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Bowen ratio, eddy correlation, and portable chamber measurements of sensible and latent heat flux over irrigated spring wheat*

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ABSTRACT

Dugas, W A , Fritschen, L J , Gay, L W , Held, A A , Matthias, A D , Reicosky, D C , Steduto, P and Steiner, J L , 1991 Bowen ratio, eddy correlation, and portable chamber measurements of sensible and latent heat flux over irrigated spring wheat Agric For Meteorol , 56 1–20

Measurements of the latent (*LE*) and sensible (*H*) heat flux density in the atmospheric boundary layer of irrigated crops have applications for understanding processes in agriculture and meteorology and for water management The objective of this research was to compare measured Bowen ratios and calculated *LE* and *H* from four Bowen ratio systems (BR1–BR4) of different design with each other and with fluxes measured by three sets of eddy correlation instrumentation (*H* and *LE*) and a portable chamber (*LE*) Measurements were made on 9 and 10 April 1989 in an irrigated wheat field at the Maricopa Agricultural Center near Maricopa, Arizona The Bowen ratio system designs varied in terms of temperature and humidity sensors and measurement arm movement Bowen ratios were lower (more negative) on 9 April for all of the systems The range of the four Bowen ratios was greatest in the early morning and late afternoon (±0 1) and least around noon (±0 02) Measured net radiation and soil heat flux density were constant in the Bowen ratio *LE* calculations The range of daytime *LE* from the four systems on 9 April and from three on 10 April was 11% and 1% of the mean *LE*, respectively The three eddy correlation *H* measurements were essentially equal to each

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other The average eddy correlation *H* was 82% and 69% of Bowen ratio *H* on 9 and 10 April, respectively whilst the eddy correlation *LE* was 77% and 67% of Bowen ratio *LE* on the two days On 9 and 10 April portable chamber *LE* was greater than Bowen ratio *LE* during periods of southerly winds owing to the effect of advected energy to the southern field edge where chamber measurements were made On 10 April, portable chamber *LE* was 125% of Bowen ratio *LE* This study has shown that (1) Bowen ratios from instrumentation of different designs were similar, (2) eddy correlation *H* from three systems were similar to each other and were slightly less than Bowen ratio *H*, (3) eddy correlation *LE* was consistently and significantly less than Bowen ratio *LE*, (4) measurements of portable chamber *LE* on the edge of a field were affected by surrounding conditions

INTRODUCTION

Measurements of latent (*LE*) and sensible (*H*) heat flux density in the atmospheric boundary layer are useful for understanding processes in agriculture and meteorology and for water management applications, including calibrating and validating crop and water balance models and remote sensing assessments of crop status Several methods exist for *LE* and *H* measurements (e g lysimeters, water balance, gas exchange with small and large chambers, micrometeorological, and remote sensing), each of which has its own assumptions, spatial and temporal measurement scales, complexity, and expense

The Bowen ratio–energy balance is a micrometeorological method for *LE* measurements that has often been used (Tanner, 1960, Fritschen, 1965, Blad and Rosenberg, 1974, Verma, 1990) with a typical accuracy of approximately 10% (Sinclair et al , 1975) Recently, there have been several presentations of new, or refined, designs of Bowen ratio instrumentation (Bingham et al , 1987, Gay, 1988, Fritschen and Simpson, 1989, Held et al , 1990) A comparison of this new instrumentation has not been conducted

The eddy correlation micrometeorological method can be used to measure *LE* and *H* directly by correlating fluctuations of vertical wind speed with fluctuations of temperature and vapor density, respectively (Swinbank, 1951) Recent availability of reasonably priced commercial instrumentation (Tanner et al , 1985, Shuttleworth et al , 1988) has increased the potential use of this method

Portable chambers are mobile and can be used to measure *LE* from a variety of treatments and locations The accuracy of this method has been demonstrated by comparison with lysimeters (Reicosky et al , 1983), but the representativeness of portable chamber measurements was not addressed in this work

There have been several studies (e g McNeil and Shuttleworth, 1975, Lang et al , 1983, Tanner, 1988) comparing two of these methods, primarily Bowen ratio and eddy correlation Few studies have included portable chambers or the new commercially available eddy correlation instrumentation

The objective of this research was to compare measured Bowen ratios and calculated *LE* and *H* from four Bowen ratio systems (BR1–BR4) of different design with each other and with fluxes measured by three sets of eddy correlation instrumentation (H and LE) and by a portable chamber (LE)

METHODS

Experimental site

Measurements were made on 9 and 10 April 1989 over irrigated spring wheat (*Triticum durum* Desf 'Aldente') at the Maricopa Agricultural Center (33 07°N, 111 98°W), Arizona The annual precipitation at the site is approximately 200 mm The 709 m by 281 m field (Fig 1) was leveled for flood irrigation Soil is a reclaimed Trix sandy loam (fine-loamy, mixed (calcarous), hyperthermic Typic Torrifluvents) Wheat was sown on 16 December 988 in east–west, 0 16 m wide rows About 112 kg N ha^{-1} had been applied t the time of these measurements

The wheat field was bordered on the south and north by bare soil with a dry surface, on the west by irrigated pecans, and on the east by irrigated wheat (Fig 1) On 11 April, the wheat was at Zadoks scale 65, i e halfway flowering (Tottman and Makepeace, 1979), the density was about 140 plants m^{-2}, the crop height was 0 97 m, and the green leaf area index and green stem area

