COMPARISON OF EVAPOTRANSPIRATION USING THE AERODYNAMIC AND BOWEN RATIO ENERGY BALANCE METHODS

by

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STATEMENT BY AUTHOR

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Abstract

The stability-corrected aerodynamic method was used to estimate fluxes of sensible and latent heat over an irrigated winter wheat field at Maricopa Agricultural Center in southern Arizona. These estimates were compared against the more precise Bowen ratio energy balance measurements made at the same location. The data were collected for 43 consecutive days over a range of canopy conditions.

The aerodynamic method performed poorly against the validated Bowen ratio method at this site. Fluxes of latent heat were underestimated by the stability-corrected aerodynamic method. Sensible heat fluxes sometimes agreed well, but were often low.

A new model was developed by combining AERO sensible heat (H_{aero}) with net radiation and soil heat flux to estimate latent energy as a residual (Le_{resid}) in the surface energy balance equation. This aerodynamic energy balance (AEB) method, produced R^2 values of 0.97 and 0.78 for the wet and dry periods respectively.

I. Introduction

Evapotranspiration is the combined loss of water evaporated from soil and water surfaces and water transpired by plants from the Earth's surface to the atmosphere. On a warm, sunny day approximately 45,000 kilograms of water can be transpired from the soil by vegetation on one hectare of land or evaporated from a water surface of equal area (Decker, 1966). Over a hectare of land in Arizona, roughly 17 times this amount of water can be evaporated from the surface, resulting in 800,000 kilograms of water lost to the atmosphere. The amount of water that can be potentially removed from the surface can be astounding when considering larger regions on the scale of lakes, farms, or watersheds. Water entering into the evaporation phase of the hydrological cycle cannot be redirected to other, more beneficial uses. For this reason, it is essential to be able to accurately quantify losses of water to the atmosphere in order to better manage this natural resource.

Numerous studies have taken place to develop methods that accurately estimate evapotranspiration from various terrain types and climate conditions. Hatfield (1990) provides a comprehensive assessment of evapotranspiration (ET) methods and found them to fall within three general categories, direct methods, indirect methods, and simulation models of the soil water balance. Direct methods are based on measures of the soil water content in the hydrologic balance. The advantages of using direct measurements include low training and operating costs, multiple site capability, relatively simple data processing, and a degree of accuracy acceptable for many applications. The disadvantages to using direct methods include the following factors: labor intensity, spatial dependence, temporal resolution, separate techniques required for upper and lower soil profiles, and definition of the rooting zone of crops.

Indirect measurement methods include micrometeorological or empirical methods which involve the partitioning of energy at the earth's surface. Micrometeorological methods (e.g. Bowen ratio, aerodynamic, or eddy correlation) depend on assumptions about vertical fluxes and gradients. Limitations within the energy balance approach are commonly associated with instrumentation, data collection, and conditions of advection. The primary weakness of statistical or empirical methods is fitting the statistical equations to the available data. These methods are popular because they utilize readily available meteorological data and can continuously record data over a wide variety of terrain types.

Finally, innovation in computer science has prompted the development of computer simulation models of ET. Contemporary models provide a means for estimating actual ET--the amount of water lost from the plant and soil to the atmosphere given the current meteorological conditions, soil water availability and plant growth stage and are also capable of separating plant transpiration from soil water evaporation. These models are being applied to a wide range of crops and conditions and will provide a more complete understanding of the physics of energy exchanges and interactions between the soil-plant-atmosphere continuum. Information on ET is used for a range of purposes from irrigation and watershed management decisions to global climate change models. Hansen (1966) points out that by understanding the distinctions and biases inherent in the methods used for estimating evapotranspiration, knowledgeable comparisons can be made between approaches and justified confidence can be established in the final estimate of evapotranspiration.

Mass Balance Approach

Many different methods have been developed and tested throughout the world to quantify evapotranspiration. Most of the methods are based on the water budget concept in which the gains, losses, and change in storage are measured and evapotranspiration (the only unmeasurable quantity) is calculated in accord with the conservation of mass principle as the residual in the water budget (Gay, 1993). The principle problem with this approach is the inability to measure water balance components with high accuracy. For example, the soil profile sampling method utilizes this technique to measure ET from only soil-water depletion analysis. The validity of this method has been questioned, largely because of the difficulties involved with minimizing water movement into or out of the sampling zone (Davidson and Nielson, 1966). Careful measurements can be made of the gains, losses, and changes in storage to the soil profile, but the very small changes in soil moisture can not be measured.

Another commonly used water budget method makes use of a lysimeter to measure

ET. Lysimetry studies began in France as early as 1688 and were used in collecting ET data at the beginning of this century (Harrold, 1966). Unlike soil profile sampling, lysimetry produces reliable data if properly designed, installed, and operated to be representative of the environment. However, lysimeters are expensive to operate, are not mobile, and can greatly disturb the environment one is attempting to measure. Problems have also arisen in extrapolating lysimeter measurements to larger fields.

Meteorological Methods

Meteorological methods are based on the evaluation of vapor transfer between the canopy and the atmosphere. They have several distinct advantages to estimating ET from natural or cultivated land; most notably they are non-destructive, can be employed continuously at any given site, do not have assumptions regarding the wetness of the surface, capable of determining relatively accurate short period rates, and the instruments allow for a great deal of mobility (Fritschen, 1966).

Bowen Ratio and Eddy Correlation Methods

The Bowen ratio and eddy correlation methods are two micrometeorological alternatives to the water balance technique. Both methods measure vertical fluxes in the surface boundary layer and are based upon the surface energy balance, which equates available energy moving into and out of the surface with the turbulent fluxes. The available energy is represented by the sum of the net radiation (Q) and soil heat flux (G), while the turbulent fluxes refer to sensible heat (H) and latent energy (LE). Available energy can be measured directly using radiometers and heat flux plates, but turbulent fluxes must be estimated using more advanced instrumentation. Once latent energy is estimated, it can be converted into a depth of water that represents the amount of evapotranspiration. One could compare measurements of the flow of water to and from the surface in the water balance method to the flows of thermal energy measured to and from the evaporating surface in the surface energy balance method.

The eddy correlation method can be used to measure flux densities of latent and sensible heat by correlating fluctuations of vertical wind speed with temperature and vapor density of the air (Dugas, et.al.,1991). It is best applied to areas where eddies dominate the exchange process, such as often found over dry, rough surfaces. The accuracy of these two methods compare well with each other (Dugas et.al.,1991) and, with the availability of reasonably priced instrumentation, have become very popular.

The Bowen ratio analysis uses measurements of the gradients of temperature and vapor concentrations above an evaporating surface combined with estimates of the net radiation and change in stored thermal energy to produce fluxes of latent and sensible heat. With an increase in surface roughness, mechanical turbulence increases and the gradients between air temperature and vapor concentration decreases reducing accuracy of Bowen ratio instrumentation. Therefore, this method produces best results when used for evaporating surfaces with well-defined canopies characteristic of irrigated, agricultural fields (Gay, 1993).

Aerodynamic Method

A final meteorological method of interest in this study is the aerodynamic method. Much like the Bowen ratio energy balance (or BREB), the aerodynamic method relies on the similarity principle which states that the diffusion coefficients for momentum, heat, water vapor, and carbon dioxide are equivalent. In other words, the eddy is interpreted as being non-discriminatory to the property being carried thus transporting momentum, heat, vapor, or carbon dioxide with equal proficiency (Oke, 1987). These two basic methods, termed profile methods, differ in that the aerodynamic approach adds a stability correction factor to evaluate fluxes, which will be reviewed more thoroughly in Chapter 2. Malek (1993) compares estimates of the turbulent fluxes of sensible and latent heat for these two methods at an irrigated alfalfa site in a semi-arid valley, northern Utah. He finds that the aerodynamic approach underestimated sensible and latent heat by approximately 30% in comparison to the BREB method and questions the validity of the stability functions in the aerodynamic model.

In order to use the energy balance equation, researchers must understand the surface-atmosphere conditions over the evaporating surface. Both sensible heat exchange (H) and latent heat flux (LE) between the surface and the air are highly dependent on the convective and advective conditions of the local atmosphere, however there have been few long-term experiments over a range of atmospheric stabilities with constant surface conditions.

Problem Statement

The increased availability of evapotranspiration measurement systems leads to more inter-method comparisons, and thus to improved instrumentation and field techniques. One may easily feel overwhelmed by the many possibilities. The problem lies in determining which systems work best and under what conditions that particular approach should be applied.

Objectives

The primary focus of this study is to compare evapotranspiration values estimated by the "2-level" aerodynamic approach to that of the Bowen ratio energy balance over winter wheat at the Maricopa Agricultural Center in southern Arizona. Data was collected continuously over 43 days with canopy conditions ranging from green, rapidly transpiring wheat to senesced, non-transpiring wheat. Atmospheric stabilities over the same time period ranged from advective (or stable) to convective (or unstable). Site conditions over the 43 days remained unchanged making the data especially unique.

The wide range of atmospheric stabilities in the data will allow a secondary investigation of the agreement between the two systems from green, rapidly transpiring wheat to senesced, non-transpiring wheat. Where estimates from the two methods are found to disagree, residual estimates of latent heat will be calculated by rearranging the terms in the surface energy balance equation and using the aerodynamic (or AERO) estimates for sensible heat.

II. Overview of BREB and Aerodynamic Methods

The purposes of this chapter will be to: (1) understand the physics and theoretical basis behind the energy balance approach, (2) explore the Bowen ratio energy balance and aerodynamic methods in more quantitative detail, and (3) review literature on the two methods, including any current research on comparisons.

Energy Balance Approach

The energy balance of an evapotranspiring body of vegetation over a time period Δt, can be written as:

$$Q + G + LE + H = 0 \tag{1}$$

The polarity convention used for this thesis is that fluxes directed to the exchange surface are positive, and those directed away are negative. The terms are energy fluxes in units of energy per unit area of evaporating surface per unit time via the following pathways:

Q = net all wave radiation
G = the change in the amount of heat stored in the body per unit area over the time interval Δt,
LE = latent energy of evaporation,
H = net output of sensible heat exchange with the atmosphere,

The energy balance tells us that evaporation must be balanced through some combination of heat inputs, from radiation and/or sensible heat, and heat energy lost in the evaporating body and/or changes in thermal storage. Atmospheric stability plays a significant role in ET, therefore it is helpful to explain stability before proceeding. Convection, either free, forced, or mixed, is the dominant process in the lower atmosphere and the type and extent of this convective activity is controlled by the vertical temperature structure as expressed by the concept of stability (Oke, 1987). Free convection occurs when a parcel of air is at a different density than the surrounding air causing it to rise or sink in the air column. If the state of the atmosphere is favorable for free convection the atmosphere is said to be unstable, whereas if the atmosphere inhibits free convection, it is said to be unstable. The aerodynamic equation makes use of this information and attempts to correct for the effect of stability conditions near the surface through stability correction factors.

Bowen ratio Energy Balance

In modifying the energy balance approach to estimating evapotranspiration, Bowen (1926) incorporated the ratio of sensible heat exchange (H) to latent-heat exchange to give Bowen's ratio (β) as:

$$\beta = H/LE \tag{2}$$

Accordingly, if $\beta > 1$, sensible heat is greater than latent heat as a route to dissipate heat. If $\beta < 1$, latent heat dominates as a pathway to dissipate heat. The former may be expected to occur in areas where water is limited and the bulk of the sensible heat being convected into the air will be warm. In the latter case, since mainly latent heat is being contributed to the atmosphere, the contribution will be to increase humidity but not significantly warm the environment. This condition is seen most often in cool and moist climates. Negative values of β occur when the fluxes have different signs. This situation most often occurs at night when evaporation is still occurring (i.e. LE is negative, away from the surface) and the sensible heat flux is toward the ground (H is positive, towards the surface) or vice versa depending on the sign convention. At the Maricopa Agricultural Center, the winter wheat field is surrounded by desert and serves as an isolated moisture source or oasis. The atmosphere advects sensible heat to the surface because the winter wheat field is cooler than the surrounding air, producing a temperature inversion gradient. This gradient causes sensible heat to be directed downward producing a negative Bowen ratio value. Typical average values of β given by Oke (1987) are 0.1 for tropical oceans; 0.1 to 0.3 for tropical wet jungles; 0.4 to 0.8 for temperate forests and grasslands; 2.0 to 6.0 for semi-arid areas; and greater than 10.0 for deserts.

The transfer of latent heat from an evaporating body to the atmosphere is always connected with evaporation. The heat loss from the evaporating body typically causes a decrease in surface temperature, but may be offset by heat transfer into the surface from radiation, sensible heat transfer from the overlying atmosphere, and/or heat transfer to the surface from within the evaporating body. The rate of latent-heat transfer from a water surface is defined by the product of the evaporation rate (E), latent heat of vaporization (λ_v), and the mass density of water (ρ_w), given in Dingman (1994) as:

$$LE = \rho_w \lambda_v E = \rho_w \lambda_v K_E \upsilon_a (e_s - e_a) \quad (3)$$

where υ_a is the wind speed, e_s and e_a are the vapor pressures of the evaporating surface and overlying air, and K_E is a coefficient that indicates the efficiency turbulent eddies of the wind transport water vapor vertically given by:

$$K_E = \frac{D_{wv}}{D_M} \lambda_v \frac{0.622\, \rho_a}{P} \frac{k^2}{[\ln\{z_m - z_d / z_o]\}^2} \quad (4)$$

where,

D_{wv} = diffusivity of water vapor in turbulent air
D_M = diffusivity of momentum
z_d = zero-plane displacement (m)
z_o = roughness height (m)
k = dimensionless coefficient = 0.4
z_m = height at which velocity and vapor pressure is measured
$D_{wv}/D_M = 1$
λ_v = latent heat of vaporization = 2.47 MJ/kg
$\rho_a = 1.23$ kg/m^3
P = 1013 mb

The flux of sensible heat exchange (H) between the water surface and the atmosphere is given by Dingman (1994) as:

$$H = K_H \upsilon_a (T_s - T_a), \quad (5)$$

where K_H is the eddy diffusivity for heat given by:

$$K_H = \frac{D_H}{D_M} c_a \rho_a \frac{k^2}{\{\ln[(z_m - z_d)/z_o]\}^2} \quad (6)$$

where D_H is the diffusivity of heat, c_a is the heat capacity of air ($c_a = 4.18 \times 10^6$ J/m^{3}K), and all other variables have been previously defined.

The Bowen ratio approach effectively eliminates the need for wind speed data and estimates of the zero-plane displacement by combining equations (3), (4), (5), and (6) to create:

$$\beta = H/LE = \frac{c_a P (T_s - T_a)}{0.622\, \lambda_v (e_s - e_a)} \frac{K_H}{K_E} \qquad (7a)$$

The Bowen ratio energy balance (BREB) method assumes that eddy diffusivity for heat (K_H) and eddy diffusivity for vapor (K_E) are equal. Further, the method is generalized for vegetated surfaces by taking the temperature and vapor gradients at two levels in the atmosphere rather than between the surface and the air. Bowen's ratio becomes:

$$\beta = H/LE = \frac{c_a P (\Delta\theta/\Delta z)}{\epsilon\, \lambda_v (\Delta e/\Delta z)} \qquad (7b)$$

where:

c_a = specific heat of air = 1010 J/kgK
P = atmospheric pressure (mb)
$\Delta\theta/\Delta z$ = potential temperature gradient with respect to height (K/m)
λ_v = latent heat of vaporization = 2.453×10^6 kg/m^{3}K
ϵ = ratio of molecular weight of water to dry air = 0.622 kg/kg
$\Delta e/\Delta z$ = vapor pressure gradient with respect to height (mb/m)

The psychrometric constant, γ is equal to:

$$\gamma = \frac{c_a P}{0.622\, \lambda_v} \qquad (7c)$$

It is important to note that the psychrometric constant is somewhat of a misnomer in that it is not strictly a constant. Pressure is a function of elevation and varies slightly over time at a given location by the equation used by Malek (1993):

$$p_z = p_o\{(288 - 0.01z)/288\}^{3.146} \qquad (7d)$$

where: p_o = mean sea level pressure = 1013.25 mb
z = site elevation (m)

Latent heat of vaporization varies slightly with temperature. I used 2.45 MJ/kg in my calculations.

Finally, using typical values of c_a = 1010 J/kgK, P = 1013 mb, and λ_v = 2.47 MJ/kg, the psychometric constant is commonly given as γ = 0.66 mb/°C at sea level, and $(p_z/p_o)\gamma$ at elevation z.

Theoretical Basis

Returning to the surface energy balance equation (1) and dividing by latent energy of yields:

$$\frac{Q+G}{LE} + \frac{H}{LE} + 1 = 0 \qquad (8)$$

From the Bowen ratio equation (2) and rearranging terms on obtains:

$$LE = -(Q+G)/\,1+\beta \qquad (9)$$

the Bowen ratio energy balance equation.

BREB analysis is limited to conditions of steady state and constant flux with height (Oke, 1987). The observations are typically averaged of periods of 0.2 to 1.0 hours to satisfy the steady-state requirement.

