CHAPTER X. MICROMETEOROLOGICAL MEASUREMENTS

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A. INTRODUCTION

Surface energy flux measurements were conducted in the spring and summer of 1994 over four different ecosystems in the Little Washita River watershed located west of Chickasha, OK. This effort was part of a multi-agency and multi-disciplinary study to estimate local and regional scales of latent and sensible heat fluxes. The spring campaign was conducted during April 4-14 (DOY 94-104), 1994, while the summer campaign took place August 16-23 (DOY 228-235), 1994. Each of the four ecosystems was selected on the basis of representativness of the total surface area of the Little Washita watershed.

Data from these experiments will be used to characterize surface energy exchange from different ecosystems and evaluated with measurements of soil moisture from the same sites. Regional estimates of latent and sensible heat flux calculated from free radiosonde and Landsat TM data sets will be compared with the surface flux data.

Bowen-ratio and eddy correlation techniques were employed to estimate latent and sensible heat flux exchange. The Bowen-ratio represents a partitioning of net radiation into sensible and latent heat fluxes (Bowen, 1926) and is generally expressed as:

$$\beta = \frac{H}{\lambda E} = \frac{PC_p}{\lambda \epsilon}\left(\frac{K_h}{K_v}\right)\frac{(\partial T/\partial z)}{(\partial e/\partial z)} \approx \frac{PC_p}{\lambda \epsilon}\left(\frac{\Delta T}{\Delta e}\right) \qquad \textbf{(1)}$$

where β is the Bowen-ratio, H and λE are sensible and latent heat flux respectively, (λ is the latent heat of vaporization for water and E is a quantity of water evaporated), P is atmospheric pressure, C_p is specific heat of moist air, ϵ is the ratio of mole weights of water vapor and air, K_h and K_v are transport coefficients for heat and water vapor respectively, ∂T and ∂e are temperature and vapor pressure gradients over an underlying surface. A simplifying assumption, when using the Bowen-ratio is that $K_h = K_v$. This assumption has been debated extensively in the literature resulting in conflicting conclusions on its validity. Nevertheless the Bowen-ratio has been shown to be acceptably accurate in many applications and is widely used.

The energy balance over an underlying surface can be written as:

$$R_n - G = H + \lambda E \qquad \textbf{(2)}$$

where R_n is net radiation, G is soil heat flux which in this study includes the soil storage term for heat above the heat flux plate, H and λE have been previously defined. Rearranging equations X-1 and X-2 and solving for λE yields the following (Suomi and Tanner, 1958):

$$\lambda E = \frac{R_n - G}{1 + \beta} \qquad \textbf{(3)}$$

where all terms have been previously defined. In this manner R_n and G are measured directly with a net radiometer and soil heat flux plates respectively, β is calculated from measurements of temperature and vapor pressure gradients at two heights, λE is estimated from equation X-3 and H is calculated as a residual from equation X-2.

In 1951 Swinbank proposed an "eddy correlation" method to estimate vertical fluxes of heat and water vapor from a fully turbulent mean flow. The upward flux of an entity is given by:

$$F = \overline{\rho_a w s} \qquad \textbf{(4)}$$

where F is the flux of the entity s, ρ_a is density of air, w is vertical velocity, and the overbar indicates an average condition over an appropriate sampling period. Terms on the right-hand side of equation X-4 can be decomposed in the following manner:

$$\rho_a = \overline{\rho_a} + \rho'_a,\ w = \overline{w} + w',\ s = \overline{s} + s' \qquad \textbf{(5)}$$

where overbars represent component means and primes denote the instantaneous deviation from the mean (ie the effects from individual eddies). With the advent of high frequency instrumentation for measurements of vapor density and vertical wind velocity, latent and sensible heat fluxes can be expressed as:

$$H = \rho_a C_p \overline{w'T'} \qquad \textbf{(6)}$$

$$\lambda E = \lambda \overline{w'q'} \qquad \textbf{(7)}$$

where q is specific humidity and all other terms have been previously defined. The overbars again indicate time averages and the primes denote deviations from the mean. The quantities on the right hand side of equations X-6 and X-7 are covariances of the instantaneous deviations for w, T, and q.