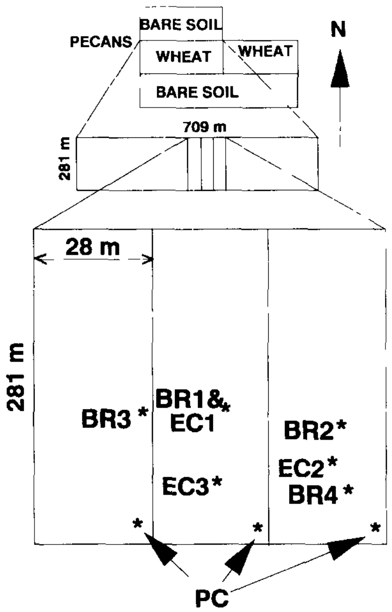

Fig 1 Position of four Bowen ratio systems (BR1–BR4), three eddy correlation systems (EC1–EC3), and portable chamber (PC) measurements in irrigated wheat field Two sets of instrumentation were used with BR1, BR4, EC1, and EC3

index were 4 9 and 1 6, respectively (P Pinter, personal communication, 1989)

The field had 238, 186, 158, and 101 mm of irrigation applied on 20 December 1988, and 16 February, 14 March, and 2 April 1989, respectively On 25 and 26 March 1989, a total of 33 mm of precipitation was measured The wind speed and direction, and wet and dry bulb temperature at 1 5 m were measured near Bowen ratio system No 1 (BR1)

Measurements

Bowen ratio

The *LE* (positive upwards) was calculated from the following

$$LE=\frac{R_n-G}{1+\beta} \tag{1}$$

where net radiation (R_n) and soil heat (G) flux densities were positive downwards and the Bowen ratio (β) was calculated from the following

$$\beta=\frac{P\times C_p}{L\times\epsilon}\times\frac{\Delta T}{\Delta e} \tag{2}$$

where P is atmospheric pressure, C_p is specific heat of dry air, L is latent heat of vaporization, ϵ is ratio of molecular masses of water to dry air, and ΔT and Δe are finite differences of above-canopy potential temperature and vapor pressure In eqn (2), it was assumed that eddy diffusivities for heat and water vapor were equal, and that ΔT and Δe were measured over the same height intervals Some previous research supports the assumption of equal diffusivities (Tanner, 1960, Dyer, 1974), but other research presents conflicting results on this, especially under stable atmospheric conditions caused by local advection (Verma et al , 1978, Motha et al , 1979, Lang et al , 1983) Measured R_n and G were common for all *LE* calculations (eqn (1)) for each Bowen ratio system

The R_n was measured at the BR1 position with a Model 622 net radiometer (Swisstecho Type S-1, Science Associates, Princeton, NJ) mounted at 1 35 m above the soil Sensor sensitivity was determined by comparison with measurements in March 1989 over grass using a laboratory transfer standard of the same design

G was calculated from storage above 50 mm and from the flux measured at 50 mm with four Model HFT-1 soil heat flux plates (Radiation Energy Balance Systems, Seattle, WA) using factory sensitivities and correcting for plate shape and differences in plate and soil thermal conductivity (Philip, 1961) Storage was calculated from soil temperature measured as an average of temperatures at 17 and 34 mm depths at four locations and from soil heat capacity (2 4 MJ m^{-3} K^{-1}) calculated from soil water content measurements (F Nakayama, unpublished data, 1989) Heat flux plates and thermocouples were placed at under- and mid-row positions near BR1

The four Bowen ratio systems (BR1–BR4) were from 55 m (BR4) to 102 m (BR1) north of the southern field edge (Fig 1) The BR1 system was 258 m west of the eastern field edge For each Bowen ratio system, temperature and humidity measurements were made at two heights The Bowen ratio systems differed in terms of sensors for ΔT and Δe measurements and measurement arm movement

Bowen ratio system No 1 (BR1) Measurements were made continuously during the two days using instrumentation similar to the design of Tanner et al (1987) Dry bulb and dew point temperatures were measured on two sets of instrumentation 3 m apart The heights of the two fixed measurement arms of the first set remained at 1 6 and 2 6 m above the soil, while those of the second set were moved from these heights to 1 3 and 2 3 m at 07 00 h, Mountain Standard Time, on 10 April On each set of instrumentation, two ΔT measurements were made using two pairs of differentially-wired, unaspirated, unshielded fine-wire (diameter, 25 4 μm) chromel–constantan thermocouples The dew point temperature for each arm was measured using one cooled-mirror hygrometer (Model DEW 10, General Eastern, Watertown, MA) that sequentially sampled air from each measurement arm for 1 min The e for each arm was calculated from dew point temperatures measured for the last 30 s of each minute Thus, there were two Bowen ratios, with a common Δe, per set of instrumentation One ΔT from the second set of instrumentation was excluded from the analyses owing to atypical values (results not shown) Dry bulb and dew point sensors were sampled every 2 s and 30 min or 10 min (after 13 10 h on 9 April) averages were calculated Three 10 min Bowen ratios were averaged to determine half-hour Bowen ratios