With the assumption that eddy diffusivity for heat (K_H) and eddy diffusivity for vapor (K_E) are equal, corrections for atmospheric stability are not normally applied to the Bowen ratio. However, there is some evidence that this may not hold true. Measurements made over alfalfa and soybean fields in Nebraska by Verma,*et al.* (1978) reveal that under conditions of regional advection, the exchange coefficient for sensible heat (K_H) is greater than that of water vapor (K_W). This phenomenon is attributed to water vapor and heat being transported in opposite directions. Whereas during non-advective (lapse or unstable) conditions, both water vapor and sensible heat are being transported away from the Earth's surface. Evapotranspiration estimates for the well-watered alfalfa were compared against lysimetrically measured values to find the BREB method underestimating daily values by about 20-30% (Verma, *et al.*, 1978).

Work by Brownridge (1985) over a field of winter wheat compares BREB and lysimetric estimates of evapotranspiration. Her study produces approximately the same estimates as Verma et al. (1978) with daily LET (or lysimetric evapotranspiration estimates) generally exceeded BRET (Bowen ratio evapotranspiration estimates) with average LET 13% greater than BRET during advection and average LET 13% less than BRET during lapse conditions.

In sharp contrast to the above findings, Denmead and McIlroy (1969) compared Bowen ratio estimates to that of lysimetry over a semi-arid field of wheat in Australia. Their paper puts forth evidence to substantiate the assumption that K_W and K_H remain equal over a range of stabilities close to the surface. The water and energy-balance techniques, which are relatively independent of each other in application, produced comparable estimates of evapotranspiration during simultaneous operation. After a total of 210 hourly comparisons, their data reveals differences in the two models within ± 0.1 mm/hr. Since this difference was equivalent to the estimated experimental error, which in turn was equal to the lysimetric readings, the Bowen ratio energy balance was pronounced to be a reliable estimate of evapotranspiration.

Applications

After reviewing many writings on the Bowen ratio method, I believe the most widely held view concerning the accuracy of the Bowen ratio method is made most completely by Tanner (1960) in describing evapotranspiration using the energy balance approach from crops. He finds BREB estimates to be suitable providing there are large variations of thermal stratification, the measurements are taken close to a homogeneous surface, and proper time sampling features are followed. With regard to Bowen's equation given by:

$$LE = -(Q + G)/(1 + \beta)$$

evapotranspiration becomes indeterminate when β approaches -1. However, this occurs during times when the heat exchange is low, such as sunrise, sunset, and some occasional night hours. Since scientists are knowledgeable about its occurrence, we can be sensitive about utilizing data during those intervals. Ohmura (1982) expands on this idea to evaluate rejection criteria for inappropriate data produced by the BREB method. Under conditions that produce a Bowen ratio very near to -1, a very small error in net radiation or subsurface heat flux can produce erroneous results. As previously stated, this condition occurs when the direction of latent heat flux opposes the sensible heat flux. Included in Ohmura's study were the intervals of late afternoon, precipitation events, and strongly stable periods of intense foehn wind.

With commercially available net radiometers, soil heat flux disks, wind vanes and anemometers, the BREB method has become the most inexpensive and efficient method to estimate ET. With the advent of specialized Bowen ratio equipment, accurate assessment of of short duration ET is possible without disturbing the soil and vegetation. To eliminate systematic errors, Osmolski and Gay (1983) used two psychrometer exchange mast systems that interchanges psychrometers between readings. In such a way, any bias in the temperature readings is cancelled. Using this unique system, latent heat data was collected over an alfalfa field located northwest of Tucson, Arizona. The linear regression relations between the 12-minute estimates of latent heat for the two systems showed excellent agreement with a regression model of $LE_2 = a + b\ LE_1$. The constant term--a, ranged from approximately -8 to +10 W/m^2 for the individual days with flux densities ranging up to 700 W/m^2. The slope coefficient-- b, varied from 0.993 to 1.018. The agreement between masts speaks to the precision of the Bowen ratio values.

A further study into the quality of Bowen ratio instrumentation was carried out by Gay (1988) in which the AZET system was used to compare latent heat values against eddy-correlation and lysimeter values over alfalfa at the US Water Conservation Laboratory in Phoenix, AZ. The study found excellent agreement as above with the Bowen ratio closely matching values from eddy correlation and lysimetry.

The validity of the BREB method has also been studied over forests by Spittlehouse and Black (1980) using the same reverse psychrometer system as mentioned above and with equally functional outcomes. The study compared the Bowen ratio against three different methods for estimating ET: stomatal diffusion resistance method, soil water balance method, and eddy correlation. An error analysis of the BREB method showed forest evapotranspiration could be measured to ±15% for $-0.5 < \beta < 2$. For large temperature and vapor pressure gradients, ET could be measured to ±15% but errors increased drastically to ±60% for small temperature and vapor-pressure gradients associated with $2 < \beta < 4$.

Agreement between the methods was well within their own errors. The study demonstrates that none of the systems was more reliable than the Bowen ratio, which has the added flexibility for use on hourly, daily, weekly, and monthly time intervals.

The Bowen ratio concept has been used with confidence to estimate ET over crops, forests, lakes, snow packs and even to determine the flux of other admixtures such as carbon dioxide. Based on the above evaluation of the success of the Bowen ratio against its competitors, this study will use Bowen ratio estimates as a legitimate set to compare calculated values of sensible and latent heat using the 2-level aerodynamic model.

Aerodynamic Method

The aerodynamic method uses wind speed to determine flux transfers between the canopy and the atmosphere. It only applies under conditions of neutral stability, steady state, constant fluxes with height, and all transfer coefficients are similar (Oke, 1987). A modified equation was used by (Malek, 1993) to calculate LE:

$$LE = \frac{0.622\, L\rho k^2\, (e_2 - e_1)\,(u_2 - u_1)}{P \ln \{[(z_2 - d) / (z_1 - d)]\}^2\, (\Phi_M \Phi_V)} \qquad (10)$$

where:

ρ = air density = 1.188 kg/m^3
k = von Karman's constant = 0.41
e = actual vapor pressure (mb)
u = wind speed (m/s) at height 1 or 2
z_2 = upper measurement height
z_1 = lower measurement height
d = displacement height $\doteq$0.63h where h is height of vegetation

$[\Phi_M \Phi_V]^{-1}$ = dimensionless stability function
L = latent heat of vaporization
P = atmospheric pressure in hPa (eq. 7d)

given by:

$$P = 1013 \{[288 - 0.01(\text{altitude})]/288\}^{3.146}$$

The equation for sensible heat is given by Malek (1993) as:

$$H = \rho C_p k^2 \frac{(\theta_2 - \theta_1)(u_2 - u_1)}{\{\ln[(z_2 - d)/(z_1 - d)]\}^2 (\Phi_M \Phi_H)} \quad (11)$$

where: θ_1 = potential temperature (K) at lower measurement height
θ_2 = potential temperature (K) at upper measurement height
C_p = specific heat of air at constant pressure=1010J/kgK
u_2 = wind speed at upper measurement height (m/s)
u_1 = wind speed at lower measurement height (m/s)
and all other terms previously defined.

According to Oke (1987), the stability function can be computed for stable atmospheres as:

$$[\Phi_M \Phi_V]^{-1} = (1-5R_i)^2 \quad (12a)$$

and for unstable atmospheres as:

$$[\Phi_M \Phi_V]^{-1} = (1-16R_i)^{0.75} \quad (12b)$$

where R_i is the Richardson number expressed as:

$$Ri = \frac{g\,(\Delta T/\Delta z)}{T\,(\Delta u/\Delta z)^2} \quad (12c)$$

where: g = acceleration due to gravity = 9.81 m/s^2
T = average air temperature (K)

The two heights at which wind speeds are measured must be within the internal atmospheric boundary layer of the canopy. Reducing the heights of the instruments within the boundary layer will reduce errors caused by non -adiabatic stability conditions (Stanhill, 1969).

Malek (1993) used the Bowen ratio energy balance and the stability corrected aerodynamic method (described above) to compare sensible and latent heat over an irrigated alfalfa site in Utah. He found the aerodynamic method to consistently underestimate BREB values by roughly 30% under conditions of light wind (averaging 1.6 m/s) to more turbulent conditions (wind > 1.5 m/s). In addition, the inconsistency of aerodynamic estimates of sensible and latent heat with net radiation and change in storage led him to conclude that the validity of the aerodynamic method is doubtful.

Prior to Malek's experiment, Vogt and Jaeger (1990) were working in a pine forest in southwest Germany to calculate the sensible heat flux using the water balance method, BREB method, and aerodynamic method. Their findings showed the aerodynamic estimates of evaporation values to be less than 15% deviation from water balance estimates. A linear regression of 280 1-hour data pairs were plotted to compare evaporation estimates of the Bowen ratio method to the aerodynamic method, yielding the relationship $E_{BR} = 0.86E_{AM} + 0.09$ (R=0.86, standard error of the estimate = 0.09mm/day). Similar estimates from the independent water balance and aerodynamic methods, in combination with the high correlation between the aerodynamic and BREB methods, supports their conclusions of validity of the aerodynamic method.

Summary of Methods

Sensible and latent heat estimates made by the Bowen ratio energy balance approach can be used as a truth set for comparison against estimates made by the aerodynamic method. Over years of study of comparison research between evapotranspiration methods, there is still great controversy over the validity of the aerodynamic model, and hence a great need for further study over longer periods of time and conditions. The rationale behind this thesis is to tip the scales of literature for or against the aerodynamic method through a comparison of quality data ranging over a wide spread of stabilities and time periods.

III. METHODS

This chapter describes the procedures used in the study of comparing the aerodynamic method to the BREB method, the source and description of the data, and the treatment of data.

Source of Data

Data were collected over a field of winter wheat at the Maricopa Agricultural Center which is located about 100 km northwest of Tucson, Arizona at 33.07° N latitude and 111.98°W longitude. The elevation is approximately 360 m above mean sea level and atmospheric pressure is 971 mb.

The climate of Maricopa Agricultural Center is semi-arid and incapable of supporting agriculutural crop species without irrigation. Precipitation averages 200 mm per year occurring in a bimodal, winter-summer distribution pattern with most of the rainfall in the summer (Sellers and Hill, 1974). The winter period begins in January and typically lasts for about three weeks. These winter storms develop from easterly moving moist air masses originating in the Pacific Ocean. This precipitation is of less duration and intensity than the second set of rainfall events which occurs in late summer. In July and August, precipitation is generated by convective thunderstorms which develop over the strongly heated desert floor.

Between February and July, and October through December, the area receives very little precipitation and drought conditions are prevalent. During this period, the fields are flood irrigated with groundwater from local aquifers.

Summer temperatures at Maricopa vary from 20° C in the morning to 40° C in the afternoon (Sellers and Hill, 1974)with mid-summer maxima occasionally reaching 50° C. Temperatures for data collected in this study range from 9° C to 40° C.

The winter wheat (*Triticum durum* Desf. 'Aldente') was sown on December 16, 1988 and emerged around the first of January of 1989. It was evenly distributed in field 32 (see Figure 1) which is approximately 1609 m wide in the east-west direction and 280 m long in the north-south direction (Gay,1989). This field was bordered on the north and south with bare soil, on the west with irrigated pecans, and on the east with irrigated wheat. Within fifty days of planting, canopy closure was complete.

Data Collection

The micrometeorological data used in this study were collected jointly by Dr. Lloyd Gay and Dr. Allan Matthias for Bowen ratio and aerodynamic analyses.

The Bowen ratio system evaluated the energy budget of the crop based on mean

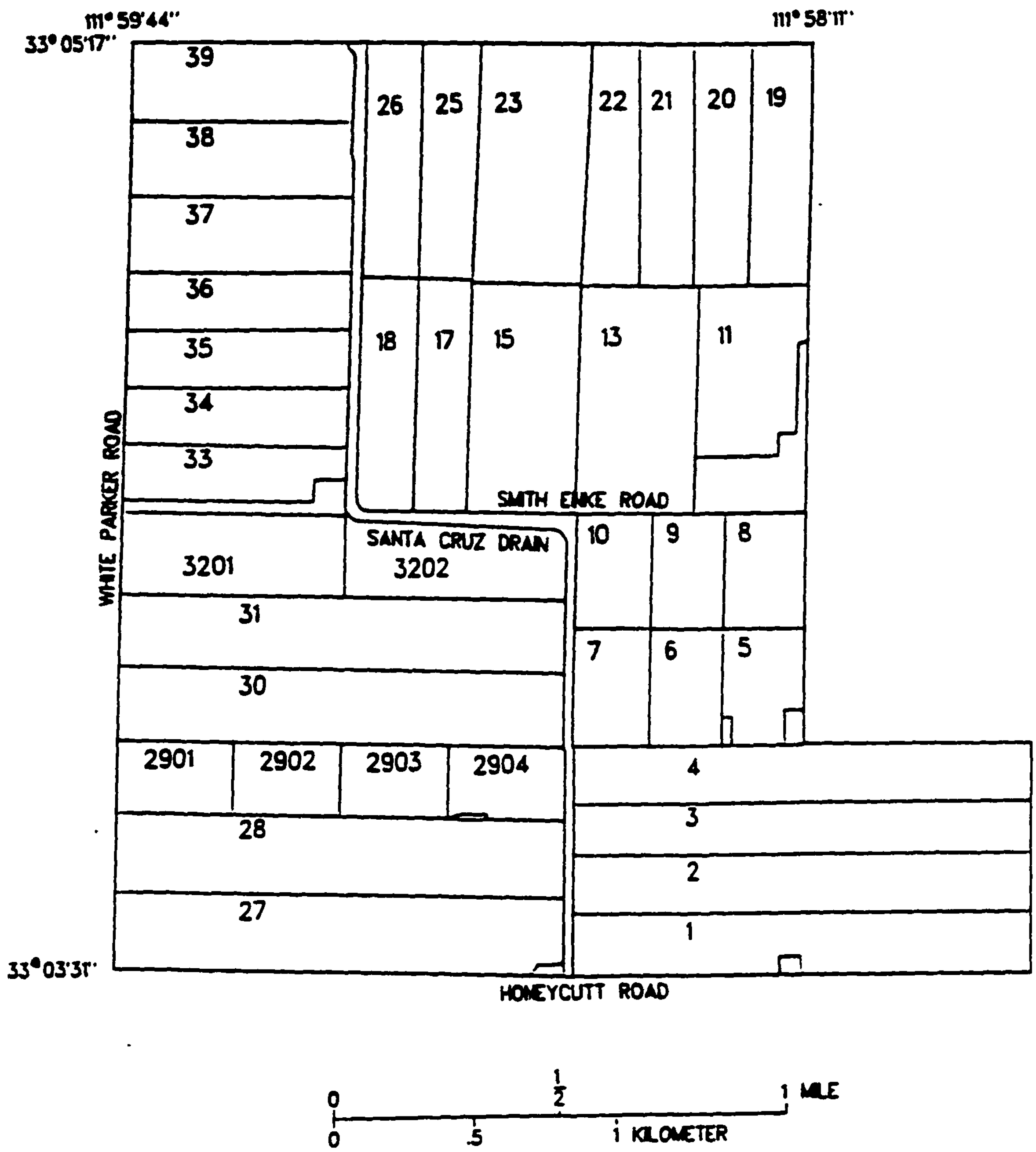

Figure 1. Maricopa Agricultural Center plan.

values of net radiation (Q), soil heat flux (G), potential temperature gradient, and vapor pressure gradient over twelve minute periods. Net radiation was measured by a net radiometer set at 1.7 m above the ground. Canopy height was .97 meters. A pair of soil heat flux disks connected in parallel one centimeter below the soil surface yielded an average value for soil heat flux. The gradients of temperature and vapor pressure were measured by two interchangeable ceramic wick psychrometers (Gay, 1988) mounted at 1.04 m and 2.03 m above the ground. The two psychrometers were interchanged at 6-minute intervals to minimize bias in the gradients. Differences in potential temperature and vapor pressure were used to evaluate latent heat flux (LE) and sensible heat flux (H) from the equations derived by Bowen (1926).

Dr. Allan Matthias averaged wind speed in meters per second over twelve minute periods, measured with sensitive, 3-cup anemometers (Qualimetrics model 2032) with a threshold windspeed of approximately 0.23 meters per second. Wind measurements were made at heights of 1.07 m, 1.52 m, 2.05 m, and 2.54 m above the ground surface at a site adjacent to the Bowen ratio system. Wind data from heights of 1.07 m and 2.05 m were combined with temperature and vapor pressure differences from the Bowen ratio system to estimate fluxes from the aerodynamic equations.

Validation of BREB Method

In order to compare aerodynamic estimates against those of the Bowen ratio method, the accuracy of the Bowen ratio fluxes must be validated. Over this same wheat field, Dugas et.al. (1991) analyzed two days of the data set used in this thesis to compare the AZET Bowen ratio system with three other Bowen ratio designs and with eddy correlation systems. All were operated side-by-side at this site on April 9 and 10. Dugas et al. (1991) concluded that the four Bowen ratio system designs were in good agreement, and that eddy correlation sensible heat agreed closely with Bowen ratio sensible heat. In much the same way, this paper will compare the performance of two side-by-side AZET Bowen ratio systems (Gay, 1988) for the period April 7-14. The comparisons will include the basic measurements of net radiation (Q), temperature at the top of the mast, difference in vapor pressure (dE), and the Bowen ratio fluxes of latent heat (LE) and sensible heat (H). Verification will be obtained by linear regression analysis of the 12-minute data from the two side-by-side Bowen ratio systems.