B. SITE NOMENCLATURE

For the months of April and August four sites were intensively monitored for a variety of micrometeorological parameters. Three of the sites were used for both campaigns, one was not. The convention used to identify the sites was simply consecutive numbering 1 through 4 moving from east to west across the watershed. Thus, site 1 was the eastern most location in the watershed and site 4 four was the western most location. Sites 1, 3, and 4 were monitored for the April and August studies, while site 2 was different for April and August.

C. MEASUREMENTS AT SITE 1

General Description - April/August

Site 1 was located in native pasture that was primarily vegetated with a mixture of Buffalograss (*Buchloe dectyloides)*, Little Bluestem (*Schizachyrium scoparium var. frequens*) and Switchgrass (*Panicum virgatum*). During the April study most of the grasses were dormant except for a few annual species that were in the initial emerging stages providing a low 2-4 cm height carpet of green vegetation. During the August campaign the surface was densely populated with several species of grasses that ranged in height from 25-75 cm filling in the areas between individual forbe shrubs. The mean elevation of this site was approximately 340 meters with a topography that was characterized with small undulating slopes. The primary land use function of this ecosystem was for cattle grazing.

April Instrumentation

In April the site was equipped with Bowen-ratio and eddy correlation stations to estimate latent and sensible heat fluxes. The Bowen-ratio system consisted of aspirated wet and dry bulb psychrometers located at two heights above the surface (50 and 150 cm). The eddy correlation system consisted of a Campbell Scientific[*] CA27 1-d sonic anemometer (with finewire thermocouple) and a KH20 krypton hygrometer which were positioned at 130 cm above the surface. Sensor orientation into the wind in response to changing wind directions was evaluated daily. Fetch in all directions from the instrument site was in excess of 180 meters. In addition, net radiation and soil heat flux were measured using a Radiation Energy Balance Systems[*] (REBS) Q[*]6 net radiometer and a REBS HFT-1 soil heat flow transducer. The net radiometer was oriented to the south and positioned 130 cm above the surface while the soil heat flux transducer was buried 8 cm below the soil surface. Soil heat-storage flux was calculated from soil temperatures measured at 2, 4, and 8 cm depths using copper-constantan thermocouples and estimates of bulk density and soil moisture. Wind speed and direction were measured with an R.M. Young[*] 3-cup anemometer and a Met-One wind direction vane mounted 2 m above the surface. Relative humidity and air temperature were measured with a Vaisala* HMP-35B sensor also located 2 m above the surface. Eddy correlation sensors were scanned at 10 hz with 10 and 30-min means recorded on a Campbell Scientific 21 X data logger for both April and August study periods. Net radiation, soil heat flux, wind speed, wind direction, air, surface, soil temperatures, and relative humidity were scanned at 60 second intervals and recorded as 30-min averages. Data collection of 30-minute averages for 24 hours of all micrometeorological parameters for the April study began on the 4th and ended on the 14th.

August Instrumentation

During the August campaign the same location at Site 1 was used for all measurements. Instrumentation included the above mentioned except for the Bowen-ratio station which was not deployed for the August study. Measurements of surface temperature were included during this period using an Everest* 4000LCS Fixed-head Infrared Thermometer (IRT) mounted at 150 cm above the surface at a 90° angle. Solar radiation was measured with a Licor* 200 pyranometer at a height of 2 m. The sampling frequency of the eddy correlation sensors was 10 hz with 10 and 30-min means recorded on a Campbell Scientific 21 X data logger for both April and August study periods. Net radiation, soil heat flux, wind speed, wind direction, air, surface, soil temperatures, and relative humidity were located at the same heights as those during April and were scanned at 60 second intervals and recorded as 30-min means and totals. The net radiometer used during this period was an upgraded version of the REBS Q^*6 denoted as Q^*7. Data collection of 30-minute averages for 24 hours of all micrometeorological parameters for the August study began on the 16th and ended on the 23rd.

