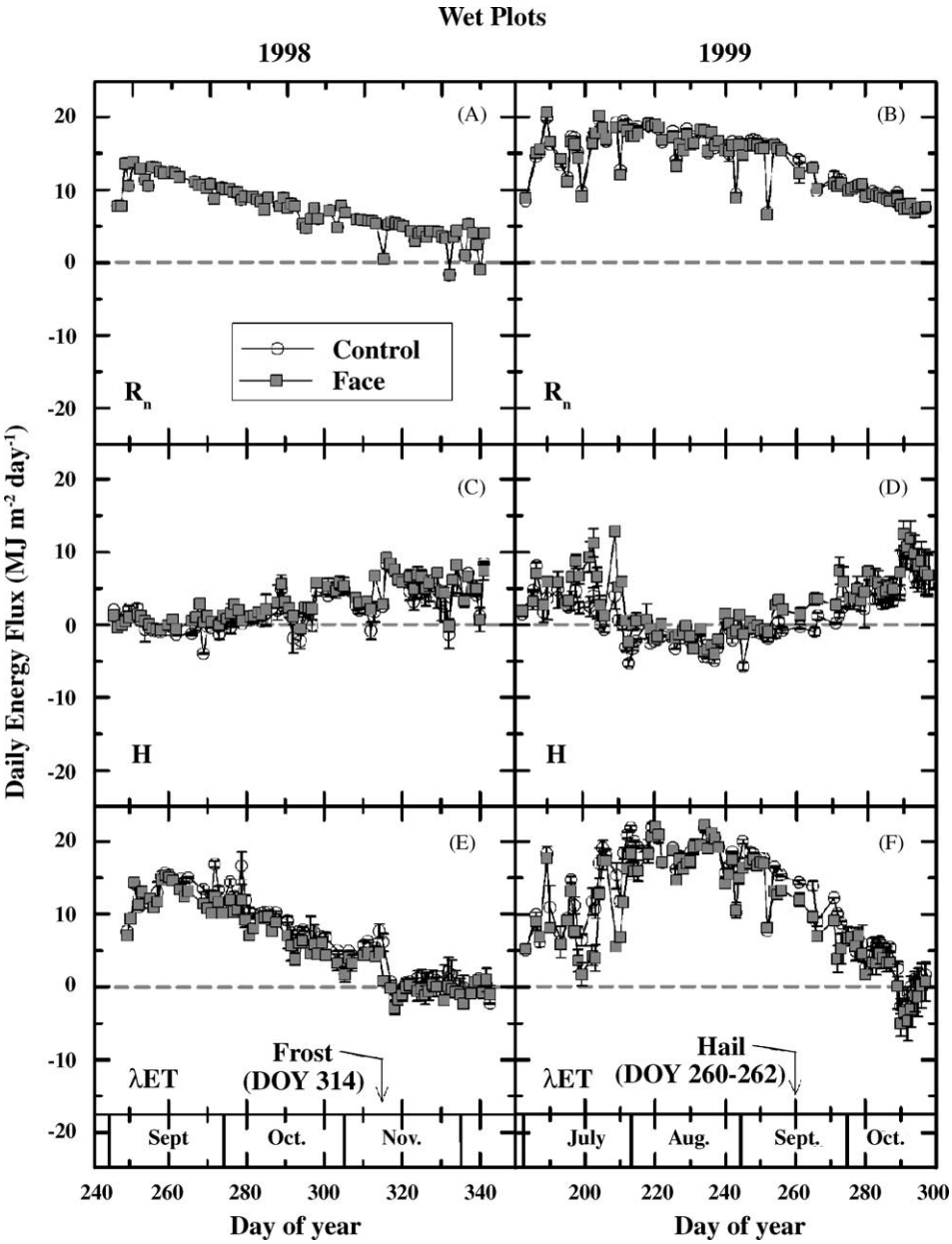


Fig. 2. Total daily energy fluxes vs. day-of-year in FACE–Wet (filled squares) and Control–Wet (open circles) for (A) 1998 $R_n$ (net radiation), (B) 1999 $R_n$, (C) 1998 $H$ (sensible heat flux), (D) 1999 $H$, (E) 1998 λET (latent heat flux), and (F) 1999 λET. Only days with complete, valid data are plotted.

although possible changes in albedo cannot be ruled out. The plant canopies and amounts of exposed bare soil in the Dry plots were more variable than those in the Wet, and except for a few days following irrigation, the Dry treatment affected leaf temperatures more than did the FACE treatment (Fig. 1). Thus, it is not surprising to find somewhat inconsistent effects of FACE on the $R_n$ of the Dry plots (Fig. 5A and B).