After determining the correlation of both sets of instrumentation using the energy balance method, sensible heat from the aerodynamic approach will be compared against sensible heat fluxes measured by an eddy correlation system. The eddy correlation system differs from the Bowen ratio method in that it determines sensible heat flux by rapidly sampling vertical wind speed (w) and air temperature (T). The covariance of w and T yields the product of instantaneous fluctuations from longer term means (w′T′), and sensible heat flux is given by:

$$H = \rho_a C_p (w'T')$$

where ρ_a is the air density, C_p is the specific heat, and (w′T′) is averaged over an appropriate period (12 minutes in this study) (Brutsaert 1982). The eddy correlation and Bowen ratio comparisons will check against system errors.

Data Processing

The data were analyzed to answer the following research questions:

(1) How do estimates of sensible and latent heat fluxes calculated using the "2-level" aerodynamic approach compare with values from the Bowen ratio energy balance method?

(2) Do atmospheric stabilities ranging from advective (or stable) to convective (or unstable) affect the agreement between methods? Do estimates from green, rapidly transpiring wheat agree more closely from those of senesced, non-transpiring wheat--or vice-versa?

(3) Can deviation of the two methods be linked to specific terms in the aerodynamic equations? In other words, is any one term responsible for the difference in the estimates (for example--wind speed or transfer coefficient,

vapor pressure differences, or temperature differences)?

The analyses employed to answer the above research questions included fitting linear regression lines to scattergrams of paired variables, and to examination of time series plots for better visual representations of the days in question. Regression was used because of its ease in interpretation and the excellent visual representation of the data. The regression analysis has restrictions as a statistical tool in comparison analyses of this kind due to serial autocorrelation connected with successive measurements of meteorological data at a point. Serial correlation in studies of this type yields erroneously higher estimates of "goodness of fit" from methods designed for normally distributed data sets. However, the fitted lines are appropriate, and the method remains a valuable statistical tool for comparing data of this magnitude.

Definition of Valid Data

Invalid entries in the data set were excluded from calculations. These values can occur when the Bowen ratio approaches -1, causing Bowen's equation $LE = (Rn - S)/(1+\beta)$ to become undefined. This commonly occurs near dawn and dusk when the sensible and latent heat fluxes are of oppcsite polarity but of similar magnitudes. Ohmura (1982) establishes several useful guidelines in rejecting data for Bowen ratio flux calculations. Under conditions where the direction of latent heat flux is opposite that of sensible heat flux, unacceptable results occur due to small errors in net radiation or soil heat flux. Since this problem occurs most frequently at night, the data set was restricted to daytime values (6:00 am to 6:00 pm) when most of the latent energy transformation occurs.

Another criterium for discriminating invalid data lies within the stability corrections that are applied to the aerodynamic analyses. Figure 2 (Oke, 1970) shows the stability function, Φ, within flow regimes associated with different stability conditions. When the Richardson number lies between ±0.01, forced convection dominates the exchange processes. Moving from neutrality towards instability (to the right) buoyant forces increase

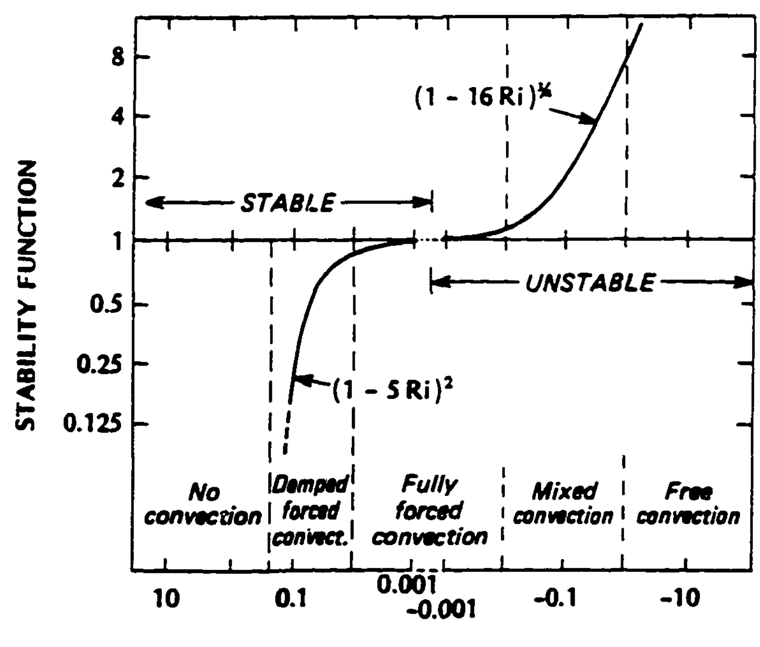

Figure 2. Stability function vs. Richardson number for varied flow regimes (from Oke, 1970).

in importance. Finally, only free convection is occurring for Richardson numbers less than -1.0. Moving into the stable regime (to the left), negative buoyancy begins to dampen turbulent exchange, and at values above 0.20 the flow is virtually laminar with no vertical mixing. In order to restrict the analyses to the turbulent region, only data associated with the region -0.2 < Ri < 0.2 were used for the aerodynamic comparisons.

IV. RESULTS

This chapter presents results of the analysis to verify the Bowen ratio data, to define the agreement between the "2-level" aerodynamic and Bowen ratio methods, to examine the effects of stability upon agreement, and to identify sources of variability between the two methods. Forty-three days of 12-minute mean data were collected over the period DOY 96-136. Because the data set is so large the analysis focuses upon two subsets of approximately 8 days each. The first, or "wet" set, covers DOY 97-104 during the period of maximum transpiration. The wet period is also the period that two Bowen ratio systems were operating at the site. The second, or "dry" period extends from DOY 129 to 136, as the wheat senesces and the transpiration rate decreases sharply. The dry period contains all of the measurements above the senesced wheat. This study is unique in that this period covers a range of stability conditions while physical conditions at the site remain unchanged. Table 1 summarizes the two subsets of data by day of year and corresponding calendar date.

Table 1. "Wet" and "dry" periods.

"Wet" Period		**"Dry" Period**	
DOY	*Date*	*DOY*	*Date*
97	07 April 1989	130	10 May 1989
98	08 April 1989	131	11 May 1989
99	09 April 1989	132	12 May 1989
100	10 April 1989	133	13 May 1989
101	11 April 1989	134	14 May 1989
102	12 April 1989	135	15 May 1989
103	13 April 1989	136	16 May 1989
104	14 April 1989		

Verification of BREB Data

The first step in testing the aerodynamic method is to verify the Bowen ratio estimates of evapotranspiration used for the "truth set." The quality of the BREB estimates were evaluated by regressions analysis of two BREB systems that operated side-by-side throughout the wet period. Meteorological variables and Bowen ratio fluxes were analyzed to determine the consistency of measurements from two systems. In addition, eddy correlation values of sensible heat (Hec) were regressed against BREB sensible heat (H) as an additional check on the validity of the BREB measurements.

Meteorological Variables

Figures 3-5 illustrate the association between system A and system B in measuring net radiation (Q), temperature at the top of the mast, and difference in vapor pressure (dE) over transpiring wheat for the "wet" period from April 7 (DOY 97) to April 14, 1989 (DOY 104). All verification data are 12-minute means for daylight periods. The linear correlation coefficients are denoted on the figures by R^2 values and show excellent agreement between the two measurement systems with correlation coefficients ranging from 0.83 to 1.0. Table 2 presents these summary regression statistics for net radiation, air temperatures, and vapor pressure difference. Standard errors were 17 W/m^2 for net radiation, 0.16°C for air temperatures, and 0.51 mb for vapor pressure differences. Slope values came very close to the desired 1.0 for all meteorological variables evaluated. Offset coefficients are small, only

Table 2. Summary regression statistics for net radiation, temperature, and vapor pressure difference.

Figure Number	Figure Title	Slope *a*	Intercept *b*	Standard Error *SE*	Correlation Coefficient *R^2*	Sample *n*
	System A vs. System B:					
3	Net radiation (A vs. B)	1.0182	9.3674	17.133	0.9931	324
4	Temperature (A vs. B)	1.01	-0.3011	0.1586	0.9987	324
5	Vapor Pressure Difference	0.9329	-0.2572	0.5103	0.8952	324

a few percent of the range and I conclude that the meteorological variables are very highly correlated between the two systems.

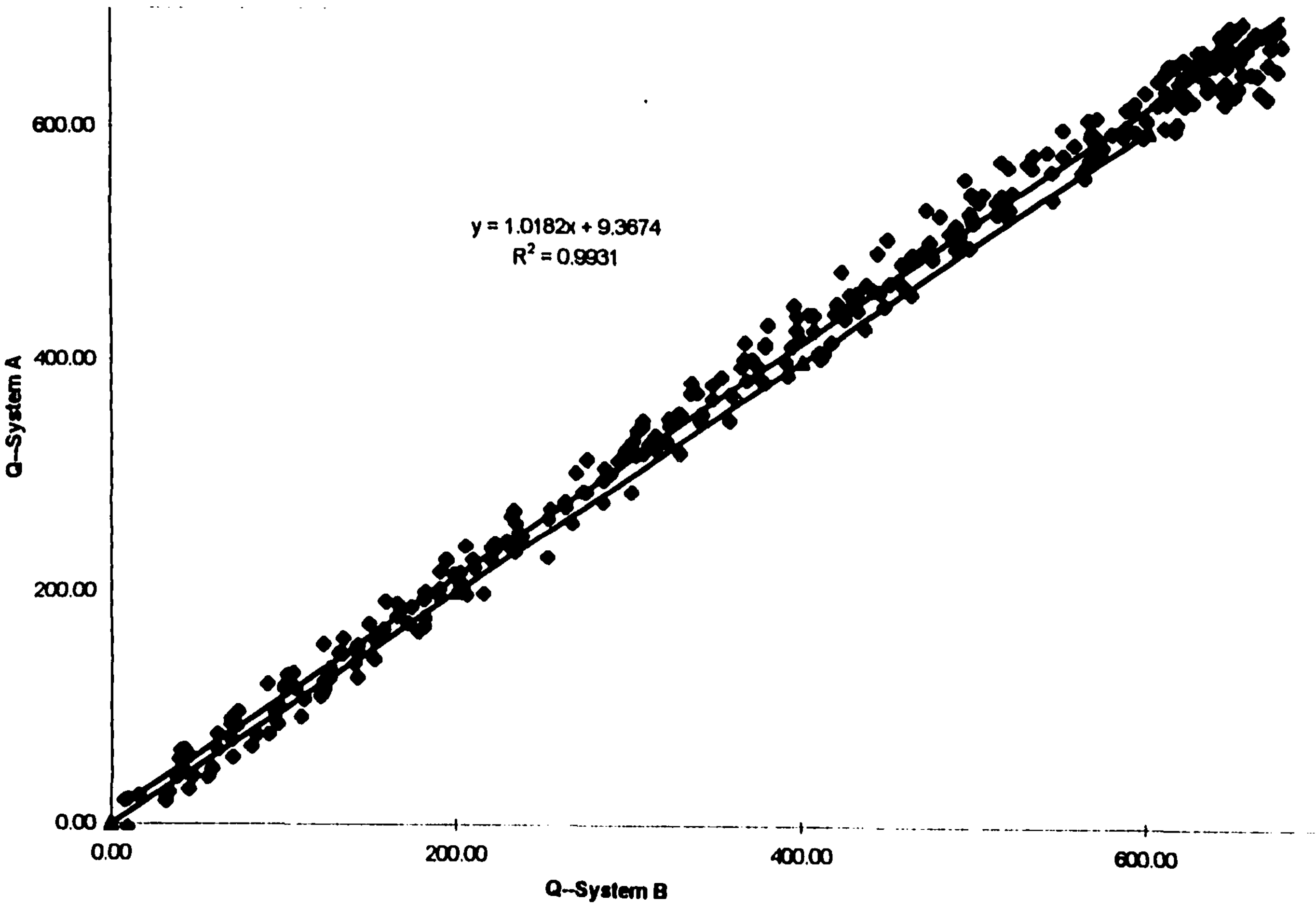

Figure 3. Net radiation regression for system A vs B. Data are 12-minute means of daylight data over the wet period.

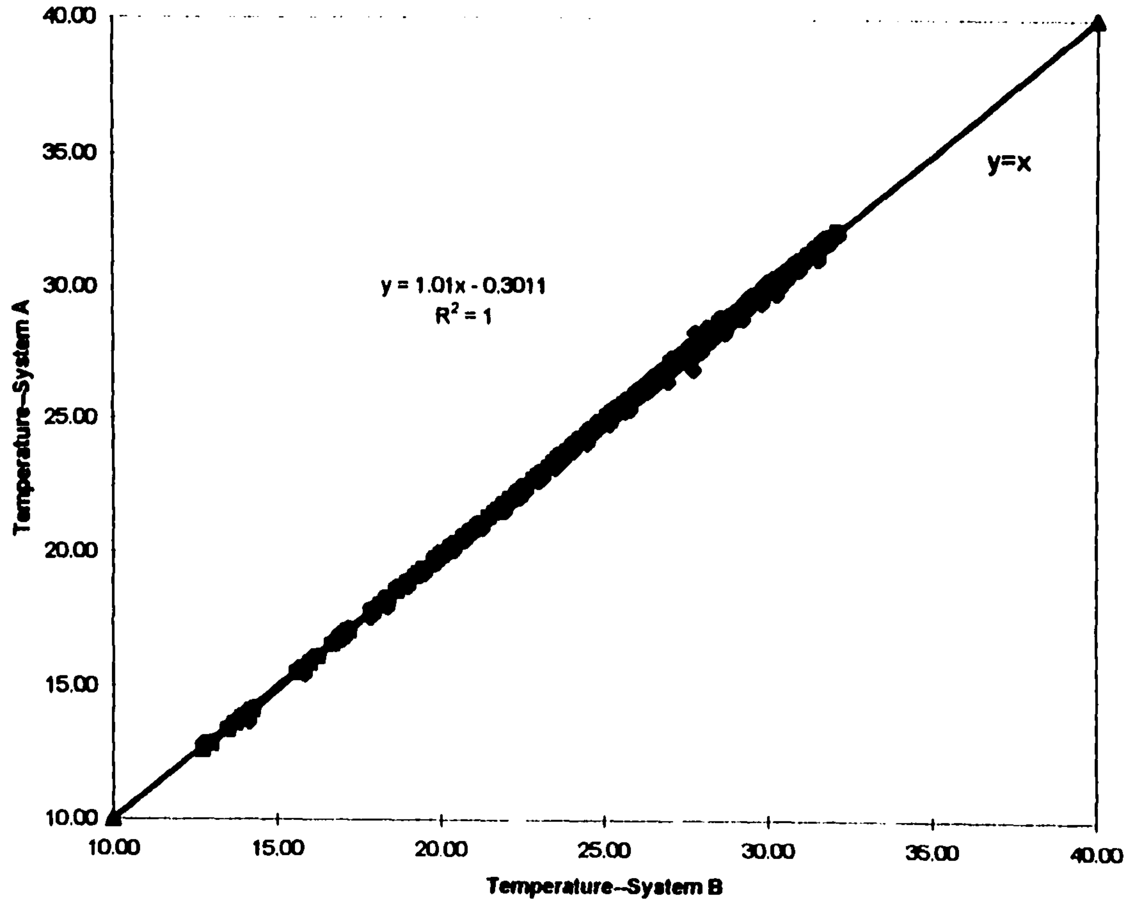

Figure 4. Temperature regression for system A vs B. Data are 12-minute means of daylight data over the wet period.

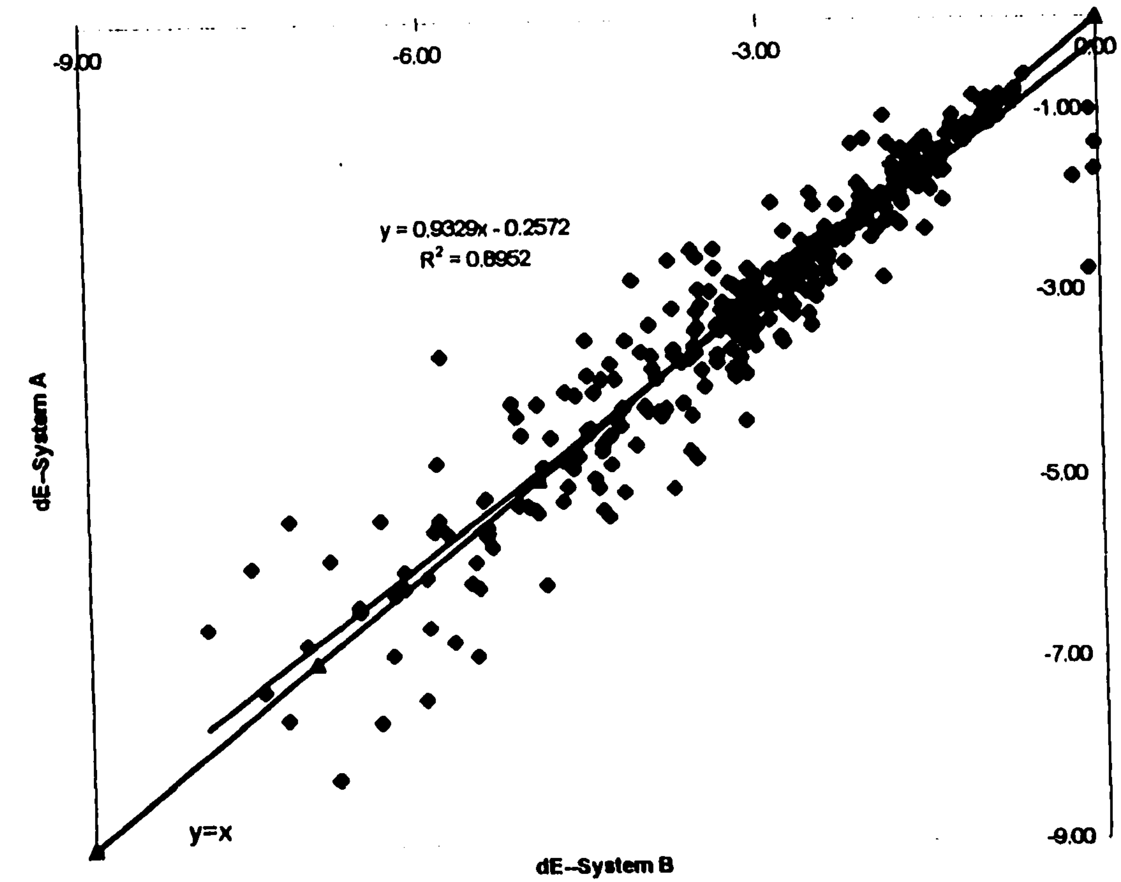

Figure 5. Vapor pressure difference regression for system A vs B. Data are 12-minute means of daylight data over the wet period.