D. MEASUREMENTS AT SITE 2

General Description - April

Site 2 was located in an improved Bermuda grass (*Cynodon dectylon*) pasture. During the April study the Bermuda grass was dormant with individual patches of weeds interspersed throughout the field. The mean elevation of this site was approximately 240 meters with a gentle sloping topography toward the south. The primary land use of this ecosystem was for cattle grazing.

General Description - August

During the August study, a different field was selected for Site 2 and was located in an poor Bermuda grass pasture that had been harvested for livestock feed. The surface was characterized by a mowed surface of dry grass stems. The mean elevation was 384 meters with a generally flat topography. This field was considerably smaller than the other three sites with dimensions of 300 meters in the north-south direction and 160 meters along the east-west direction. A small hill was located midway along the length and eastern edge of the field where daily radiosonde balloon launches were conducted by the National Severe Storms Laboratory (NSSL).

April Instrumentation

A Bowen-ratio station described for Site 1 was installed with accompanying net radiation, soil heat flux, soil temperature thermocouples, wind speed and direction sensors, and a Vaisala humidity probe. The anemometer, wind vane and humidity probe were placed at height of 2 m above the Bermuda grass while the aspirated psychrometers were positioned at 50 and 100 cm above the surface. The net radiometer, soil heat flux plate and soil temperature probes were located at the same heights and depths as those at Site 1. No eddy correlation data were collected at this site. The data acquisition system, sampling frequencies, and averaging times were the same as those used at Site 1. A low voltage electric fence was erected around the site to protect the instrumentation from grazing cattle.

August Instrumentation

The instrumentation at Site 2 for the August measurement period consisted of eddy correlation sensors described earlier to measure latent and sensible heat fluxes. Net radiation was measured with a Q^*7 radiometer positioned at 1.2 m above the surface while the soil heat flux plate and accompanying soil thermocouples were placed at the same depths as in Site 1. Wind speed, direction, pyranometer, and humidity probe were all located at 2 m. The data acquisition system, sampling frequencies, and averaging times were the same as those used at Site 1. The location of the eddy correlation system was to the north end of the field to ensure sufficient fetch. The mean wind direction for all days except one was from the south.

E. MEASUREMENTS AT SITE 3

General Description - April/August

Site 3 was also located in an improved Bermuda grass (*Cynodon dectylon*) pasture along the western edge of the watershed near Apache. During the April study the Bermuda grasses were dormant with individual patches of weeds interspersed throughout the field. The average height of the dormant Bermuda was approximately 10 cm. During the August study the Bermuda grass surface was considerably greener having a mean height of approximately 20 cm. The mean elevation of this site was approximately 437 meters with a relatively flat topography. The dimensions of this field were 800 meters along the north south direction and 200 meters along the east-west transect. As with the Sites 1 and 2 the function of this field was for cattle grazing.

April Instrumentation

A 10 m instrumented tower is located at Site 3. The tower is part of the Oklahoma Mesonet program used to monitor climatic changes near the surface in 105 counties of Oklahoma. Instrumentation of the tower consisted of wind speed anemometers at 2 and 10 meters, wind direction at 10 meters, air temperature sensors at 1.5 and 9 meters, solar radiation at 1.8 meters and relative humidity at 1.5 meters. Other instrumentation included a tipping bucket rain gauge, leaf wetness sensor, soil temperature probes (5 and 30 cm depths) and a barometric pressure sensor. Located near the tower is a precision weighing lysimeter with dimensions of 1 x 1 x 1.5 m.

Eddy correlation and Bowen-ratio systems were installed next to the lysimeter along with net radiation and soil heat flux sensors. The eddy correlation instruments were the same as those described at Site 1 and 2. The Bowen-ratio station was a REBS surface energy balance system to estimate latent and sensible heat fluxes. Air-temperature and vapor-pressure gradients at two heights (60 and 160 cm) were measured with modified Vaisala HMP35A temperature-relative humidity sensors. An exchange mechanism alternated the positions of the sensors every 15 minutes to reduce the effect of sensor bias. A 2 minute equilibration period was allowed after each position exchange. The scan rate of the Bowen-ratio sensors was 30 seconds and recorded on a Campbell Scientific CR21X data logger. Data from the two 15 minute periods were averaged to produce a 30 minute Bowen-ratio which were subsequently used to produce 30-minute estimates of latent and sensible heat fluxes. Wind speed and direction were provided by the Mesonet tower.

