SURFACE FLUX MEASUREMENT AND MODELING AT A SEMI-ARID SONORAN DESERT SITE.

By

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DEDICATION

This thesis is dedicated to the memory of my faithful companion Jacques whose life I was fortunate to share for twelve years. His recent passing-on reminds me of how fragile life is, and that we shall do our utmost to treasure and protect all life forms throughout the world. I hope this work will make a small contribution toward achieving this goal, and I will continue to do all I can to let the smallest cry in the universe be heard.

I am the voice of the voiceless,
Through me the dumb shall speak
Till the deaf world's ear be made to hear
The wrongs of the wordless weak.

And I am my brother's keeper,
And I shall fight his fight;
And speak the word for beast and bird
Till the world shall set things right.

-Ella Wheeler Wilcox, 1850-1919

TABLE OF CONTENTS

Page

LIST OF ILLUSTRATIONS.

LIST OF TABLES

ABSTRACT

Continuous measurements of near-surface weather variables using an automatic weather station and intermittent measurements of surface energy, momentum and carbon dioxide fluxes using Bowen ratio, eddy covariance, and sigma-T systems were collected for 13 months at a semi-arid Sonoran Desert site near Tucson, Arizona. Comparisons between measured fluxes made simultaneously with different instrumental systems show acceptable agreement. To investigate the influence of Crassulacean Acid Metabolism plants on carbon dioxide flux, measurements were sustained through the night. Observations were analyzed to characterize the typical magnitude of diurnal and seasonal variations in surface energy and carbon dioxide exchanges for this vegetation type and were then used to validate and calibrate the surface energy balance simulated by the *Biosphere-Atmosphere Transfer Scheme*. Using the standard "*semi-desert*" soil and vegetation parameters specified in the National Center for Atmospheric Research *Community Climate Model version 2* gave a poor description of surface energy exchange. However, a combination of site-specific soil and vegetation parameters, and a simple optimization to modify the value of minimum surface resistance and plant wilting parameters, substantially improved the model performance. The site-specific parameters reflect the fact that the vegetation fraction is greater than assumed in the standard parameter set, leaf area index and minimum stomatal resistance are less, soils at the study site contain more clay, but the plants' wilting point is lower than this clay fraction would imply. These modified parameters more accurately describe the conservative character of the semi-desert vegetation and the moderate nature of its response to the seasonal water cycle.

1. INTRODUCTION

1.1 Scope of Study

Semi-arid environments cover 40% of the Earth's land surface, and therefore are a significant component of the Earth's climate system (Moran *et al.*, 1994). Semi-arid regions are climatologically sensitive - slight shifts in global climate may have a significant impact on local surface conditions, leading to major changes in the local climate. It is therefore essential to develop an understanding of the complex interactions between unique plant physiology, extreme seasonality in precipitation and solar forcing, and large diurnal temperature ranges which characterize these semi-arid environments and determine their role in the Earth's climate system. Surprisingly little is known about the spacial and temporal variation in energy and water fluxes and how they are affected by vegetation and soil properties in semi-arid regions. Though several field studies have been conducted to address these issues, these have mainly been focused on investigating spatial, rather than temporal variability, and were generally of short duration (see Section 1.2.1 below).

The primary objective of this research was to investigate the temporal variability of energy, water and carbon dioxide exchanges in a pristine semi-arid environment, by measuring and modeling surface fluxes over a period of one year in order to better characterize the climate-related signals in the surface fluxes. To compare direct and indirect measurement methods, fluxes were measured simultaneously using eddy covariance, Bowen ratio and sigma-T instrumentation. A secondary objective was to investigate whether there was evidence that plants utilizing the Crassulacean Acid Metabolism pathway of photosynthesis influence the over-all carbon dioxide uptake of this environment.

1.2 Literature Review

1.2.1 Previous Surface Flux Measurement Studies

Several field experiments have been conducted in order to investigate the complexities of the energy, water and carbon dioxide exchanges in semi-arid environments, and to predict the interactions between these fragile land covers and the atmosphere which determine the climate in these regions. Though these experiments provided valuable insights, they generally focused on a variety of issues related to spatial, as opposed to temporal variability of energy fluxes, and usually were of short duration, relying on measurements taken during intensive field campaigns (IFCs). Other field experiments such as FIFE (see below) are relevant to this study because their results provide a basis for comparison. Results of the most important of these studies are summarized and contrasted with the present study below.