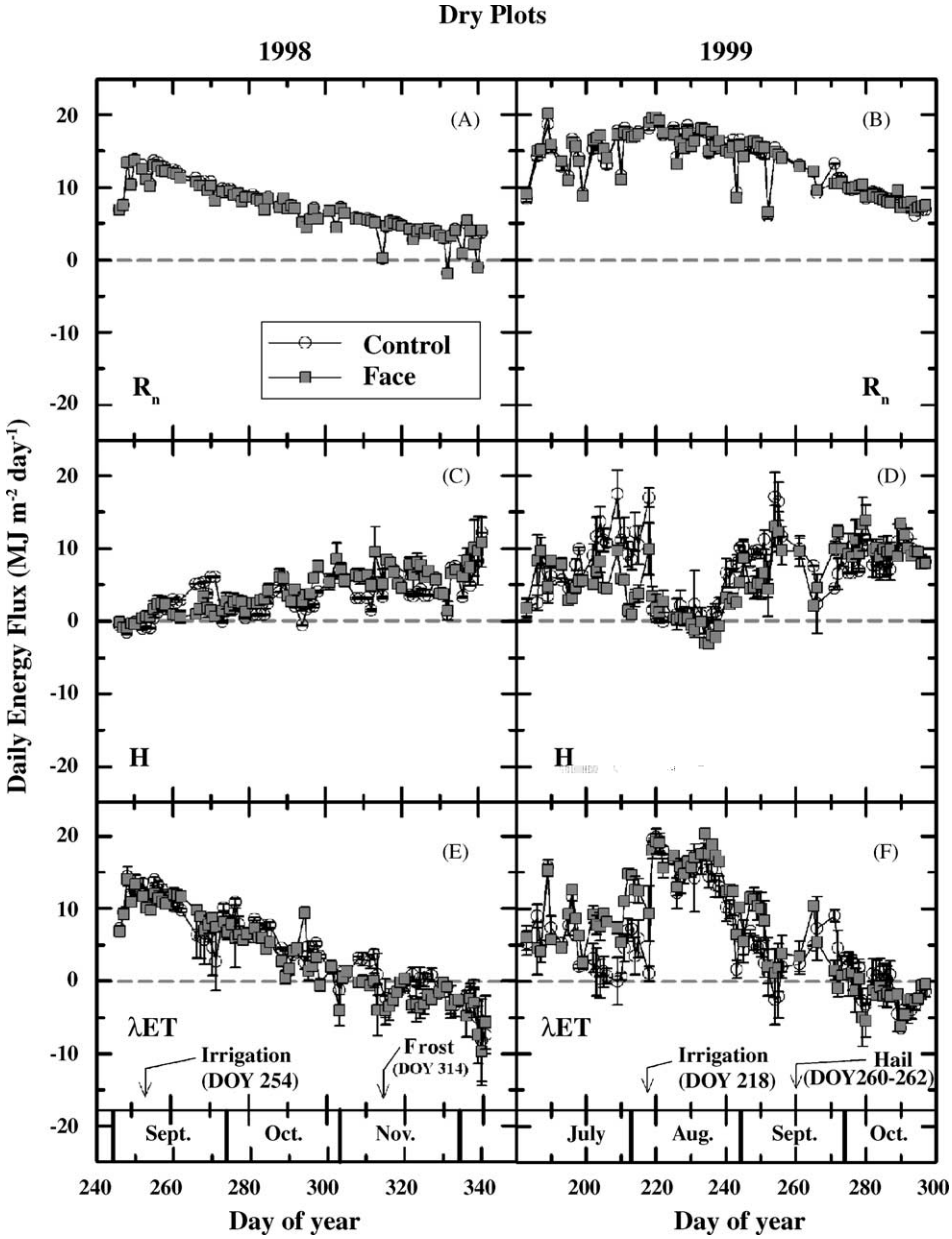


Fig. 3. Total daily energy fluxes vs. day-of-year in FACE–Dry (filled squares) and Control–Dry (open circles) for (A) 1998 $R_n$ (net radiation), (B) 1999 $R_n$, (C) 1998 $H$ (sensible heat flux), (D) 1999 $H$, (E) 1998 λET (latent heat flux), and (F) 1999 λET. Only days with complete, valid data are plotted.

### 3.3. Soil heat flux, $G_0$

For most of the season, daily totals of $G_0$ ranged between $-1.0$ and $+1.0\,\mathrm{MJ\,m^{-2}}$ per day (data not shown). Differences between FACE and Control $G_0$ were even smaller, and therefore, any relative differences in λET due to $G_0$ were minimal. The primary factors affecting $G_0$ were solar radiation and surface soil moisture. Early in the season, when more soil was exposed, the $G_0$ component was typically higher