August Instrumentation

During the August study the same site was selected using the above mentioned instrumentation described for the April campaign. An Eppley pyranometer and infrared thermometer both positioned at 1.5 meters above the surface were included for the August measurement period. Sampling frequencies and averaging periods were the same as those for April.

F. MEASUREMENTS AT SITE 4

General Description - April/August

Site 4 was planted to winter wheat in the fall of 1993. In April the mean height of the wheat canopy was approximately 25-30 cm increasing to a height of approximately 40 cm by the end of the April study. The mean elevation of this site was 435 m with a gentle rolling topography. The dimensions were 400 meters along an east-west direction and 800 meters along the north-south. The wheat canopy was dense and relatively uniform. During the August study the wheat had been harvested and the field plowed and disced so that the surface could be described as uniform bare soil.

April Instrumentation

During April a Bowen-ratio energy balance system was installed in the wheat field. The system consisted of aspirated psychrometers located at 60 and 160 cm above the wheat canopy. Net radiation and soil heat flux were measured with a REBS Q^*6 net radiometer at a height of 130 cm and a HFT-1 soil heat flux plate located 8 cm below the soil surface. Soil temperature probes were placed at 2, 4, and 8 cm to measure the soil temperature gradient. Wind speed and direction were measured at 2 meters above the canopy using the same models of instruments as at sites 1 and 2. The fetch to height ratio was in excess of 200 along the north-south transect and 100 along the east-west transect. The sampling and output frequency were the same as those described at sites 1 and 2.

August Instrumentation

During the August campaign the Bowen-ratio station was replaced with an eddy correlation system. Site 1 contains the description of the eddy correlation instruments. The 1-d sonic anemometer and krypton hygrometer were located 160 cm above the bare soil surface. The net radiometer was an upgraded REBS Q^*7 positioned at a height of 160 cm. The soil heat flux plate and soil temperature sensors were the same as those used during the April study and were placed at the same depths as in April. A Licor-200 pyranometer was placed 2 meters above the surface and a fixed-head Everest IRT sensor was mounted 160 cm above the surface.

G. PRELIMINARY RESULTS

Figures X-1 and X-2 show a typical partitioning of the surface energy balance over the Bermuda pasture and bare soil fields into net radiation, soil heat flux, sensible and latent heat flux for DOY 97. Net radiation is the dominant source of the available energy. Latent heat flux from the Bermuda pasture is significantly lower than that from the wheat field. LE fluxes from the Bermuda pasture grass were less than 100 W m^{-2} between the hours of 1000-1200 while those for the wheat field for the same time period were greater than 200 W m^{-2}. This is reasonable and expected since the pasture Bermuda was dormant and thus not actively transpiring as compared to the verdant surface of the winter wheat field. Sensible heat fluxes were larger over the dormant Bermuda surface than that of the green wheat surface indicating that more of the net radiation was partitioned into heating the dormant Bermuda grass than into evaporating water as compared to the wheat field in which more of the available energy was consumed for evaporation of water.

The LE and H fluxes shown in figures X-1 and X-2 were calculated using the Bowen-ratio method (eqns. X-3). LE and H fluxes associated with sunrise, sunset, and nighttime periods are generally regarded as unreliable due to very small vapor pressure gradients which can produce Bowen-ratios which approach -1 resulting in unreliable fluxes as can be seen in Fig. X-2 for LE and H after approximately 1800 hours. LE fluxes in excess of 200 W m^{-2} in the downward direction would suggest precipitation when in fact there was none. In general for periods in which R_n is strongly positive the Bowen-ratio produces estimates fluxes which are normally quite reliable while during sunrise-sunset and nighttime periods estimates of LE and H will not be evaluated.

A comparison between the Bowen-ratio and eddy correlation techniques for determining turbulent fluxes for DOY 97 from the Bermuda pasture is shown in Fig X-3. Estimates of LE fluxes from the Bowen-ratio technique are seen to be in close agreement with measured fluxes using eddy correlation. Sensible heat fluxes from the Bowen-ratio system tracked well with those from eddy correlation but were consistently larger than those measured with eddy correlation. This was expected since any measurement error associated with R_n, G, temperature and vapor pressure will be accumulated in H since in this case H is calculated as a residual of eqn. X-2.