Bowen ratio system No 2 (BR2) Measurements were made continuously on 9 April and up until 14 00 h on 10 April using instrumentation described by Fritschen and Simpson (1989) Dry and wet bulb temperatures were measured at 1 2 and 2 2 m above the soil with fan-aspirated, platinum resistance temperature sensors mounted on measurement arms that interchanged every 15 min to minimize sensor bias Ceramic wicks were used for wet bulb temperature measurements The e was calculated from dry and wet bulb temperatures Sensors were sampled every 30 s and 30 min averages were calculated

Bowen ratio system No 3 (BR3) Measurements were made between, approximately, 08 00 and 18 00 h during the two days using instrumentation described by Held et al (1990) Dry and wet bulb temperatures were measured at 1 1 and 1 9 m above the soil with fan-aspirated, platinum resistance temperature sensors that were mounted on fixed measurement arms Braided cotton wicks were used for wet bulb measurements Because of fixed measurement arms, ΔT and Δe measurements were adjusted using a constant bias taken from Held et al (1990) The e was calculated from dry and wet bulb temperatures Sensors were sampled every 10–20 s and 5 or 10 min averages were calculated Half-hour averages of Bowen ratios were calculated as a weighted average from 5 or 10 min averages

Bowen ratio system No 4 (BR4) Measurements were made continuously during the two days using instrumentation described by Gay (1988) This instrumentation is similar to that of BR2 Two sets of instruments, approximately 25 m apart, were used Dry and wet bulb temperatures were measured at 1 0 and 2 0 m above the soil on both sets of instrumentation with fan-aspirated, nickel-iron resistance temperature sensors mounted on measurement arms that interchanged every 15 min to minimize sensor bias Ceramic wicks were used for wet bulb measurements The e was calculated from dry and wet bulb temperatures Sensors were sampled every 10 s and averages for 12 min periods were calculated using measurements from 3 and 6 min and from 9 and 12 min after measurement arms interchanged The two Bowen ratios were averaged into a single Bowen ratio for BR4 Half-hour averages of Bowen ratios were calculated as a weighted average, from 12 min averages

Eddy correlation

Eddy correlation instrumentation used in this study has been described by Tanner et al (1985) and Tanner (1988) For H, instrumentation consisted of Campbell Scientific, Inc , (CSI, Logan, UT) Model CA27 single-axis sonic anemometers (pathlength, 0 1 m, frequency response, 40 Hz) and fine-wire thermocouples (type E, diameter, 12 5 μm, positioned 30 mm from sonic anemometer acoustic path) The LE was measured using the sonic anemometer and a CSI Model KH20 hygrometer Factory calibrations were used for all sensors Scanning frequency, measurement height, position in the field, and azimuthal orientation differed between the three sets of instrumentation

The H was calculated from the following (Tanner et al , 1985)

$$H=C_{\mathrm{p}}\times\rho\times\overline{w'T'} \quad (3)$$

where ρ is air density which was calculated (Fritschen and Gay, 1979) from air temperature and pressure (assumed to be a constant 97 15 kPa), w is vertical wind speed, and T is air temperature It was assumed the long-term mean vertical wind speed was zero (Dyer, 1961) The overbar indicates a time-averaged mean and primes indicate deviations from the time-averaged mean

The LE was calculated from the following

$$LE=L\times\overline{w'\rho_{\mathrm{v}}'} \quad (4)$$

where ρ_v is vapor density and LE was corrected for effects of oxygen absorption on ρ_v measurement (Tanner and Greene, 1989) and of air density on w (Webb et al, 1980) These two corrections were typically -20 W m^{-2} and -10 W m^{-2}, respectively at midday

Eddy correlation No 1 (EC1) Two sonic anemometers and one hygrometer were used in this set of instrumentation Measurements were made continuously for two days The two sonic anemometers were 3 m apart, 2 15 m above the soil, at the BR1 position (Fig 1) and oriented toward the west The spacing between the first sonic anemometer and hygrometer measurement paths was 0 13 m At 07 30 h on 10 April, the second sonic anemometer was moved to 1 64 m Signals from the two sonic anemometers were scanned at 5 Hz and 10 Hz, respectively Prior to 13 20 h on 9 April, the averaging interval for covariance calculations (Tanner and Greene, 1989) was 15 min and half-hour averages of H were output Averaging and output intervals were 10 min thereafter Half-hour H averages were calculated from 10 min averages

The two H values from the two sonic anemometers were averaged for EC1 since they were essentially equal and independent of scanning rate or measurement height The root mean square error of the half-hour H was 21 W m^{-2} and 9 W m^{-2} on 9 and 10 April, respectively The maximum difference between the two half-hour H values was ± 40 W m^{-2} on each day and there was no consistent pattern of differences between the two H values The average daytime H from the two sonic anemometers differed by only 11 W m^{-2} and 7 W m^{-2} on 9 and 10 April, respectively

Eddy correlation No 2 (EC2) The one sonic anemometer used in this set of instrumentation was 1 8 m above the soil, positioned 84 m north of the south field edge (Fig 1), and oriented toward the west Measurements were made continuously for the two days Signals were scanned at 5 Hz Output and averaging intervals were 12 min Half-hour averages of H were calculated as a weighted average from 12 min averages

Eddy correlation No 3 (EC3) The two sonic anemometers used in this set of instrumentation were 2 m apart, 2 0 m above the ground, positioned 60 m north of the south field edge (Fig 1), and oriented toward the south Measurements were made from 09 00–19 00 h on both days Signals were scanned at 5 Hz Output and averaging intervals were 5 min Half-hour averages of H were calculated from 5 min averages