Turbulent Fluxes

The two independent Bowen ratio systems A and B measured turbulent fluxes concurrently only during the wet period of predominately stable conditions from April 7 through April 14 (DOY 97-104). Bowen ratio system B and the eddy correlation system measured sensible heat concurrently during the dry period of predominately convective, unstable conditions from May 10 through 10:00 am, May 16 (DOY 130-136). Thus, the flux verification is from sensible and latent heat fluxes of system A vs. B in the wet period, and sensible heat fluxes from system B and eddy correlation sensible heat during the dry period.

Figures 6a and 6b represent the relationship between the sensible and latent heat fluxes from system A versus those of system B during the wet period. Table 3 shows that the correlation coefficients and slopes for sensible and latent heat fluxes are very near to 1.0 and the standard errors are low for the large ranges in magnitude of the observed fluxes. Based on the high degree linearity for both sensible and latent heat fluxes, I conclude that these two systems are working to produce the same flux measurements.

Table 3. Summary regression statistics for sensible and latent heat–BREB and sensible heat–BREB vs eddy correlation.

Figure Number	Figure Title	Slope *a*	Intercept *b*	Standard Error *SE*	Correlation Coefficient *R^2*	Sample *n*
	Wet period					
6a	Sensible Heat–BREB	1.003	3.9439	18.1451	0.9316	324
6b	Latent Heat–BREB	1.0676	-3.4524	27.3801	0.9824	324
	Dry period					
7	Sensible Heat–BREB vs Eddy	0.7272	5.8768	44.607	0.8677	541

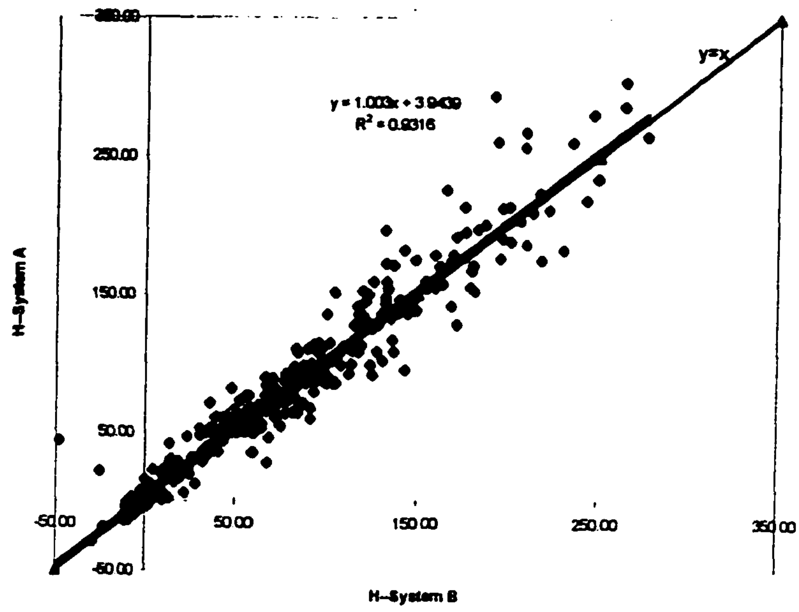

Figure 6a. Sensible heat regression for system A vs B. Data are 12-minute means of daylight data over the wet period.

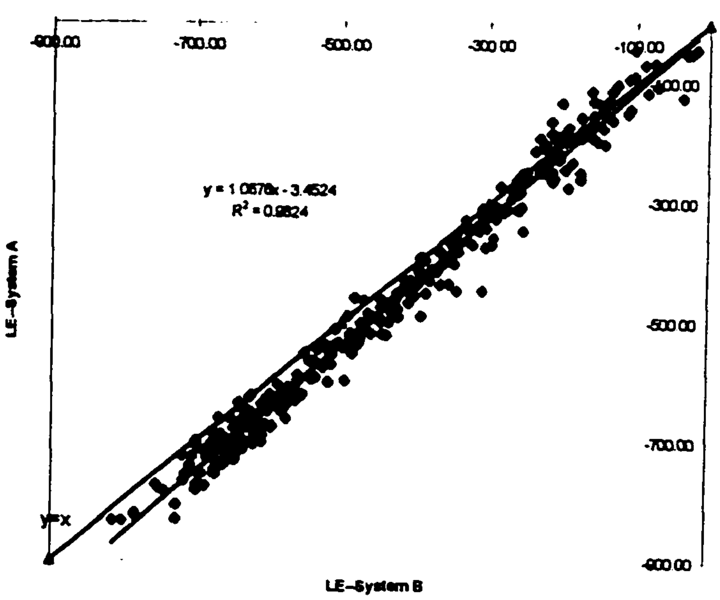

Figure 6b. Latent heat regression for system A vs B. Data are 12-minute means of daylight data over the wet period.

Figure 7 compares measured values of BREB sensible heat against eddy correlation values over the dry period. Table 3 gives the regression statistics for this figure with an R^2 value of 0.87, slope value of 0.73, and low standard error which demonstrates reasonable agreement between these two methods. These comparison show good agreement from system to system and method to method during the 7-day period. Hence, I proceeded with justified confidence in using BREB values as a truth set in which to compare calculated flux values for the aerodynamic (or AERO) method.

Agreement Between BREB and AERO Systems

Research question 1 asked: How do estimates of sensible and latent heat fluxes calculated using the "2-level" aerodynamic approach compare with values from the Bowen ratio energy balance method? In considering this question, linear plots and time-series figures were created to compare data at both locations. On a daily basis, the 43 days of data had varying degrees of correlation but were consistently poor. For latent heat fluxes, the AERO method consistently underestimated values of the BREB method, while sensible heat estimates varied more widely, with some days correlating well and others poorly.

Figures 8a-b and 9a-b illustrate, and Table 4 summarizes, regression relationships for sensible and latent heat fluxes in the wet period and in the dry period. In both periods, sensible heat values of the AERO method correlated with BREB to a higher degree than did

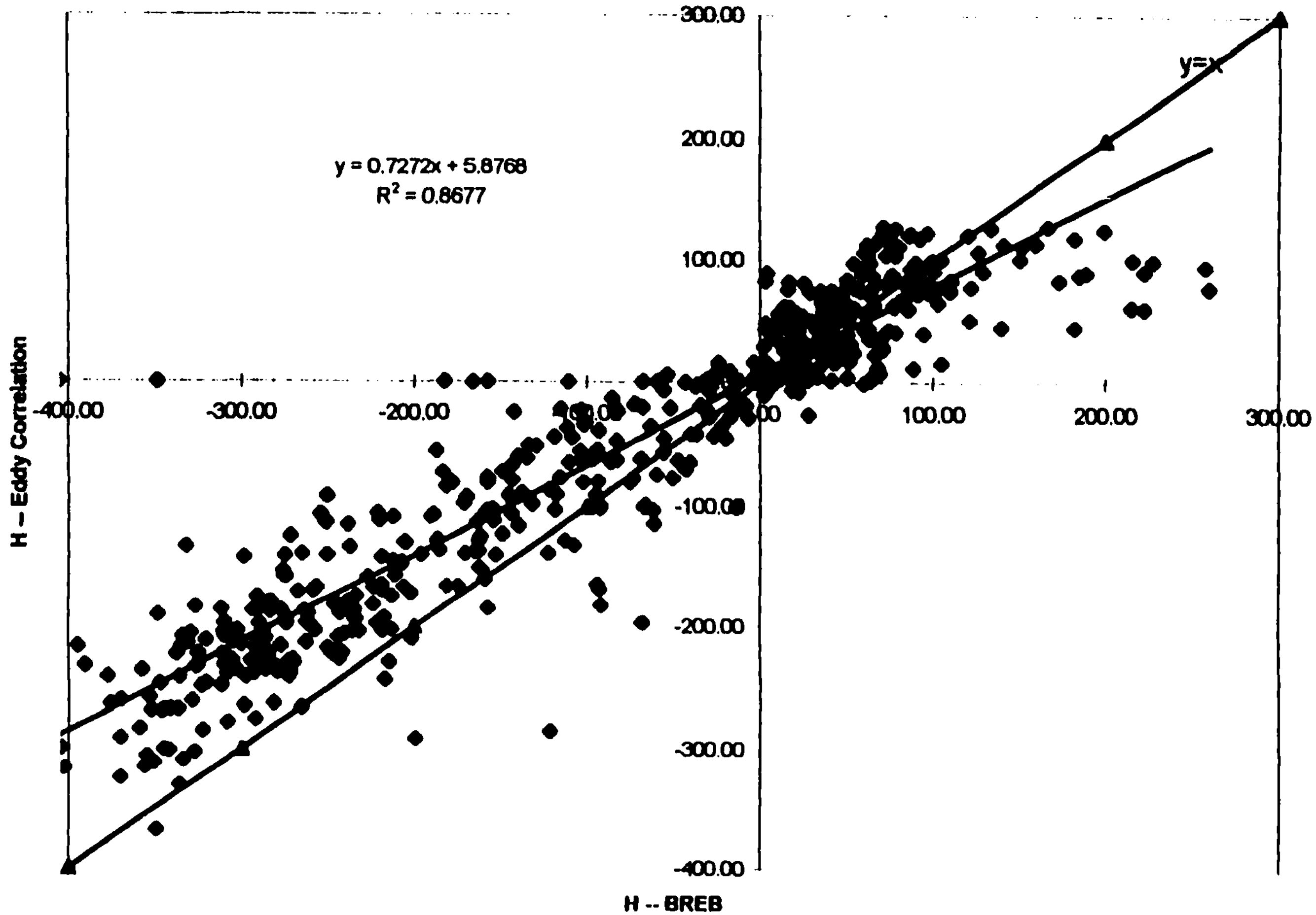

Figure 7. Sensible heat regression for eddy correlation vs BREB during the dry period. Data are 12-minute means of daylight data.

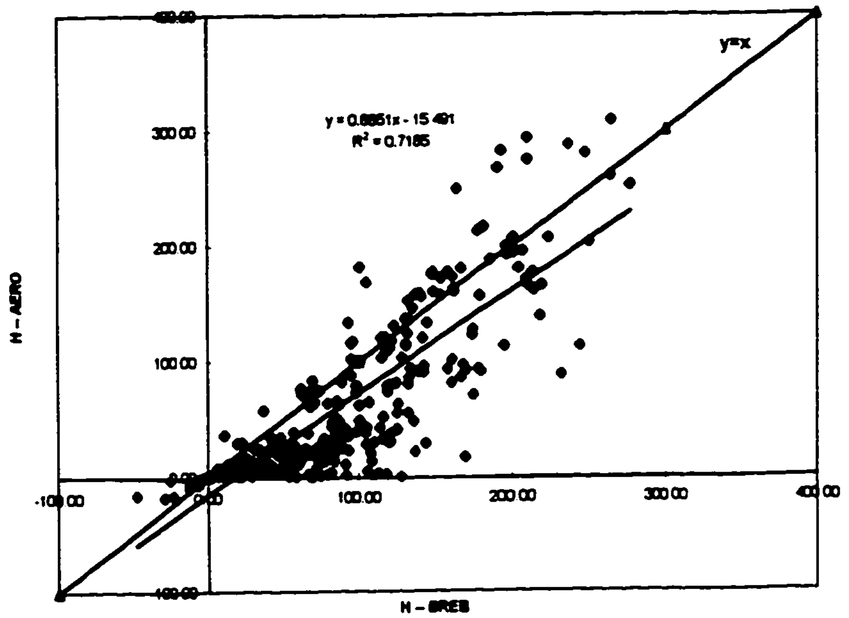

Figure 8a. "Wet period" regression for sensible heat: AERO vs. BREB. Data are 12-minute means of daylight data.

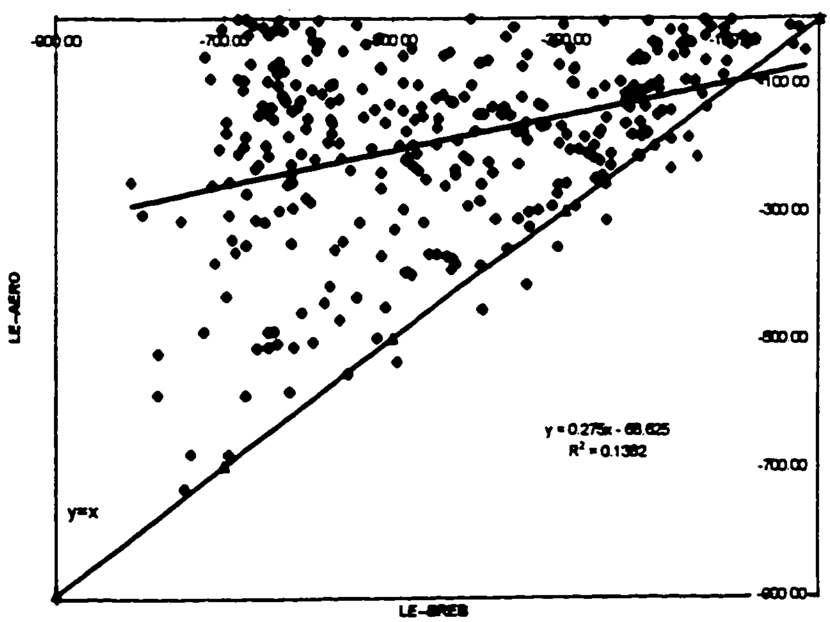

Figure 8b. "Wet period" regression for latent heat: AERO vs. BREB. Data are 12-minute means of daylight data.

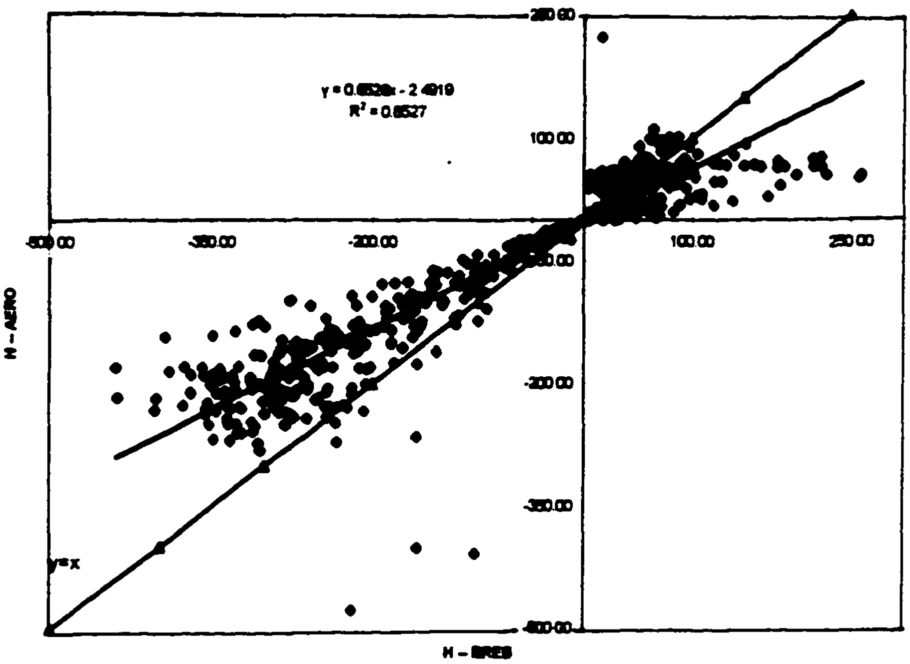

Figure 9a. "Dry period" regression for sensible heat: AERO vs. BREB. Data are 12-minute means of daylight data.