Figures X-4 and X-5 show the surface energy partition over native pasture and bare soil in late August. Differences in the magnitude of the LE and H fluxes were large and consistent with reference to the available water and vegetative cover at each site. The native pasture canopy was tall, dense and green indicating a larger supply of available water with an actively transpiring surface. In contrast the bare soil surface was hot, dry and completely devoid of any type of vegetation. Lower net radiation was observed from the bare soil field indicating more longwave radiation from the light colored bare soil relative to the darker green vegetative surface of the native pasture. Significantly larger values in soil heat flux (G) were found from the bare soil field as compared to the native pasture.

Evaporative fraction defined as the ratio between latent heat and net radiation fluxes will be analyzed to evaluate diurnal trends as a function of surface cover. Energy balance closure calculations will also be evaluated for the eddy correlation measurements to assess the reliability of the sensible and latent heat flux measurements.

In general, the spatial variation in latent and sensible heat fluxes from different surfaces in the Little Washita watershed were evident and considerable indicating the need to better understand and predict differences in surface energy partitioning as a function of vegetative cover and available soil water. Enhanced understanding of these complex coupling processes between the surface and atmosphere will aid in local and regional modelling efforts to predict turbulent transport of scaler fluxes.

H. REFERENCES

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Suomi, V.E., and C.B. Tanner. 1958. Evapotranspiration estimates from heat-budget measurements over a field crop. Transactions, American Geophysical Union. 39: No. 2, 298-304.

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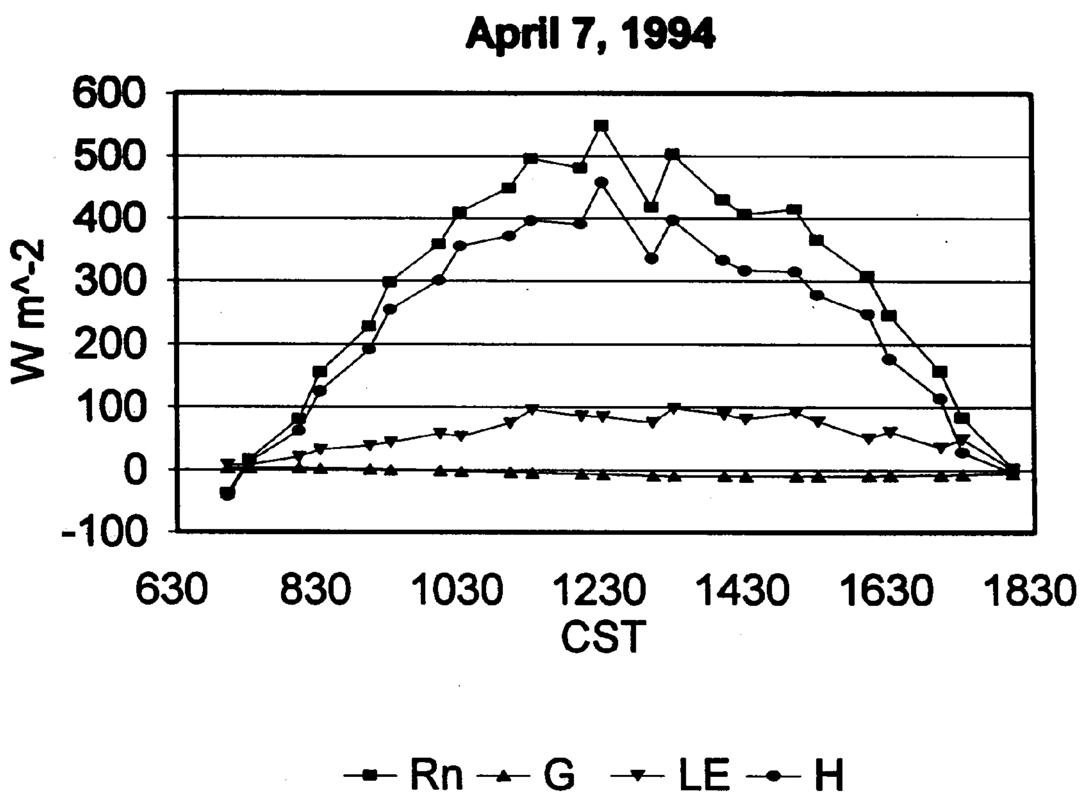

Figure X-1.