Because of equipment malfunction, several H measurements from the second sonic anemometer were not available The average H from the two sonic anemometers was used, except when data from the second anemometer was not available When H from both sonic anemometers was available, H from the second sonic anemometer was approximately 10% lower (more negative), especially at large negative H The root mean square error of half-hour H was 23 W m^{-2} and 17 W m^{-2} on 9 and 10 April, respectively

Portable chamber

The portable chamber in this study was operated following the procedures of Reicosky and Peters (1977) The LE was calculated from the slope of vapor density vs time, chamber volume, soil surface area, and latent heat of vaporization (Reicosky and Peters, 1977, Reicosky et al , 1983, Reicosky, 1990, Reicosky et al , 1990) Clear plastic (Lexan) covered a square metal frame with a volume of 3 25 m^3 and an area of 2 67 m^2 The vapor density differences were measured with a BINOS (Inficon Leybold-Heraeus, Inc , E Syracuse, NY) infrared gas analyzer, operated in the differential mode with a range of ±5 mmol mol^{-1} and calibrated (Reicosky et al , 1983) for a 5°C dew point

Measurements were made at the southern edge of three of the 28 m wide borders (Fig 1) Measurements were made near the field edge because of the need for tractor access On 9 April, the southeast corner of the chamber was 5 5 m north and 3 7 m west of the southeast field border corner Until 14 00 h on 10 April, the southeast chamber corner was 8 2 m north and 5 5 m east of the field corner Thereafter, it was 11 9 m north and 6 7 m east of the corner Measurements were made once per hour for 1 min in each border The gas analyzer output was measured every 2 s and data recorded between 30 and 60 s after the chamber was in place were used Measurements within half-hour periods (e g 10 00–10 30 h) and across borders were averaged There was little variation in LE between the three borders The coefficient of variation of daily LE from the three borders was 7% and 3% on 9 and 10 April, respectively

The large diurnal range of dew point temperatures over the wheat caused problems because the gas analyzer output became non-linear when dew point temperatures exceeded 15°C When dew points in the chamber exceeded 15°C (typically, early afternoon), the slope of vapor density vs time was calculated from 30–50 s after the chamber placement Data recorded between 12 00 and 15 30 h on 9 April were not available due to equipment failure

RESULTS AND DISCUSSION

On 9 and 10 April in the irrigated wheat field, maximum temperatures were approximately 33°C, minimum temperatures were 10 and 16°C on the two days, dew point temperatures varied from about 3°C in the early morning to about 15°C in the early afternoon, and maximum R_n and G on each of these two clear days were approximately 600 W m^{-2} and 100 W m^{-2}, respectively Wind speeds were greater on 9 April and gradually increased throughout the

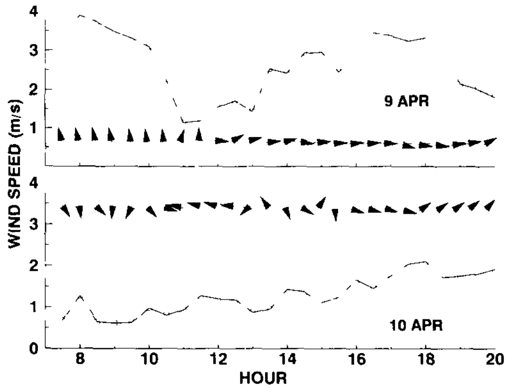

Fig 2 Half-hour averages of wind speed and direction (arrows point in the direction the wind is blowing) on 9 and 10 April Averages are plotted at the end of the period

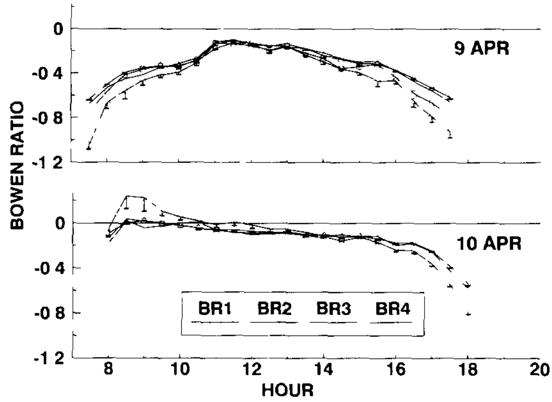

Fig 3 Half-hour averages of Bowen ratio from four Bowen ratio systems (BR1–BR4) on 9 and 10 April Standard deviation of three Bowen ratios for BR1 and absolute value of the range of two Bowen ratios for BR4 are shown as horizontal bars below data points Averages are plotted at the end of the period

day on 10 April (Fig 2) The wind direction varied throughout each day (Fig 2) On 9 April, the wind direction was southerly up until 11 30 h and westerly thereafter On 10 April, the wind direction was northwesterly to northeasterly up until 10 30 h, was variable until 15 30 h, and was westerly or southwesterly thereafter

Bowen ratio

Bowen ratios were lower (more negative) on 9 April (Fig 3) The large negative Bowen ratios, up until 10 00 h on 9 April, were a result of energy advected to the wheat from the dry bare soil field to the south (Fig 1), caused by high southerly winds (Fig 2) Increases in Bowen ratios between 10 00 and 11 00 h on 9 April were associated with a decrease in wind speed (Fig 2)