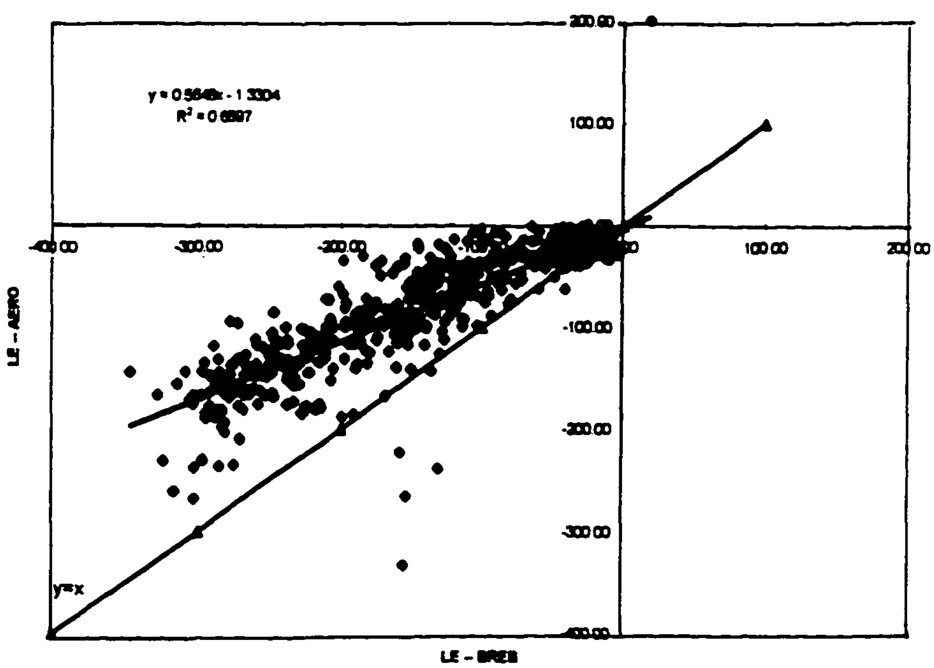

Figure 9b. "Dry period" regression for latent heat: AERO vs. BREB. Data are 12-minute means of daylight data.

latent heat, with R^2 values of 0.72 for the wet period and 0.85 for the dry period. AERO estimates of latent heat underestimated BREB values substantially, and R^2 values dropped as low as 0.14 in the wet period. Table 4 and Figure 8 show a definite relationship between AERO and BREB sensible heat, and for latent heat only in the dry period.

Table 4. Summary regression statistics for sensible and latent heat – AERO vs BREB for the wet and dry periods.

Figure Number	Figure Title	Slope *a*	Intercept *b*	Standard Error *SE*	Correlation Coefficient *R^2*	Sample *n*
	Wet period:					
8a	Sensible Heat–AERO vs. BREB	0.8851	-15.491	37.003	0.7185	324
8b	Latent Heat–AERO vs. BREB	0.275	-68.625	131.74	0.1382	324
	Dry period:					
9a	Sensible Heat–AERO vs. BREB	0.6526	-2.4919	42.497	0.8527	540
9b	Latent Heat–AERO vs. BREB	0.5648	-1.3304	34.171	0.6897	540

Within the wet period, April 8,9,10, and 12 had the highest degree of correlation between sensible heat estimates from the two methods. These wet period data are presented as time series in Figures 10-13 to illustrate the performance of the aerodynamic method for estimating sensible heat. April 8, 1989, represents the best relationship I found between the two methods with an R^2 value of 0.70 for sensible heat flux. April 9 and 10 followed with R^2 values for sensible heat of 0.42 and 0.62, respectively. R^2 was 0.15 for sensible heat on April 12. In considering that these were the best values obtained over a 43-day period, agreement of sensible heat flux from the two methods is unsatisfactory.

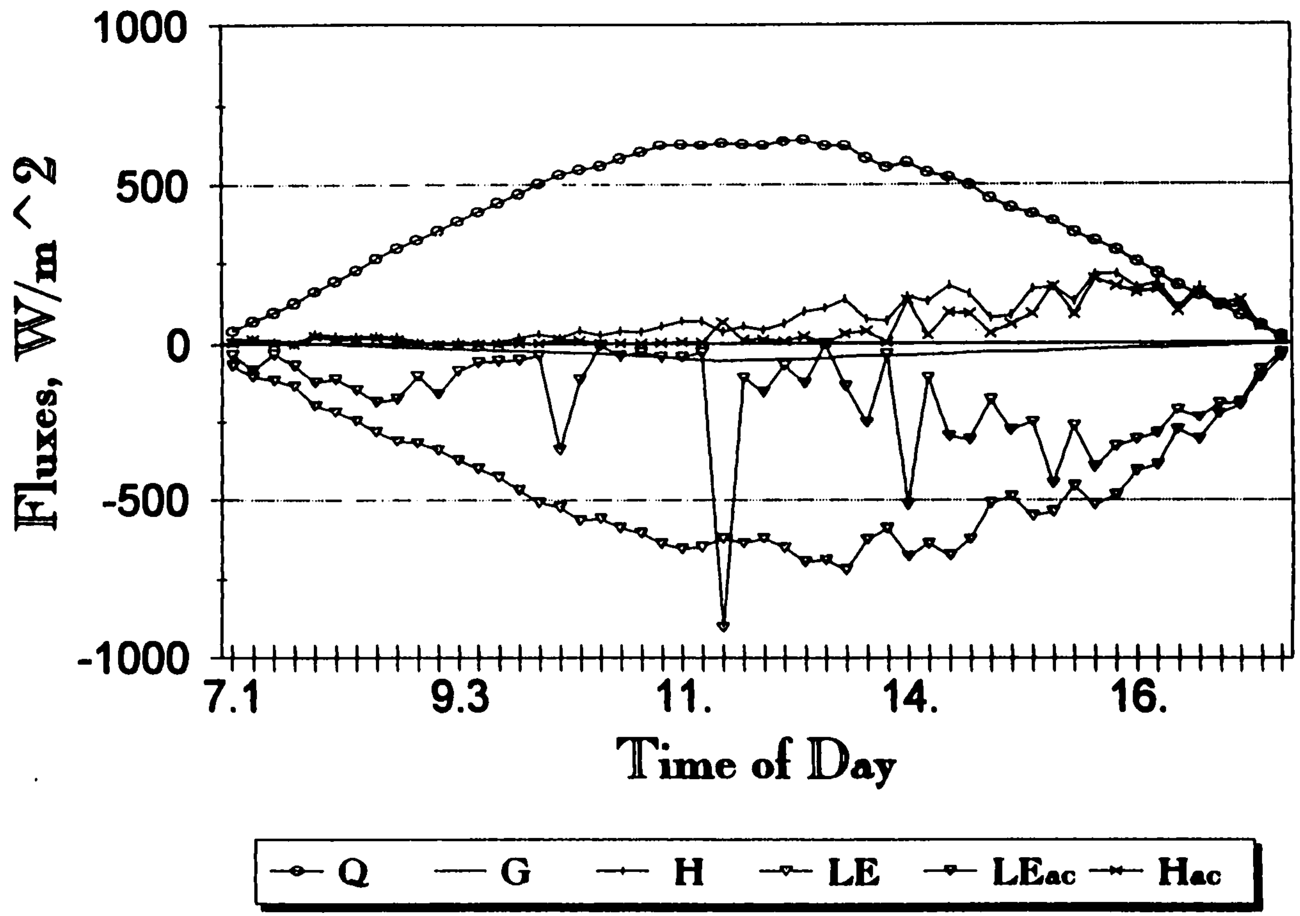

Figure 10. Surface energy balance in the wet period: April 8, 1989.

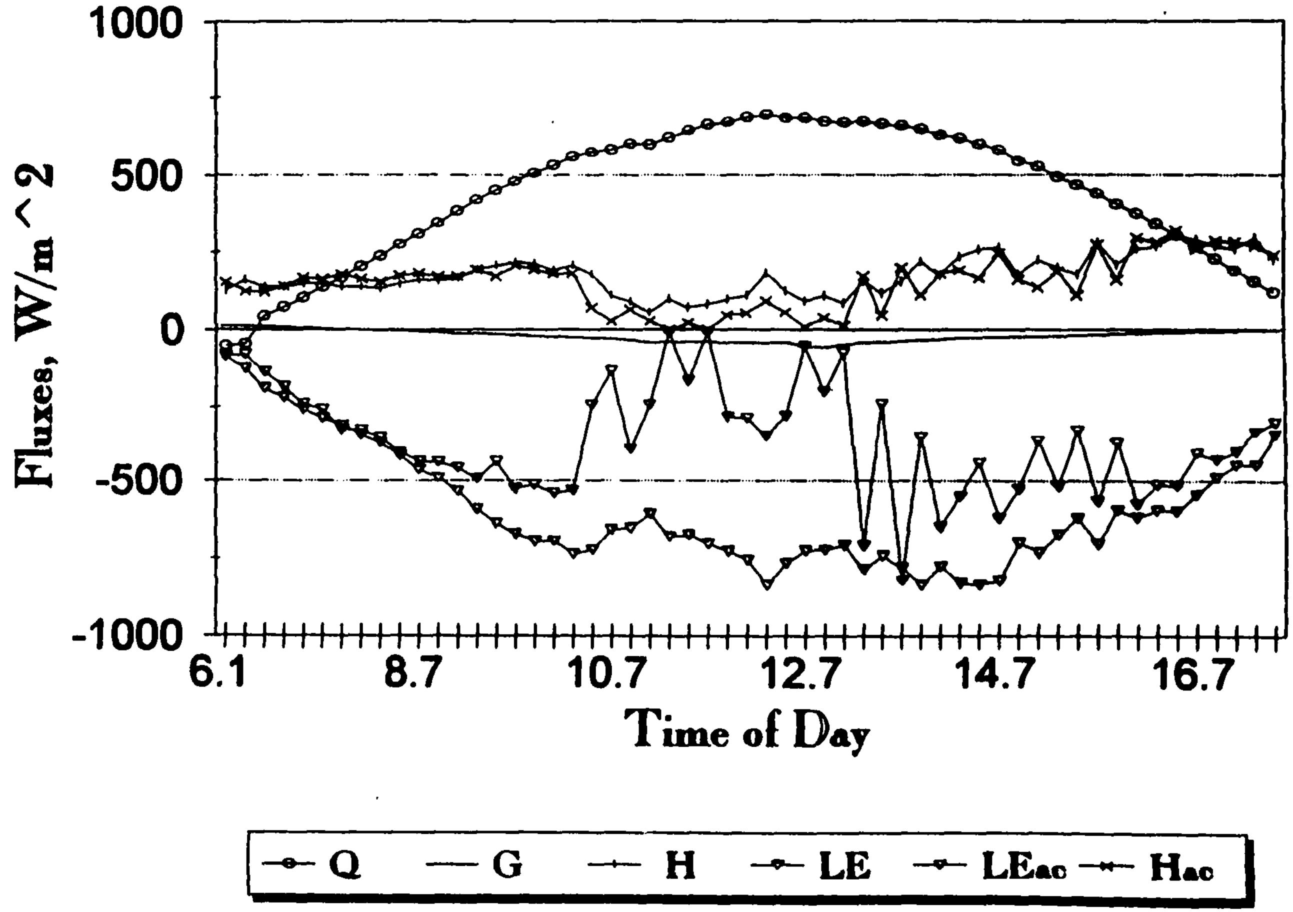

Figure 11. Surface energy balance in the wet period: April 9, 1989.

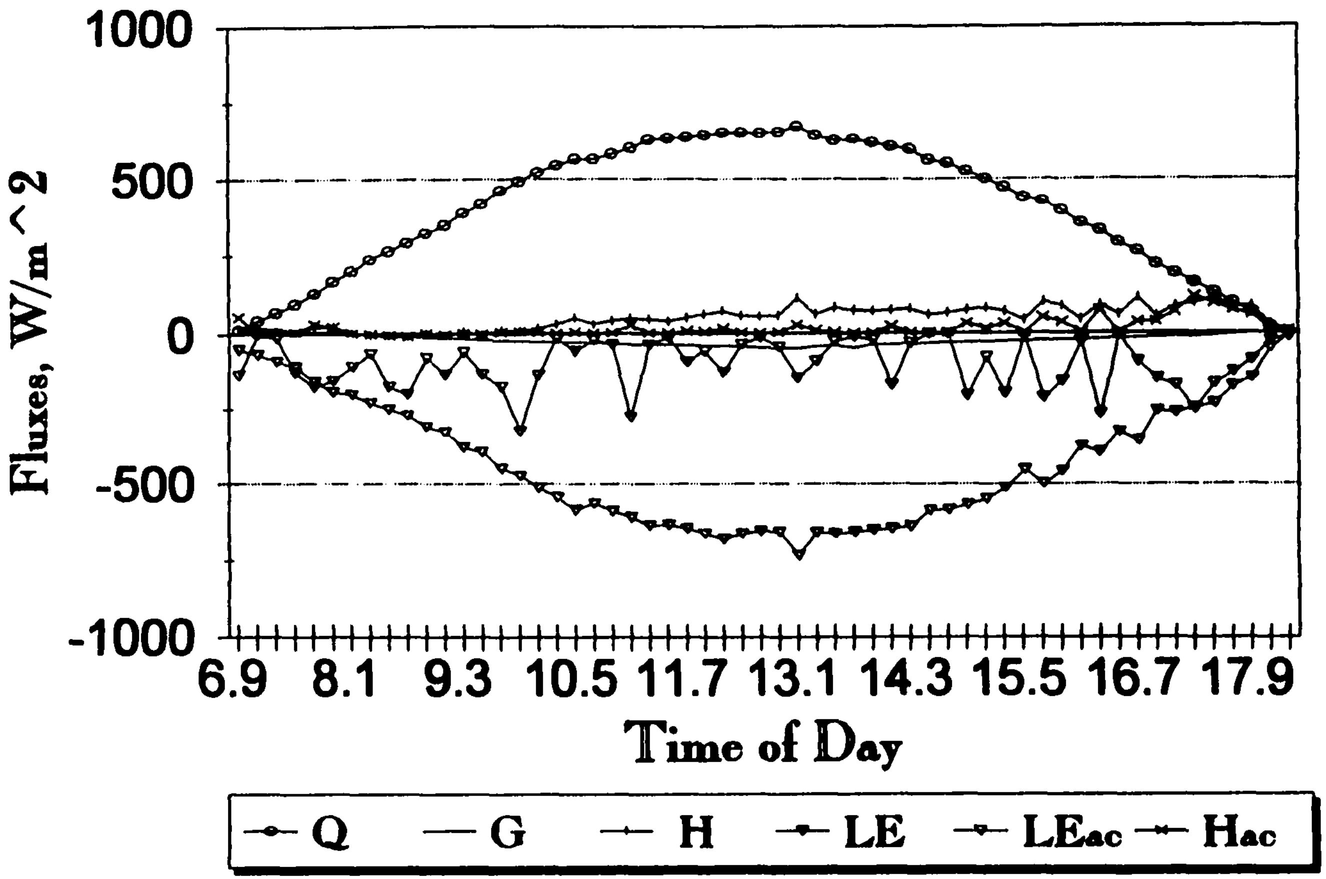

Figure 12. Surface energy balance in the wet period: April 10, 1989.

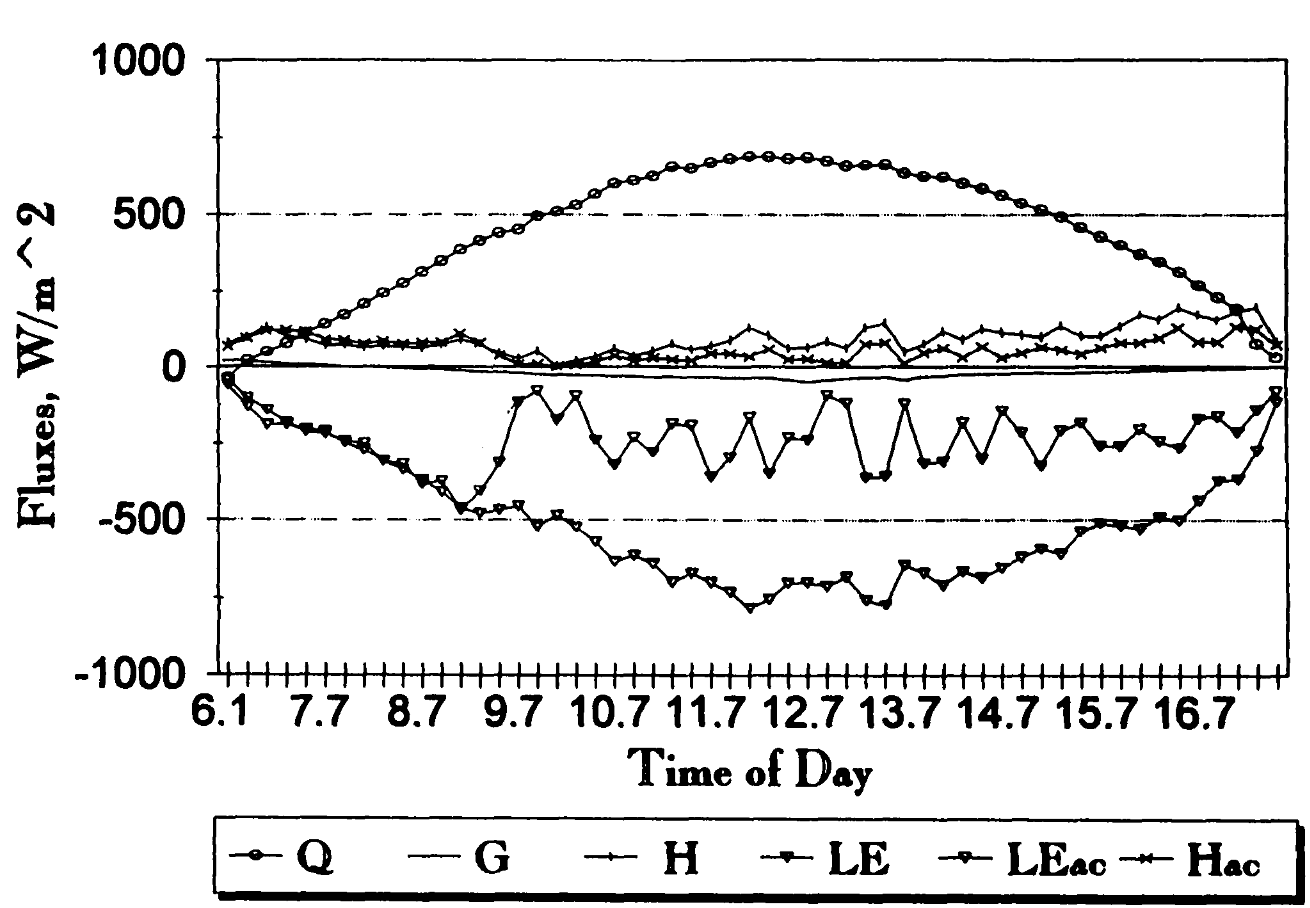

Figure 13. Surface energy balance in the wet period: April 12, 1989

Aerodynamic estimates of latent heat during the wet period were much less satisfactory than for sensible heat, with R^2 values against BREB ranging from 0.02-0.61. April 9, 1989, had the highest correlation for latent heat estimates between the two methods (R^2 = 0.50), followed by^{2}R values of 0.03, 0.27, and 0.41, on April 8, 10, and 12 respectively. Latent heat estimates using the aerodynamic approach consistently underestimated values of the Bowen ratio method over the entire 43-day period. Not only were the R^2 values low in the wet period, but visual impressions from time series plots of the best days (Figures 10-13), confirm that AERO latent heat grossly fails to agree with BREB latent heat. Within the dry period, however, the latent heat comparisons improve somewhat, as discussed in the following section.