Figure X-1. Surface energy partitioning over Bermuda pasture on DOY 97, 1994. Rn is net radiation, G soil heat flux, LE and H are latent and sensible heat fluxes respectively.

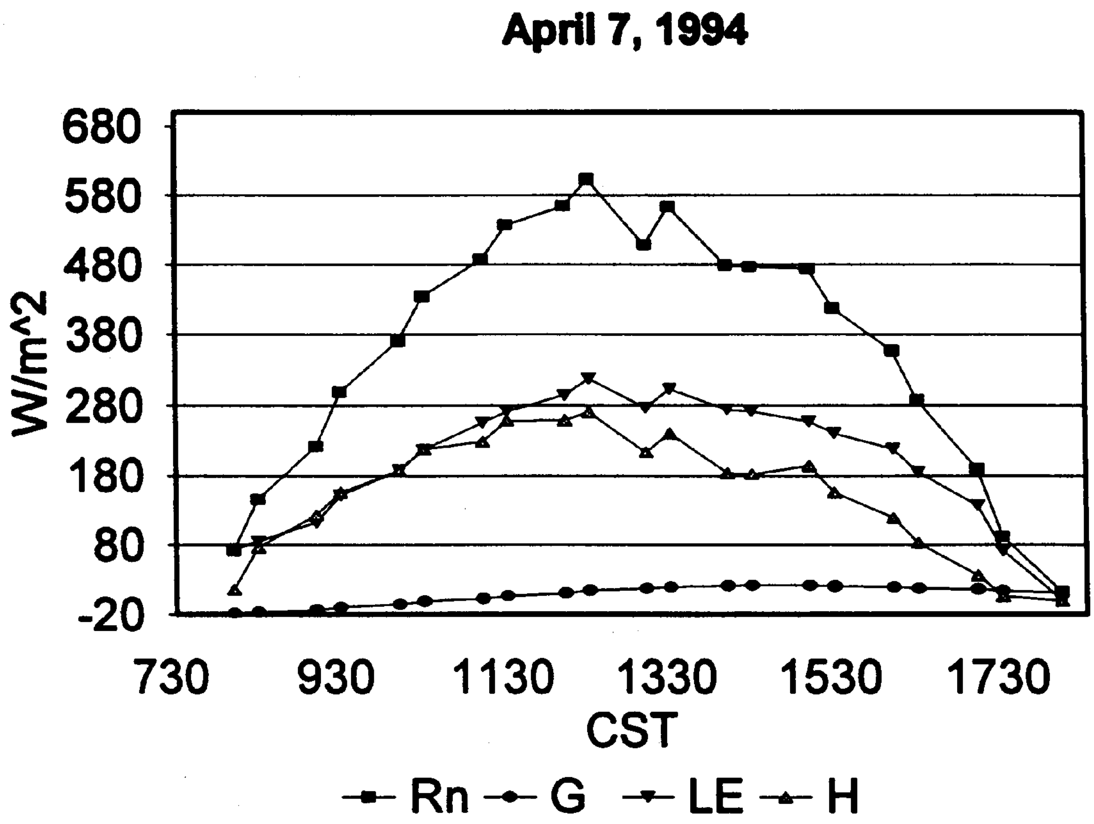

Figure X-2.

Figure X-2. Surface energy partitioning over spring wheat on DOY 97, 1994. Rn is net radiation, G soil heat flux, LE and H are latent and sensible heat fluxes respectively.