There was little variation in the multiple Bowen ratios from BR1 and BR4 (Fig 3), except in the morning on 10 April The variation in Bowen ratios from BR4 was less than that from BR1 The average of the standard deviations of the three Bowen ratios from BR1 was 0 03 on both days, while the average of the absolute values of the range of two Bowen ratios from BR4 was 0 01 on both days There was no consistent bias of individual Bowen ratios for either system (results not shown)

Variability between Bowen ratios from different systems can be more clearly seen by examining the differences between the Bowen ratio from each system and the mean of the four Bowen ratios (Fig 4) On both days, the range of Bowen ratios was greatest in the morning and afternoon (about ±0 1) and least at around noon (about ±0 02) On 9 April, the differences were consistently positive for BR1, generally negative for BR4, and fluctuated from slightly positive to slightly negative for BR2 and BR3 On 10 April, Bowen ratios from BR2, BR3, and BR4 were similar throughout the day whilst those from BR1 were slightly lower in the morning and greater in the afternoon

On both days, changes in wind direction (Fig 2) did not affect the relationship between the four Bowen ratios (Fig 4) Since temperature and vapor conditions of the surrounding surfaces varied markedly due to surface cover and irrigation amounts this lack of variation in Bowen ratios, despite changes in wind direction, suggests there was adequate fetch for all systems This is also supported by the small range of Bowen ratios from the two sets of instrumentation for BR4 which were 55 and 80 m north of the southern field edge

Differences in measurement arm heights affected ΔT and Δe The ΔT and

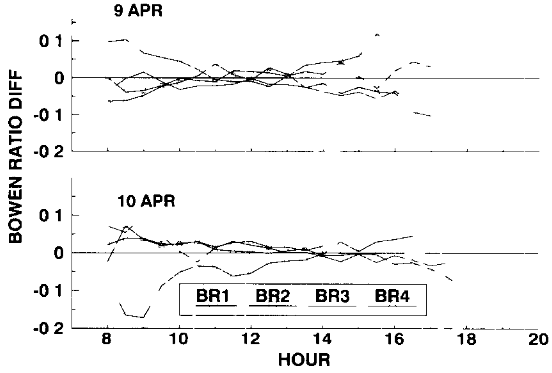

Fig 4 Differences of half-hour Bowen ratios from four Bowen ratio systems (BR1–BR4) on 9 and 10 April Differences were calculated as the mean of the four Bowen ratios (three after 14 00 h on 10 April) minus the individual Bowen ratio and are plotted at the end of the period

Δe from BR3 were biased low because measurement arm spacing was only 0 8 m vs 1 0 m for the other systems The ΔT was consistently greatest (least negative) from BR1, which had the highest sensors, and least (most negative) from BR4, which had the lowest sensors (Fig 5) The decrease in wind speed at 11 00 h on 9 April (Fig 2) caused an increase in ΔT from all the systems

Variability of temperature differences, as with the Bowen ratios, was less for BR4, which used interchanging arms and aspirated, shielded temperature sensors, than for BR1 The mean of the standard deviations of the three temperature differences for BR1 was 0 06°C and 0 11°C on 9 and 10 April, respectively The mean of the absolute values of the range of the two temperature differences for BR4 was 0 04 and 0 02 on the two days The larger variability on 10 April for BR1 was caused by changing measurement arm heights on the second set of instrumentation

The Δe was greatest for BR4 and least for BR1 (Fig 6) and the variability was similar for both BR1 and BR4 The mean of the absolute values of the range of the two vapor pressure differences for BR1 was 0 01 and 0 04 kPa on the two days, comparable means for BR4 were 0 01 and 0 02 kPa Again, the variation for BR1 increased because of changing arm heights

The LE calculated from the Bowen ratios was high for both days (Fig 7) On 9 April, the LE calculated between 08 00 and 10 30 h was especially high because of the advected energy The LE calculated from all of the systems decreased in association with the decrease in wind speed at 11 00 h (Fig 2) The LE was still high, approximately 400 W m^{-2}, at 17 00 h on 9 April The

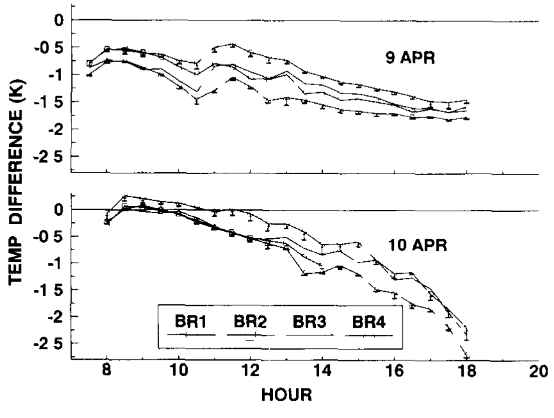

Fig 5 Half-hour averages of dry bulb temperature difference (lower minus upper measurement) from four Bowen ratio systems (BR1–BR4) on 9 and 10 April Standard deviation of three temperature differences for BR1 and absolute value of the range of two differences for BR4 are shown as horizontal bars below data points Averages are plotted at the end of the period