Effects of Stability

A secondary objective of this study was to determine the effect of atmospheric stability on aerodynamic estimates. Atmospheric stabilities were generally advective (or stable) during the "wet" period, and convective (or unstable) during the "dry" period. The site made a rapid transition from stable to unstable conditions when the wheat senesced. On DOY 130, daytime sensible heat switched direction from "to the canopy" to "away from the canopy" in association with sharply reduced transpiration and senescence of the wheat. The effect of stability is illustrated in Figures 8 and 9 and Table 4, based upon pooled daylight data for the wet and dry periods. AERO latent heat estimates are better correlated with BREB estimates during the dry period than in the wet period. On a daily basis, R^2 values for DOY 130 through 136 are quite reasonable, ranging from 0.85 to 0.92 for sensible heat and 0.70 and 0.85 for latent heat. These dry conditions are associated with unstable conditions, and it seems likely that this is the cause of the improved agreement.

Source of Variation: wind

The final research question attempts to identify the source of variability in any of the terms in the aerodynamic approach that cause it to deviate from the Bowen ratio model. In other words, is any one term responsible for the difference in the estimates, for example--wind speed, vapor pressure differences, or temperature differences?

The basic equation for determining aerodynamic latent heat in neutral stability is:

$$LE = K_{LE}\,(u_2 - u_1)\,(e_2 - e_1) \qquad (9)$$

which shows that latent heat depends on the product of the wind speed and the difference between vapor pressures near the surface and in the overlying air (Dingman, 1994). The equivalent equation for determining sensible heat gives:

$$H = K_H\,(u_2 - u_1)\,(T_2 - T_1) \qquad (10)$$

demonstrating that sensible heat transfer depends on the wind speed and the difference in temperature near the surface and in overlying air (Dingman, 1994).

Equations 9 and 10 both use the same wind speed, and equation 10 is in reasonable agreement with BREB sensible heat. This suggests that the vapor pressure differences must be responsible for latent heat comparing so poorly with BREB estimates. However, in examining the time series figures and raw data tables for each day, I found the greatest divergence of AERO and BREB fluxes occurred during periods of low wind speed.

An example of this phenomenon is illustrated in Figure 13 (April 12) which shows a radical and abrupt decline (less negative) in latent heat just after 9:00 in the morning. The data show no large variations in vapor pressure or temperature, but the decline coincides with a reduction in wind speed at the top mast from above 2 m/s to below 1 m/s. The aerodynamic values of latent heat then maintain low values through most of the day with wind speeds hovering just below 1 m/s. In Figures 10-13, when wind speeds begin to pick up above 2 m/s at the end of the day, the values of latent heat tend to agree more closely.

The effects of wind speed were examined after stratifying the data into two classes: low wind data for $u < 2$ m/s, and medium wind data for $u > 2$ m/s. There were very few occurrences of $u > 4$ m/s during the experiment. Regression comparisons of AERO versus BREB estimates were repeated for the two groups of data: low wind and medium wind.

Sensible heat flux scattergrams are illustrated for the two wind speed classes in the wet and dry periods (Figures 14 and 17). Table 5 summarizes the regression statistics for sensible heat during the wet and dry periods for the two classes of wind speed. The correlation between AERO and BREB sensible heat estimates improved slightly with higher wind speed in the wet period (R^2 increased from 0.59 to 0.64) and improved greatly with higher wind speed in the dry period (R^2 increased from 0.69 to 0.92).

Table 5. Summary regression statistics for sensible heat at low and medium wind speeds.

Figure Number	Figure Title	Slope *a*	Intercept *b*	Standard Error *SE*	Correlation Coefficient *R^2*	Sample *n*
	Sensible Heat--BREB vs. AERO					
	Wet period					
14a	--low wind speeds	0.5199	-3.4338	23.011	0.5933	255
14b	--medium wind speeds	0.9605	8.4877	37.5534	0.6449	67
	Dry period					
17a	--low wind speeds	0.708	-13.277	57.386	0.6897	163
17b	--medium wind speeds	0.6075	-4.3091	27.099	0.9168	208

Latent heat flux scattergrams are illustrated for the two wind speed classes in the wet and dry periods (Figures 15 and 16). Table 6 summarizes the regression statistics for latent heat during the wet and dry period for both wind speed classes. The correlation between AERO and BREB latent heat estimates vastly improved with higher wind speed in the wet period (R^2 increased form 0.13 to 0.71) and improved greatly with higher wind speed in the dry period (R^2 increased from 0.46 to 0.76).

Table 6. Summary regression statistics for latent heat at low and medium wind speeds.

Figure Number	Figure Title	Slope *a*	Intercept *b*	Standard Error *SE*	Correlation Coefficient *R^2*	Sample *n*
	Latent Heat--BREB vs AERO					
	Wet Period					
15a	--low wind speeds	0.1811	-63.587	94.0217	0.1269	255
15b	--medium wind speeds	0.6976	-50.719	73.5388	0.714	67
	Dry Period					
16a	--low wind speeds	0.6309	1.5456	51.595	0.455	163
16b	--medium wind speeds	0.5213	-5.5195	20.41	0.7573	208

In summary, I conclude that agreement between AERO and BREB methods improved substantially for wind speeds greater than 2 m/s. The improvement was especially noticeable for the latent heat estimates.

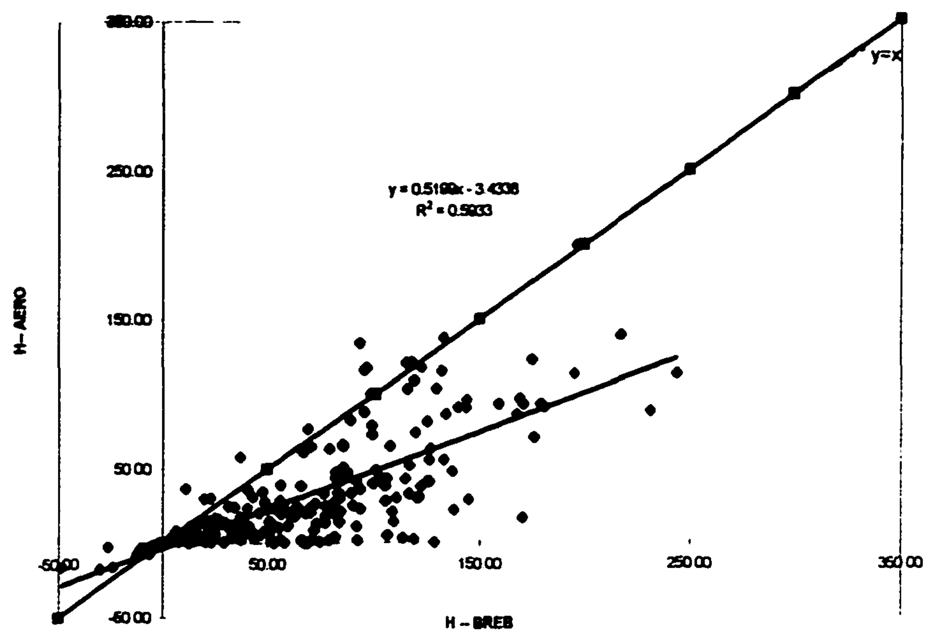

Figure 14a. "Wet period" regression for sensible heat: low wind. Data are 12-minute means of daylight data.

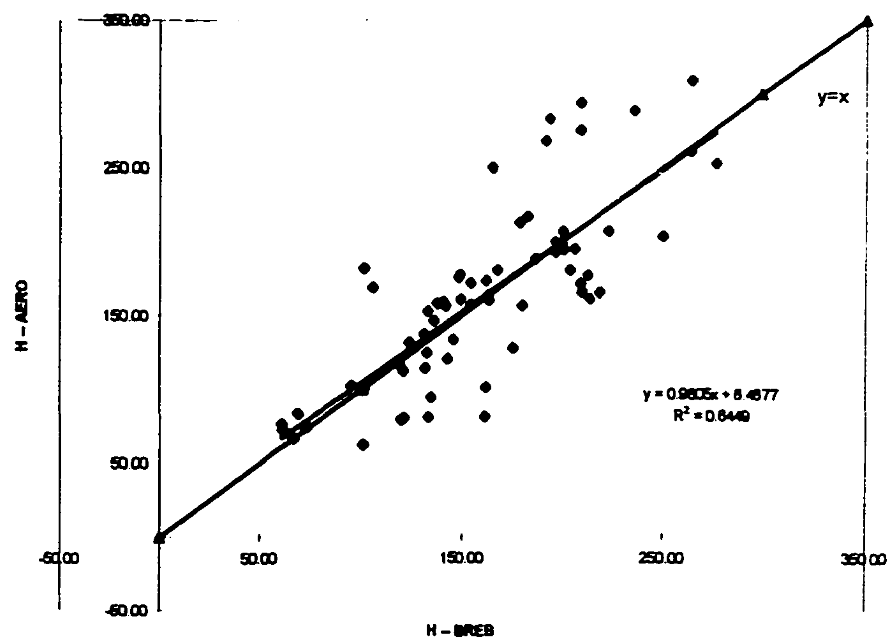

Figure 14b. "Wet period" regression for sensible heat: medium wind. Data are 12-minute means of daylight data.

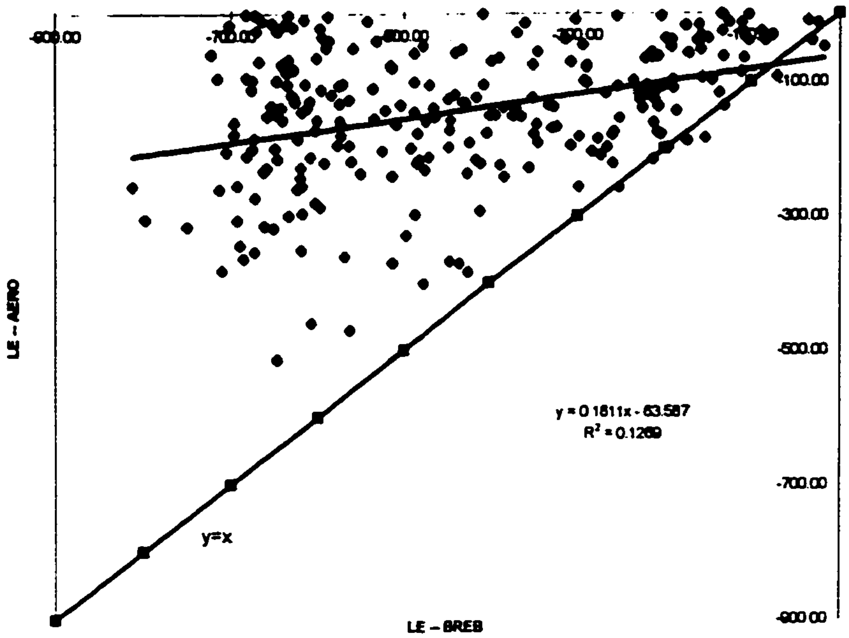

Figure 15a. "Wet period" regression for latent heat: low wind. Data are 12-minute means of daylight data.

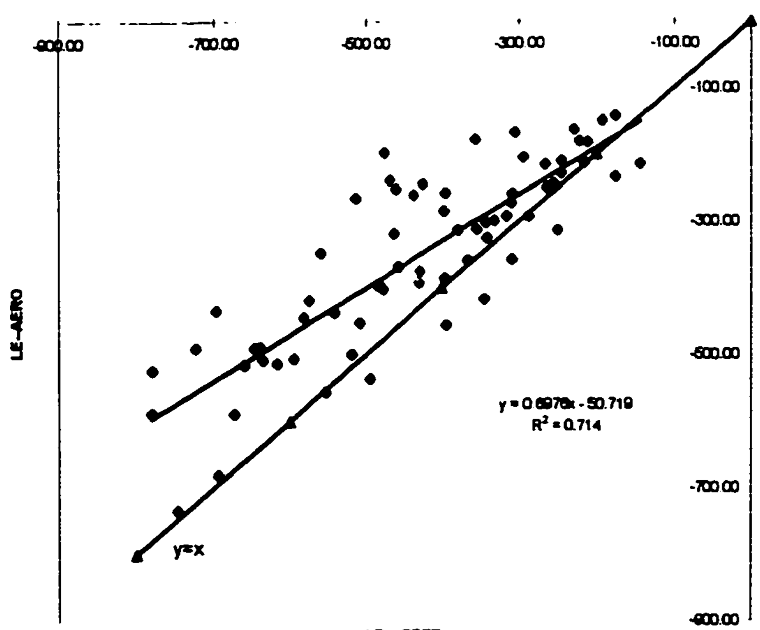

Figure 15b. "Wet period" regression for latent heat: medium wind. Data are 12-minute means of daylight data.

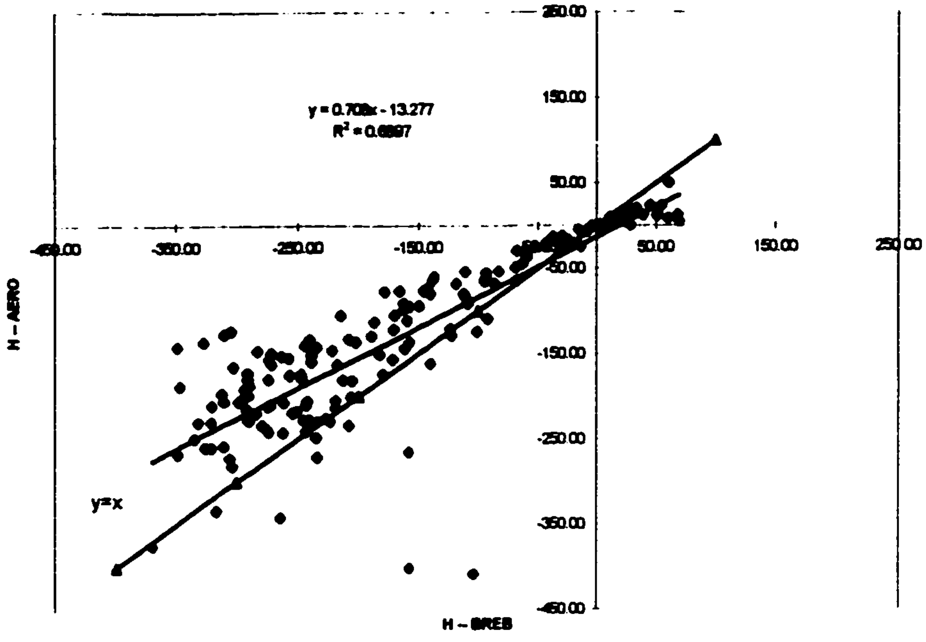

Figure 16a. "Dry period" regression for sensible heat: low wind. Data are 12-minute means of daylight data.