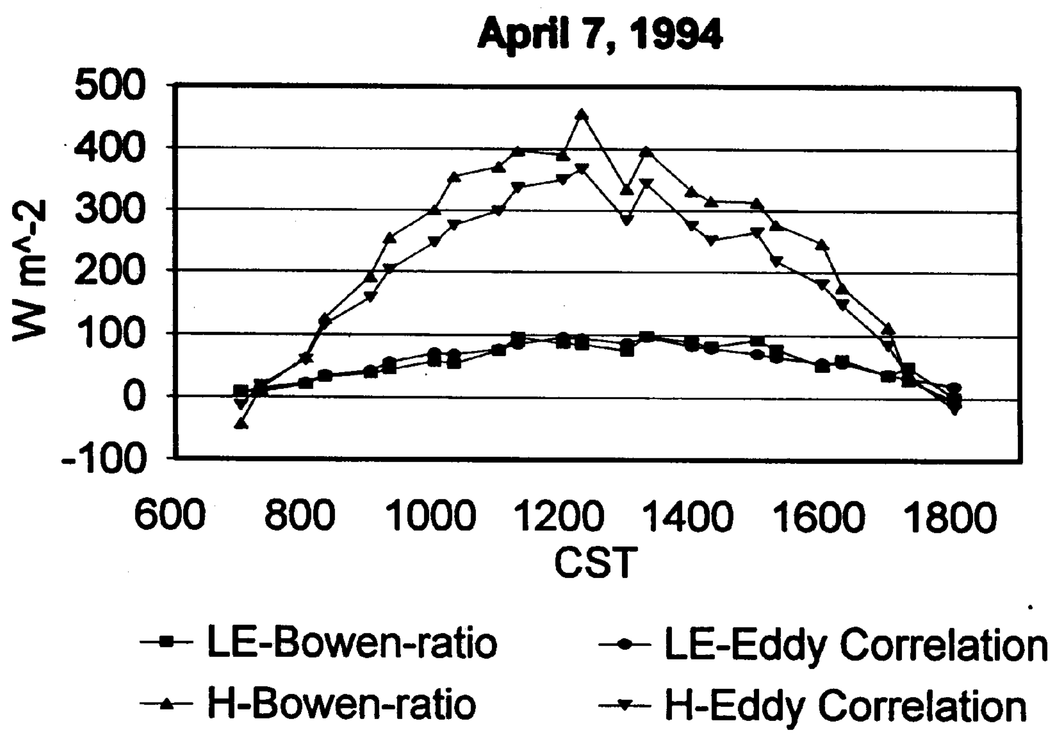

Figure X-3.

Figure X-3. Comparison of latent and sensible heat fluxes using Bowen ratio and eddy correlation techniques.