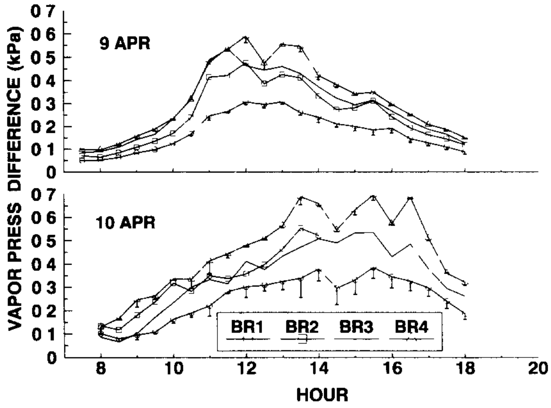

Fig 6 Half-our averages of vapor pressure difference (lower minus upper measurement) from four Bowen ratio systems (BR1–BR4) on 9 and 10 April Absolute value of the range of two differences for BR1 and for BR4 is shown as horizontal bars below data points Averages are plotted at the end of the period

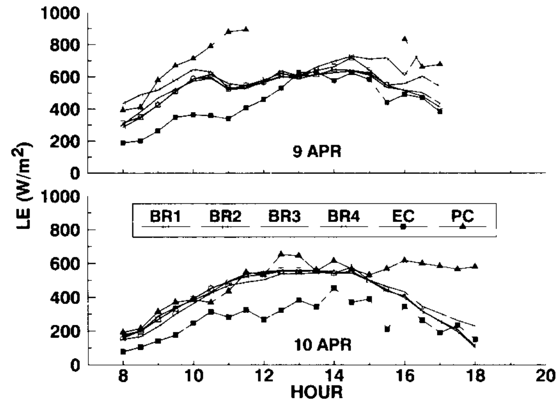

Fig 7 Half-hour latent heat flux density (*LE*) calculated from measurements from four Bowen ratio systems (BR1–BR4) and measured by eddy correlation (EC) and portable chamber (PC) instrumentation on 9 and 10 April Values are plotted at the end of the period

larger *LE* calculated from BR1 and BR2 after 16 00 h on 9 April was associated with Bowen ratios from these two systems approaching – 1 0 (Fig 3) On 10 April, the *LE* was lower in the morning and afternoon than on 9 April The range of *LE* across the four systems was less on 10 April (Fig 4), primarily because Bowen ratios were near values where calculated *LE* is relatively insensitive to variation in Bowen ratios (Angus and Watts, 1984)

The range of daytime *LE* (07 30–16 00 h) from the four systems was 11% of the mean *LE* on 9 April (Table 1) A greater *LE* from BR1 was caused by Bowen ratios near – 1 0 in both the morning and afternoon (Fig 3) On 10

TABLE 1

Average latent heat flux density (W m^{-2}) calculated from four Bowen ratio systems (BR1–BR4) and measured by eddy correlation (EC) and portable chamber (PC) instrumentation on 9 and 10 April

Date	Hours (h)	BR1	BR2	BR3	BR4	EC	PC
9 April	7 30–16 00	603	554	540	545	–	–
	7 30–17 00	631	556	533	535	436(77)	-
10 April	7 30–14 00	404	432	431	428	-	–
	7 30–18 00	399		399	396	266(67)	497(125)

Values in parentheses represent a percentage of average Bowen ratio latent heat flux density

April, the range of daytime *LE* from BR1, BR3, and BR4, which had data the entire day (07 30–18 00 h), was only 1% of the mean *LE* When data from all the systems were available, the range of *LE* from the four systems was 6%

Eddy correlation

The *H* was more negative on 9 April from all three sets of eddy correlation instrumentation (Fig 8) The three eddy correlation *H* measurements were similar Dugas (1991) also showed internal consistency for *H* measurements using this instrumentation The EC3 *H* was usually the greatest (least negative), whilst *H* measurements from EC1 and EC2 were similar to each other

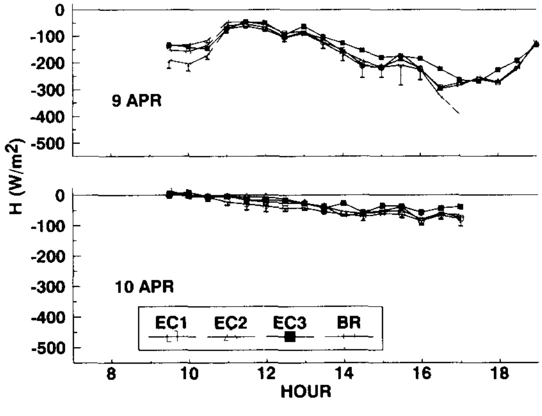

Fig 8 Half-hour sensible heat flux density (*H*) measured by three eddy correlation systems (EC1–EC3) and calculated as an average from Bowen ratio measurements (BR) on 9 and 10 April Standard deviations of Bowen ratio *H* are shown below data points, except for the last two standard deviations on 9 April because they were off scale Averages are plotted at the end of the period

and were lower than those for EC3 (Table 2 and Fig 8) The similarity of H from EC1 and EC2 was also reflected in similarity of vertical wind speed and temperature variances (results not shown) The greater (less negative) EC3 H was probably caused by two factors

(1) The 5 min averaging interval for EC3 excluded low frequency eddies (Tanner, 1988, Verma, 1990) and is most likely too short