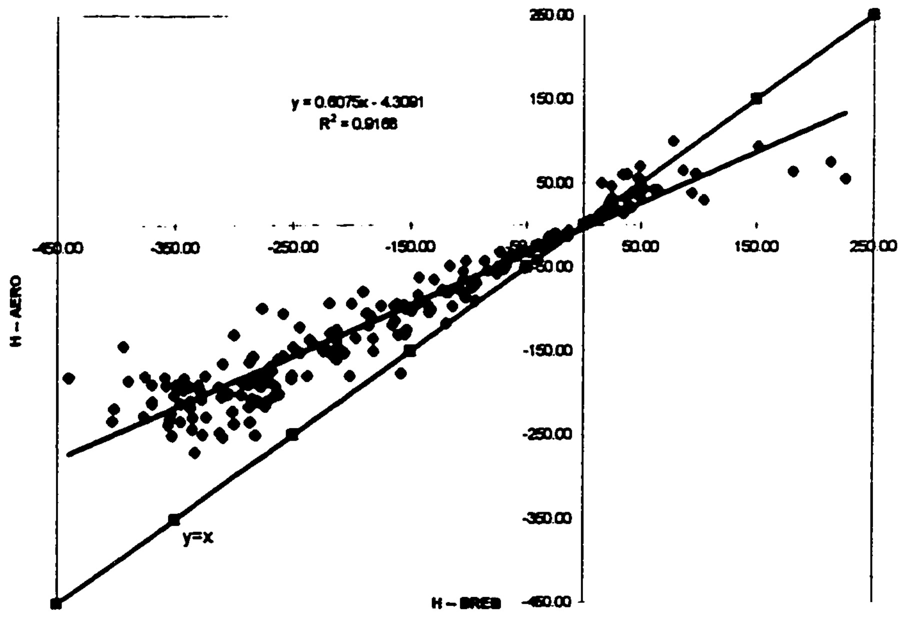

Figure 16b. "Dry period" regression for sensible heat: medium wind. Data are 12-minute means of daylight data.

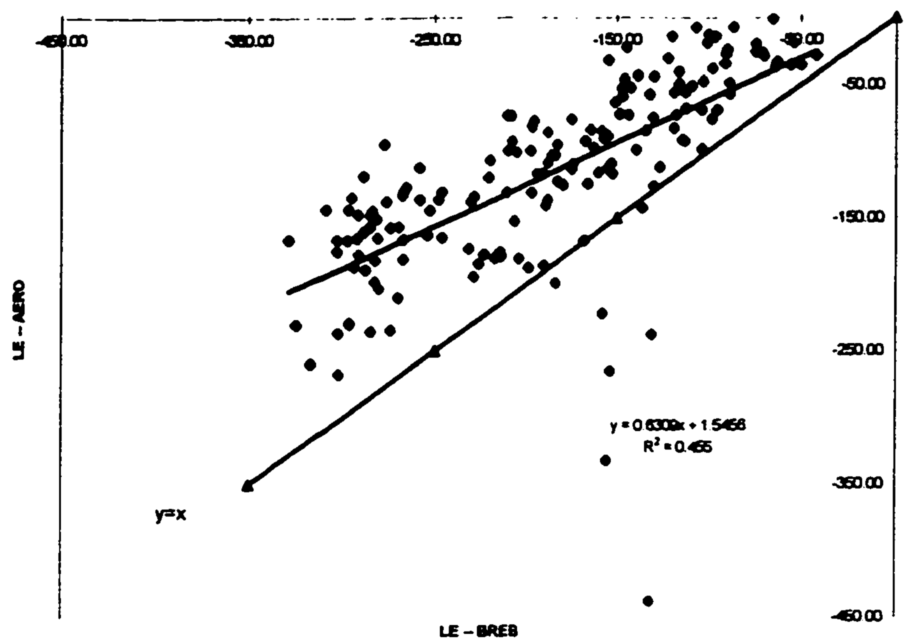

Figure 17a. "Dry period" regression for latent heat: low wind. Data are 12-minute means of daylight data.

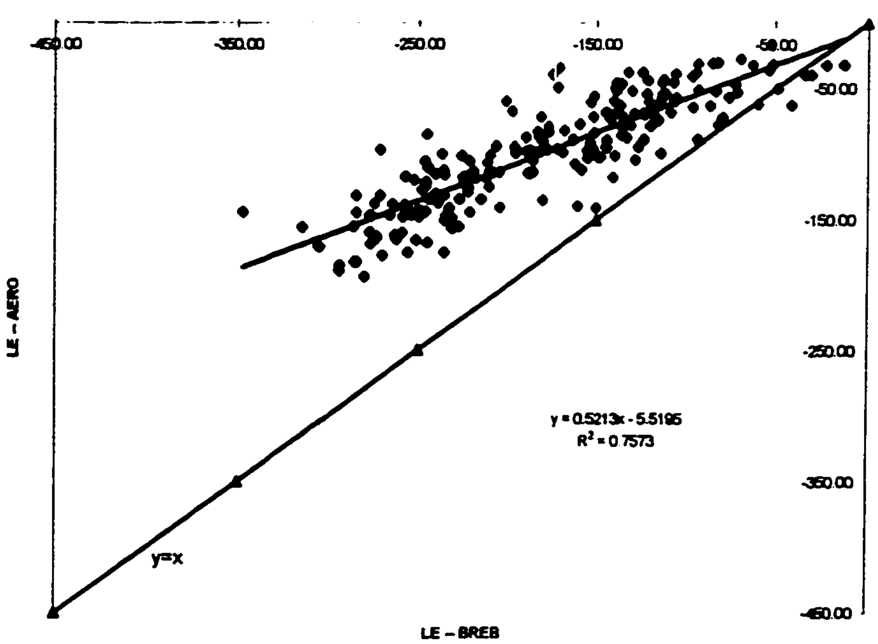

Figure 17b. "Dry period" regression for latent heat: medium wind. Data are 12-minute means of daylight data.

A New Aero-Energy Balance Model for Latent Heat

At this point, it seems reasonable to state that the AERO and BREB sensible heat values agree reasonably well, while the latent heat values agree poorly. Consequently, it seems natural to apply the AERO sensible heat estimates in the surface energy balance to obtain an estimate of latent energy heat flux as a residual.

The surface energy balance equation is the sum of the radiant and turbulent fluxes into and out of the surface, given by the equation:

$$Q + G + LE + H = 0,$$

where Q is the net radiation, G is the soil heat flux, LE is the latent heat flux, and H is the sensible heat flux. IF Q, G, and AERO H are measured, latent energy can be estimated as a residual:

$$LE_{resid} = -(H_{aero} + G + Q)$$

This was accomplished initially for April 8,9,10 and 12 using data from system A. The excellent agreement between LE_{resid} and BREB latent heat is clearly evident in the time series plots of Figure 18-21. The LE_{resid} values are in excellent agreement with the BREB estimates, with only slight deviations during the middle of the day.

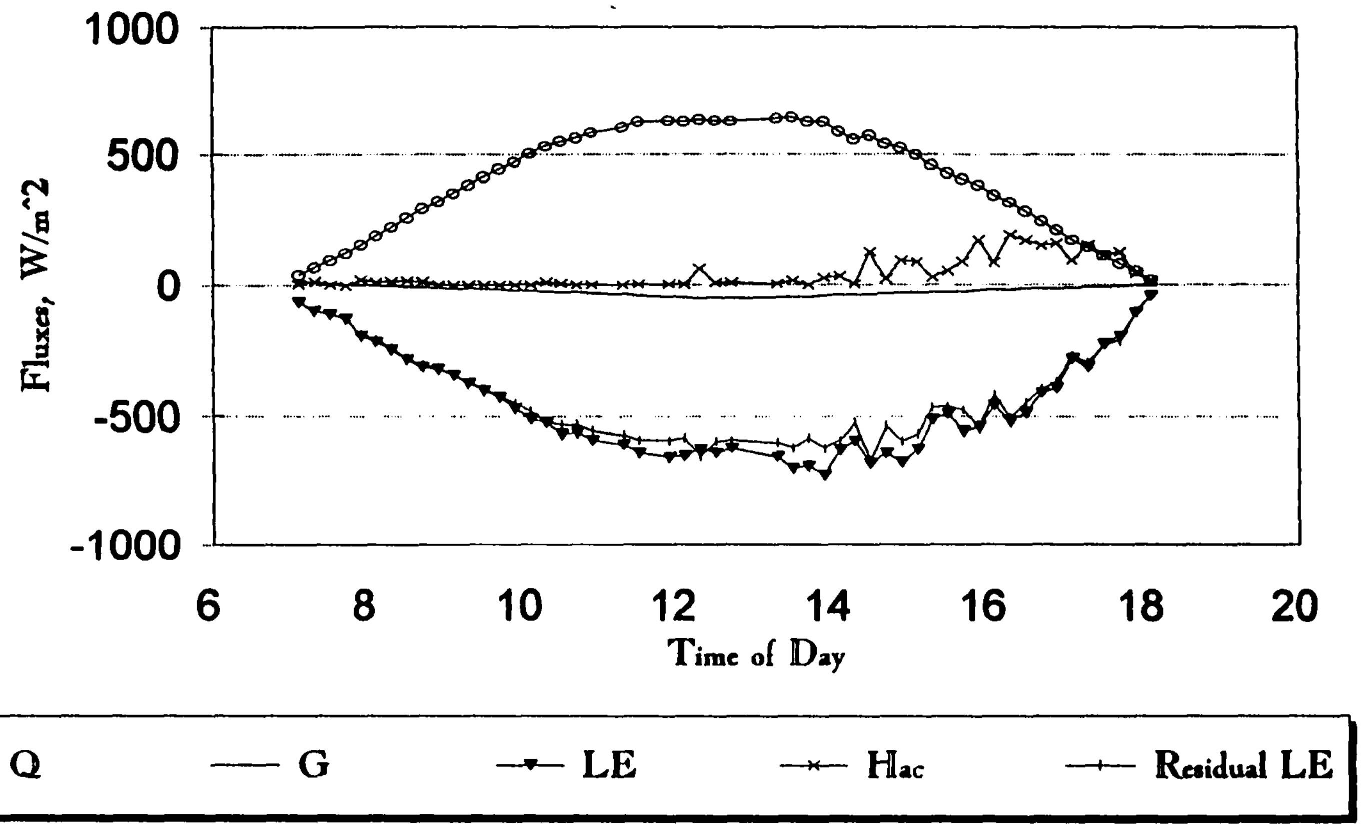

Figure 18. Surface energy balance for residual LE estimates: April 8, 1989.

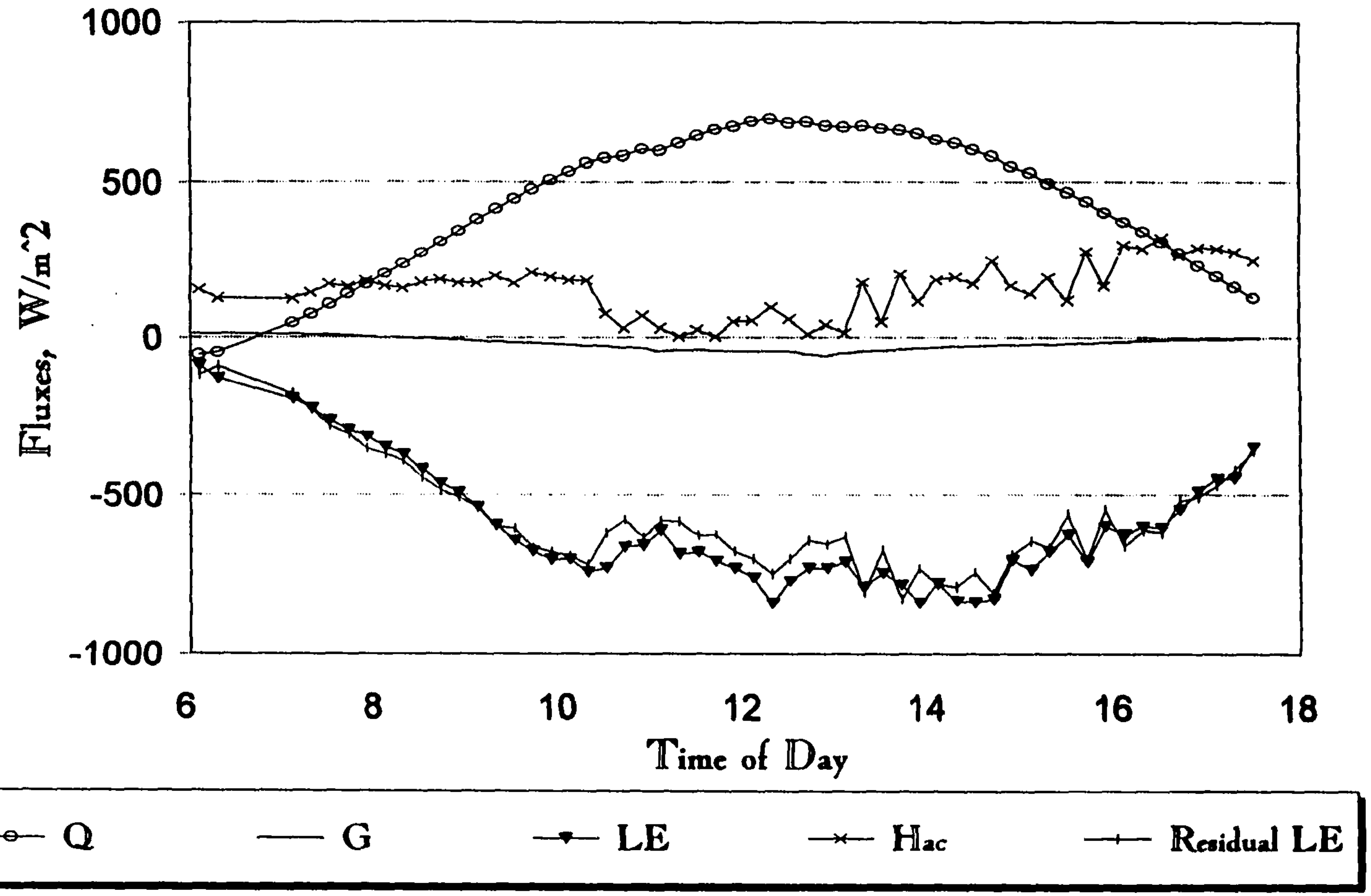

Figure 19. Surface energy balance for residual LE estimates: April 9, 1989.

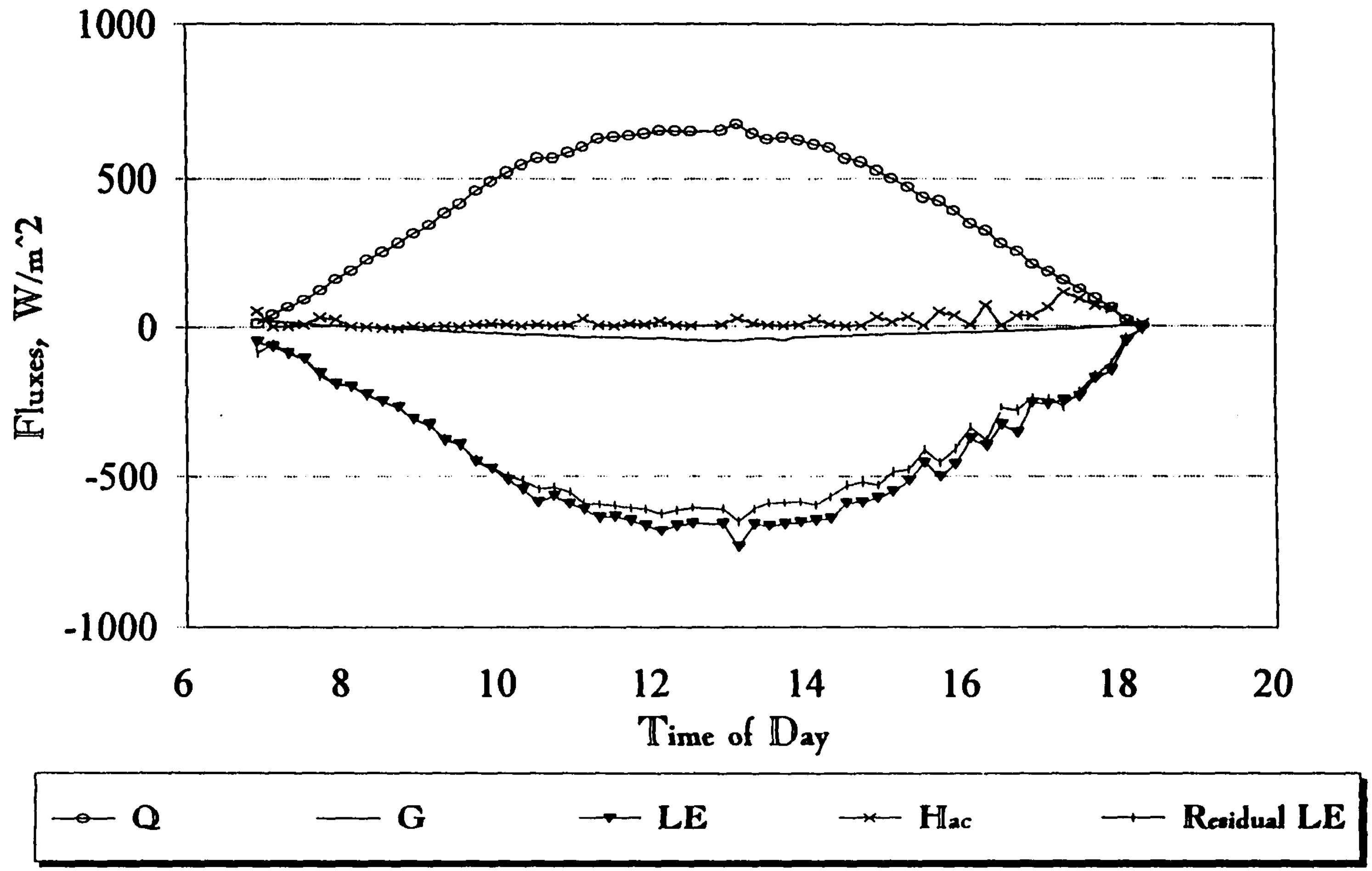

Figure 20. Surface energy balance for residual LE estimates: April 10, 1989.