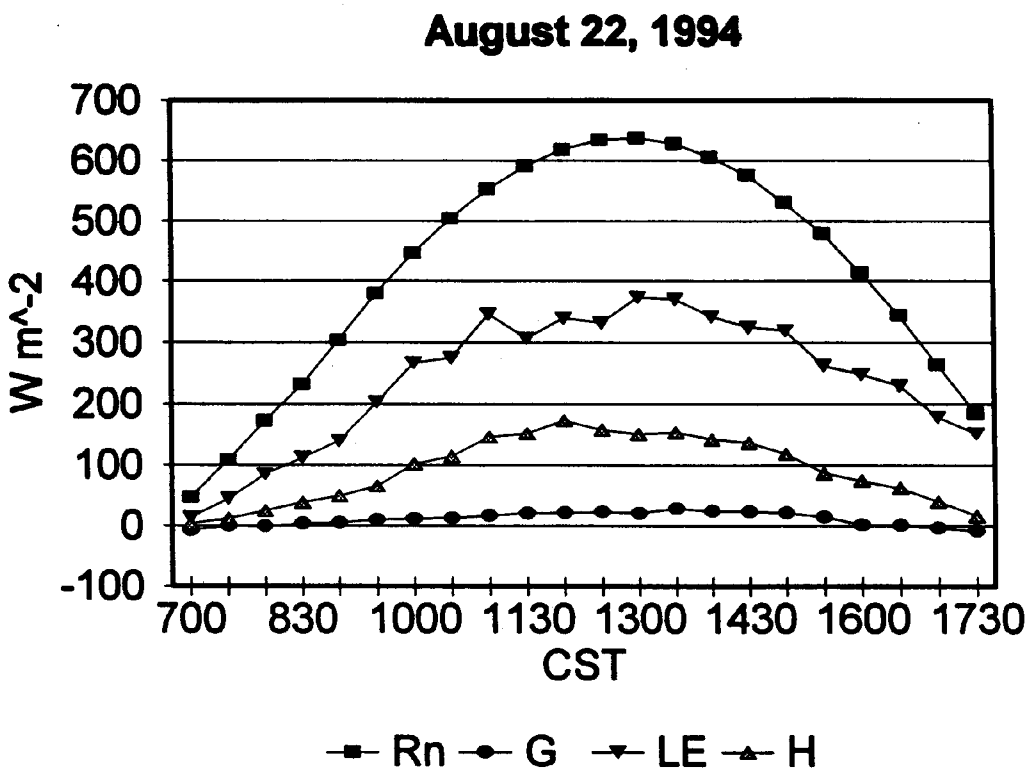

Figure X-4.

Figure X-4. Surface energy partitioning over native pasture on DOY 234, 1994. Rn is net radiation, G soil heat flux, LE and H are latent and sensible heat fluxes respectively.

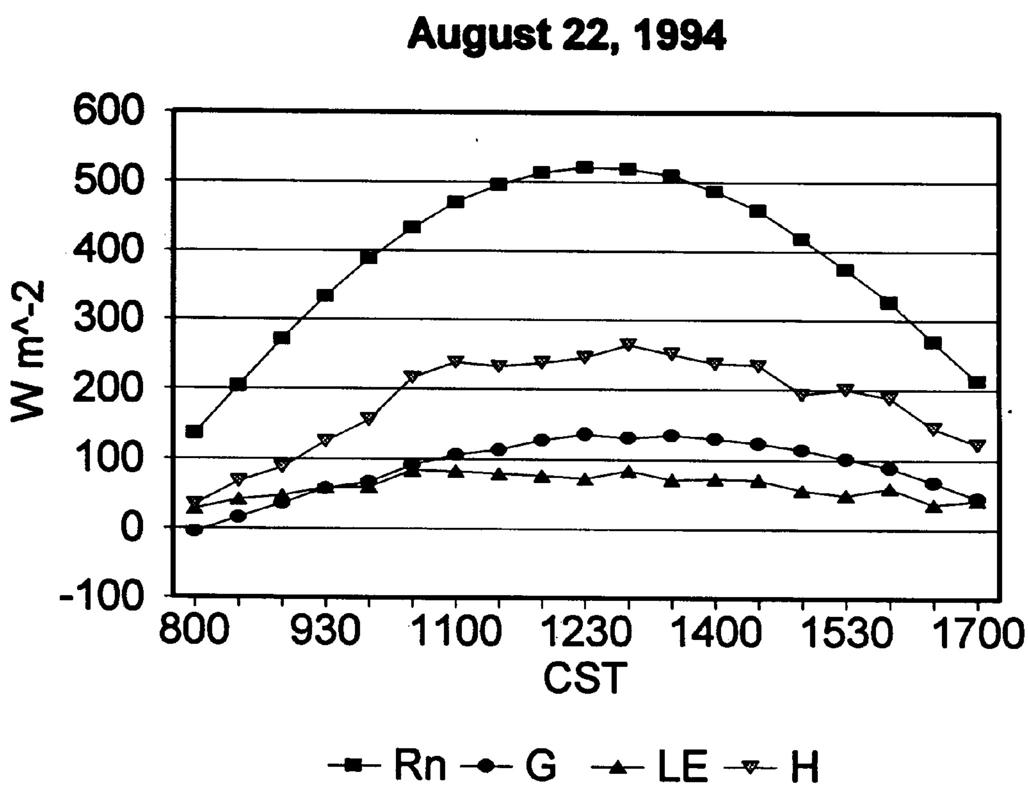

Figure X-5.

Figure X-5. Surface energy partitioning over bare soil on DOY 234, 1994. Rn is net radiation, G soil heat flux, LE and H are latent and sensible heat fluxes respectively.