(2) The southern azimuthal orientation of the EC3 sonic anemometers resulted in periods when they were not pointed into the wind The EC3 H was very different from the other two (Fig 8) during periods of westerly winds (Fig 2) The EC1 and EC2 sonic anemometers were oriented to the west

The Bowen ratio H, calculated as a residual from the energy balance equation using R_n, G, and the Bowen ratio LE, was often less (more negative) than that from eddy correlation instrumentation (Fig 8 and Table 2) Differences were greatest in the early morning and late afternoon of 9 April, partially because of unstable calculations of Bowen ratio LE owing to Bowen ratios approaching -1 The differences between the eddy correlation and Bowen ratio H were generally less than the standard deviation of the Bowen ratio H (Fig 8) The average eddy correlation H was 82% and 69% of average Bowen ratio H on 9 and 10 April, respectively The differences between the Bowen ratio and eddy correlation H were less in this study than those shown by McNeil and Shuttleworth (1975), perhaps because of the faster response of the sonic anemometer used in this study The underestimate of eddy correlation H relative to Bowen ratio H may be explained by the following

(1) Systematic overestimation of available energy This would have decreased Bowen ratio H (i e , made it more negative) There is, however, no reason to believe R_n measurements were systematically high or G measurements were low Other measurements of R_n and G in the same field (L J Fritschen and L W Gay, unpublished data, 1989) compared favorably with measurements used in this study

(2) Sonic anemometer frequency response Given the atmospheric stability conditions, sensor and canopy heights, and wind speeds during this exper-

TABLE 2

Average sensible heat flux density (W m^{-2}) measured by three eddy correlation systems (EC1–EC3) and calculated from Bowen ratio (BR) measurements on 9 and 10 April The BR values were calculated as an average from four systems

Date	Hours (h)	EC1	EC2	EC3	BR
9 April	9 00–17 00	−148(83)	−155(87)	−135(76)	−178
10 April	9 00–17 00	−35(78)	−33(73)	−25(56)	−45

Values in parentheses represent a percentage of BR sensible heat flux density iment, corrections to eddy correlation H because of sonic anemometer frequency response (Moore, 1986) would have been to make H more negative by approximately 5% This correction was not made

(3) The reference temperature time constant for the T' measurements (eqn (3)) may have been too short for averaging periods (Gaynor and Biltoft, 1989) This could have reduced the magnitude of eddy correlation H, although there were no abrupt changes in diurnal temperatures which would exacerbate this problem This would have reduced the magnitude of the flux

(4) Assuming the equality of heat and vapor eddy diffusivities may not be valid under these stable atmospheric conditions If the ratio of heat and vapor diffusivities was less than 1, as suggested by Lang et al (1983) for stable conditions caused by local advection, the Bowen ratio H would have been increased (i e been made less negative) and would have been more similar to the eddy correlation H However, if this diffusivity ratio was greater than 1, as suggested by Verma et al (1978) and Motha et al (1979), the differences would have been increased It was not possible to independently calculate this diffusivity ratio from eddy correlation H and LE measurements (e g Lang et al , 1983) owing to lack of energy balance closure using eddy correlation H and LE

The sum of the average of the three H measurements and the one LE measurement, from eddy correlation instrumentation, was always less than the available energy, except at 13 00 and 13 30 h on 9 April (Fig 9) Canopy heat storage was not a significant factor in the canopy energy balance at this time (Tanner, 1960) Results also demonstrating a lack of energy balance closure with this instrumentation were presented by Tanner et al (1985)

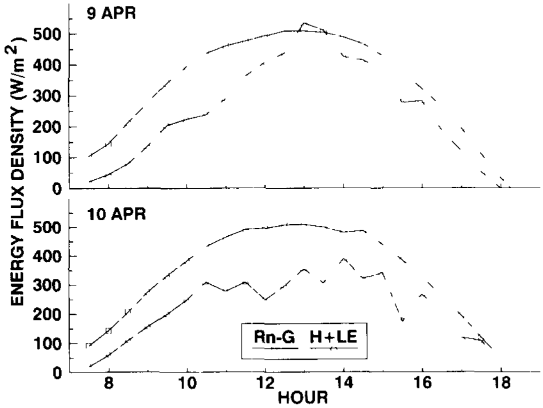

Fig 9 Half-hour averages of available energy (net radiation (R_n) minus soil heat (G) flux density) and the sum of eddy correlation sensible (H) and latent (LE) heat flux density on 9 and 10 April Averages are plotted at the end of the period

More recent work (Tanner, 1988) showed a good energy balance closure with this instrumentation. However, *LE* in the latter study averaged only approximately 110 W m^{-2} and an underestimate of *LE*, the most likely cause of lack of energy balance closure, would have had a smaller effect on closure

The small differences between *H* from eddy correlation and Bowen ratio instrumentation (Fig 8), especially when Bowen ratios were not approaching -1 (Fig 3), and the consistent and large underestimate of *LE* by eddy correlation instrumentation relative to that calculated from Bowen ratio measurements (Table 1 and Fig 7) support the premise that the lack of energy balance closure from eddy correlation instrumentation was primarily a result of underestimated *LE* Periods of energy balance closure (Fig 9) coincided with times when the eddy correlation *LE* and Bowen ratio *LE* were about equal (Fig 7) Kizer et al (1988) showed that alfalfa *LE* measured with the same eddy correlation instrumentation was only 81% of *LE* calculated as a residual from R_n, G, and eddy correlation *H* measurements