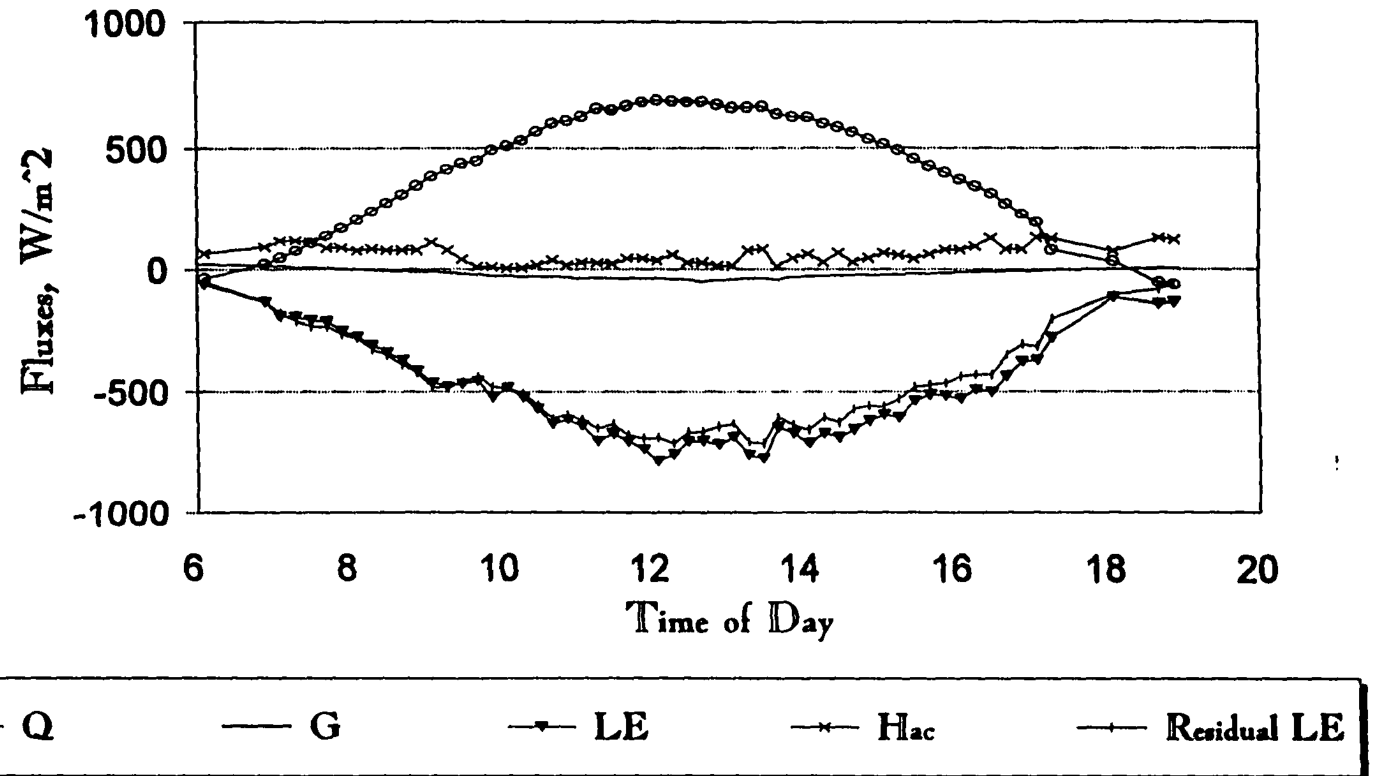

Figure 21. Surface energy balance for residual LE estimates: April 12, 1989.

This approach was expanded to include the wet and the dry period data set from system B. Residual values of latent heat were regressed against BREB latent heat for these periods, as illustrated in Figures 22 and 23, and summarized in Table 7. Excellent agreement was obtained between these two methods when using the simplified residual approach. The R^2 correlation was better during the wet period (0.97) than during the dry period (0.78). This curiosity can be explained by the fact that more accurate measurements can be taken to determine available energy in the wet period than in the dry period. In the wet period, sensible heat is moving toward the field and energy is being advected over the surface from the surrounding desert region. The available energy or evapotranspiration can simply be estimated by measuring the wind speed and temperature difference over the surface. In the dry period, sensible heat is moving away from the surface and it is therefore much harder make an accurate measurement of the available energy.

Table 7. Summary regression statistics for latent heat: BREB vs residual LE.

Figure Number	**Figure Title**	**Slope** *a*	**Intercept** *b*	**Standard Error** *SE*	**Correlation Coefficient** *R^2*	**Sample** *n*
22	*Wet Period* Latent Heat --BREB vs residual	0.9037	-17.037	32.963	0.9651	324
23	*Dry Period* Latent Heat--BREB vs residual	1.316	15.153	62.532	0.7808	540

Blanford and Gay (1992) carried out a similar experiment of combining sensible heat flux measurements from eddy correlation with net radiation and soil heat flux measurements to determine residual estimates of latent heat. Just as in this experiment, the residual estimates of latent heat were found to be precise and of high quality, confirming the adequacy of the sensible heat flux measurements. By utilizing the surface energy balance to determine residual estimates of latent heat, accurate results can be obtained with simple, robust measurements versus the more complex measurements associated with the Bowen ratio and aerodynamic approaches.

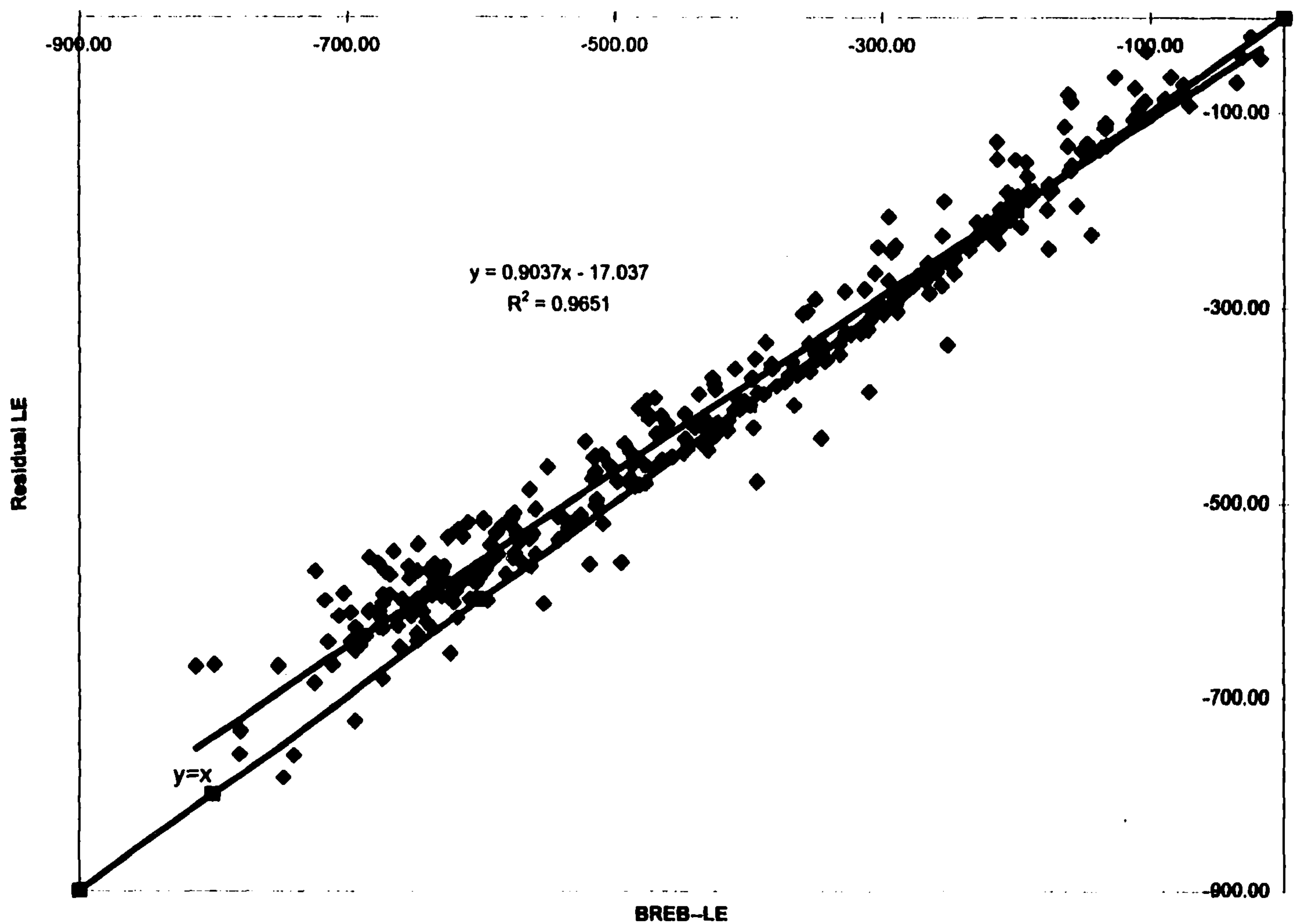

Figure 22. Latent heat regression for residual LE vs BREB LE during the wet period. Data are 12-minute means of daylight data.

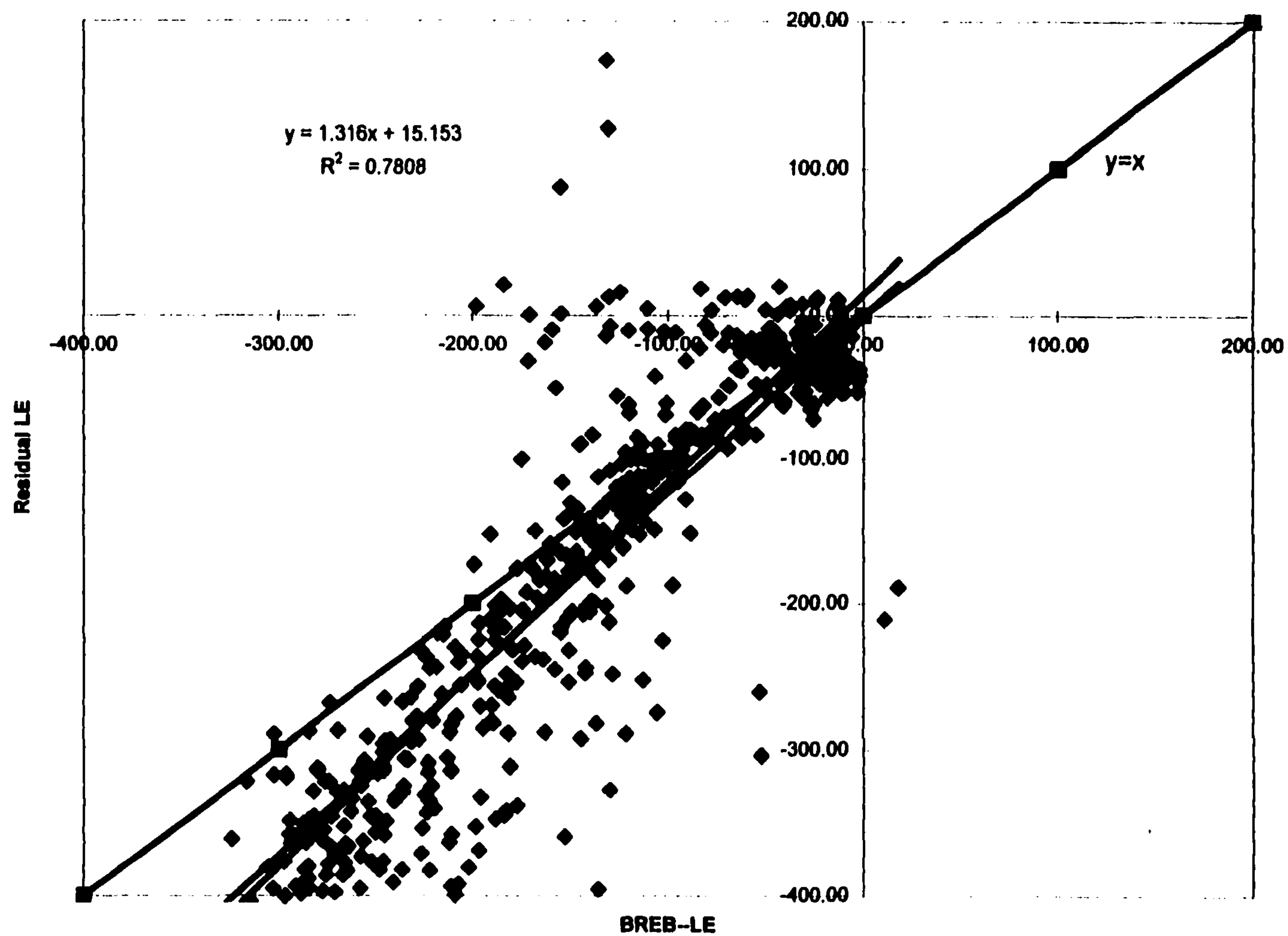

Figure 23. Latent heat regression for residual LE vs BREB LE during the wet period. Data are 12-minute means of daylight data.

V. Summary and Conclusions

Presented in this chapter is a summary of the results found in this study which compared evapotranspiration estimates of winter wheat from the aerodynamic method against the Bowen ratio energy budget. The analyses were based upon 12- minute means of micrometeorological data collected over irrigated winter wheat at Maricopa Agriculture Center from April 6 - May 16, 1989. The AZET Bowen ratio system measured surface fluxes for soil heat, net radiation, sensible heat, and latent heat. The gradients of air temperature and vapor concentration from the Bowen ratio system were augmented by wind profile measurements to compute sensible and latent heat fluxes by a stability-corrected aerodynamic (AERO) method. The aerodynamic fluxes were compared with "ground truth" fluxes from the Bowen ratio energy balance (BREB) system.

Bowen ratio measurements were validated by comparing two side-by-side systems for an 8-day period when the wheat was rapidly growing and transpiring heavily. The two systems had excellent correlation for net radiation (Q), air temperature (Ta), vapor pressure difference (dE), sensible heat (H), and latent heat (LE). BREB estimates of sensible heat were further compared with eddy-correlation measurements over a 6-day period at the end of the experiment after the wheat had ripened (senesced) and the transpiration rate had decreased substantially. Sensible heat from these two independent methods was in excellent agreement. The aerodynamic analyses were restricted for convenience to the two calibration periods: the 8-day "wet" period of high water use, and the 6-day "dry" period of low water use.

Based on the results of the study, the following conclusions can be made:

(1) Latent heat fluxes calculated with the AERO method compare poorly against those from the BREB approach during the wet period. AERO latent heat consistently underestimated BREB latent heat under transpiring conditions. Sensible heat estimates from the two methods agreed reasonably well, but not aways, during the wet conditions.

(2) Relationships between sensible and latent heat fluxes from the AERO and BREB methods improved markedly in the dry period after the wheat ripened. The correlations improved, but slopes and offsets differed substantially from the desired values of 1.0 and 0, indicating that local calibration would be needed to use the AERO results.

(3) The greatest source of variability between the AERO and BREB estimates of latent heat is attributed to wind speed (u). The data were classified according to low wind ($u < 2$ m/s) or medium wind ($u > 2$ m/s). The agreement between AERO and BREB estimates of sensible and latent heat for the medium wind environment improved markedly over those obtained initially for the unclassified data. The improvement was greater for the wet period than for the dry.

(4) A promising new model was developed by combining AERO sensible heat (H_{aero}) with net radiation and soil heat flux to estimate latent energy as a residual (LE_{resid}) in the surface energy balance equation. The new method is called the aerodynamic energy balance (AEB) approach. It works extremely well during the heavily transpiring period, as LE_{resid}= 0.90$\cdot$ LE_{BREB}-17 (W/m^2), with $R^2 = 0.97$, and standard error of 33 over data ranging from 0 to 800 W/m^2. The AEB method is a substantial improvement over the conventional AERO method.

Recommendations

Based on this study, I would recommend that the stability-corrected aerodynamic method not be used without some sort of calibration as a means of determining latent and sensible heat fluxes for evapotranspiration. The Bowen ratio method is more accurate and should be utilized in cases where reliable estimates are required. Application of the AERO method can be recommended only for windy environments.

I also recommend a broader analysis of the stability corrections for the aerodynamic formulas, as these appear to be associated with the deviations between the two methods. I conclude that the wind speed plays the main role in the poor relationship between these two methods, but future studies could possibly pinpoint the one or more variables responsible for the aerodynamic method's poor performance. Suitability of the stability corrections lies beyond the scope of this study.

Closing

For numerous reasons, a quantitative understanding of evapotranspiration is of primary importance. The difference between precipitation and evapotranspiration is the water left over for human consumption and management. Much of the water lost through evapotranspiration if used to grow plants and irrigated crops. In order to understand this ecosystem and its response to climate change we depend upon accurate knowledge of evapotranspiration.

In some of the earliest records of human history man became aware of the occurrence of evaporation and began to speculate at its origins and effects. If history can teach us anything about evapotranspiration it is not to discredit its importance in the hydrologic cycle. I conclude with words passed on from Thales of Miletos in Ionia, who lived around 585 B.C.and maintained that water is the main principle of everything and gave three reasons for this assertion as he said (Brutsaert, 1982) " that even the fire of the sun and of the stars, and even the kosmos itself, are fed by the evaporation of the waters."

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