Portable chamber

The portable chamber *LE* was consistently greater than the average Bowen ratio *LE* on 9 April (Fig 7) The portable chamber *LE* did not show the same decrease, as did Bowen ratio and eddy correlation *LE*, at 10 30 h on 9 April associated with the decrease in wind speed (Fig 2) On 10 April, the portable chamber and Bowen ratio *LE* were similar up until 15 00 h (Fig 7), where upon the portable chamber *LE* continued at a higher rate whilst the Bowen ratio *LE* and the available energy (Fig 9) decreased On 10 April, the portable chamber *LE* was 125% of the average Bowen ratio *LE* (Table 1)

The greater portable chamber *LE* in the morning of 9 April and the afternoon of 10 April was a result of energy advected to the southern field edge, where portable chamber measurements were made, owing to southerly winds up until 11 30 h on 9 April and southwesterly winds after 15 30 h on 10 April (Fig 2) This energy increased the portable chamber *LE* relative to that measured by Bowen ratio instrumentation, even though once the chamber was in place, plants were isolated from the surrounding conditions A similar effect on *LE* at the edge of a field of well-watered crops due to energy advected from bordering dry conditions has been documented by others (Davenport and Hudson, 1967, Brakke et al , 1978, Dugas and Bland, 1989)

CONCLUSIONS

In an irrigated wheat field, *LE* and *H* measurements were made using Bowen ratio, eddy correlation, and portable chamber instrumentation The Bowen ratios and calculated *LE* from four Bowen ratio systems were similar The range of Bowen ratios from the four systems was approximately ±0 1 in the morning and afternoon and approximately ±0 02 around noon The range of the four *LE* values was approximately 10% for the two days Given the similarity of the Bowen ratio and the *LE* from these different Bowen ratios systems, it is appropriate to discuss aspects of each design

For BR1, fixed measurement arms simplify power and electronic requirements and allow for extended, non-attended field use (e g Dugas and Mayeux, 1991) Using a cooled-mirror hygrometer for dew point temperature measurements on both arms eliminates the problems of sensor bias for this measurement, although condensation in tubing and bottles upstream from the mirror may occur under high humidities Using unaspirated, unshielded fine-wire thermocouples, although easily repaired and replaced, introduces a possible problem associated with radiation-induced temperature errors (Bingham et al , 1987) especially with low wind speeds Thermocouples are also susceptible to breakage

The BR2 and BR4 are similar in design and will be discussed simultaneously Systems of this design have been operated reliably for long periods in a variety of environments In this study, variations of the Bowen ratio and ΔT between the two systems for BR4 were less than those for BR1 Interchanging arms minimize problems with sensor bias, but increase electronics complexity and power requirements Resistance temperature sensors used in this study require adequate shielding and ventilation, increasing power consumption Wet bulb temperature sensors require a system for maintaining a steady flow of water to ceramic wicks and a periodic evaluation to ensure wicks are clean

The BR3 is similar to BR2 and BR4 except measurement arms do not interchange This simplifies electronics and power requirements, but may introduce errors in temperature and humidity measurements owing to sensor bias This bias can, however, be accounted for by using the measured difference in wet and dry bulb temperatures when a common air source is passed over all sensors simultaneously (Held et al , 1990) However, this correction is not likely constant over time, sensors, or surfaces and must be known

Eddy correlation *H* measurements using three sets of instrumentation, were essentially equal to each other on both days and were slightly greater (less negative) than those calculated from Bowen ratio measurements The eddy correlation *LE* was significantly and consistently less than the Bowen ratio *LE*

The portable chamber *LE* was consistently greater than that calculated from Bowen ratios at times when the wind direction caused dry air from an adjacent bare soil field to be advected to the field edge where chamber measurements were made These results suggest portable chamber *LE* measurements, which are typically made near a field edge, may be significantly affected by energy advected from a nearby dry surface and thus may not be representative of the entire field

Each of these types of instrumentation has positive and negative features Bowen ratio systems are relatively inexpensive A complete system (BR1), including data logger, sensors, and power supplies, costs approximately US$6300 Bowen ratio measurements are independent of weather and provide a measurement that is a spatial average of upwind conditions Fluxes, however, are calculated from and dependent upon the accuracy of other measurements Assuming equal eddy diffusivities may not be valid under certain conditions

Eddy correlation instrumentation provides absolute measurements of *H* or *LE* without any assumptions regarding diffusivities (Verma, 1990) The costs for eddy correlation systems used in this study are similar to those for Bowen ratio systems (sonic anemometer about US$2100, hygrometer about US$3900, and data logger about US$2000) These sonic anemometers do not operate properly during precipitation and can be damaged by precipitation

Portable chambers provide an absolute, instantaneous measurement of *LE* at one point in space They are mobile, which allows for measurements at multiple locations over a reasonably short time period The costs for components (Reicosky, 1990) are high (about US$55 000 for the equipment used in this study) The key components, an infrared gas analyzer for water vapor and a data acquisition system, can be purchased for about US$12000 Systems are not commercially available Measurement representativeness may be affected by the short temporal and small spatial extent of the measurements and by the surrounding surface conditions since measurements are often made near a field edge

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