1.2.1.1 **FIFE**

Desjardins *et al.* (1992) compared spatial variability of energy and carbon dioxide fluxes obtained from airborne measurements over a 15 km x 15 km tallgrass prairie site in northeastern Kansas, as part of the First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE). Spatial flux variability was examined for three single days in the years 1987 and 1989, respectively. The analysis of temporal variations in solar radiation, surface energy and carbon dioxide fluxes was limited to four so-called "Golden" days: one day in each of the months July, August and October 1987 and one day in August 1989 (Desjardins *et al.*, 1992).

In an earlier study at the FIFE site, Verma *et al.* (1989) examined the diurnal patterns of the energy budget components and CO_2 fluxes using an eddy covariance system. This study evaluated the influence of high atmospheric evaporative demand and low soil water availability on energy partitioning as well as the magnitudes and patterns of atmospheric carbon dioxide exchange. Measurements were taken for a short 10-day period during late July and early August, 1986, and four of these days were analyzed to reveal the diurnal flux pattern.

Fritschen *et al.* (1992) conducted a comparison study of several types of surface flux measurement systems used at the FIFE site. Two types of comparisons were made during and after the fifth intensive field campaign (IFC 5). The first type compared the performance of three different Bowen ratio sensors, collocated at the same site (site 916, August 13 to 15, 1989). The second type consisted of comparisons of a Bowen ratio system with an eddy correlation system at two sites (sites 906 and 926). Data for site 906 were taken throughout IFC 5, comparisons are shown for three selected days (July 27, August 2 and August 4, 1989). For site 926 data were available only from August 13 to 15, 1989.

The Bowen ratio systems used in the first comparison experiment were: (1) the Arizona evapotranspiration (AZET) system described in detail by Gay (1988) which used wet and dry bulb temperature sensors mounted on mechanically interchanging measurement arms to minimize effects of sensor bias; (2) the surface energy and radiation balance system (SREBS) which is very similar to the AZET system except for the time between interchanging measurement arms (5 minutes for AZET vs. 15 min for SREBS, for details see Fritschen and Simpson, 1989); (3) a standard Campbell Scientific Instruments Bowen ratio system, implementing a DEW10 cooled-mirror hygrometer (General Eastern, Watertown, Massachusetts) to take dew point measurements and fine-wire thermocouples to measure air temperature. This Bowen ratio system is essentially identical to that used in the present study (for details see Section 2.2.4 of Appendix A).

Two eddy covariance systems were used in the second comparison experiment: (1) a 10-cm pathlength, single-axis sonic anemometer combined with a fine-wire thermocouple (both manufactured by Campbell Scientific, Logan, Utah), and a lyman-alpha humidity sensor (Electromagnetic Research, Rockville, Maryland) to measure sensible and latent heat fluxes; (2) a Hydra system (Shuttleworth *et al.*, 1988), combining a 20-cm pathlength sonic anemometer, a fine-wire temperature sensor, an infrared hygrometer and a cup anemometer to derive fluxes of sensible, latent heat and momentum. These two eddy covariance systems were installed at sites 906 and 926, respectively.

In the first comparison study, only data for August 14, 1989 were used in the analysis. Fritschen *et al.* (1992) showed good agreement of sensible heat fluxes between the different Bowen ratio systems, however, latent heat fluxes showed larger variability (in percentage terms) which was ascribed to differences in net radiation and soil heat fluxes measured by the different systems, and to the fact that the magnitude of sensible heat fluxes measured was much greater than that of the latent heat fluxes. Vapor pressure and vapor pressure gradients showed greater variability than air temperature and air temperature gradients for all three systems.

Very interestingly, only the cooled-mirror Bowen ratio systems manufactured by Campbell Scientific (Logan, Utah) exhibited a pronounced morning spike in vapor pressure between 0800 and 1000 hours, peaking about 0.3 kPa higher than the average vapor pressures measured by the other Bowen ratio systems at the same time (0900 hours, August 14, 1989; see Figure 9(b), Fritschen *et al.*, 1992). Similar morning peaks in vapor pressure measurements were also observed for the Bowen ratio system used in the present study at the much more arid Tucson Mountain field site (see Section 2.2.4 of Appendix A).

The second experiment showed better agreement for sensible heat than for latent heat fluxes. However, there were significant and occasionally large discrepancies for both sensible and latent heat fluxes when comparing Bowen ratio and eddy covariance instruments at both sites 906 and 926. These discrepancies may be due to several complicating factors: (1) Eddy covariance fluxes were more strongly affected by advection from upwind steep slopes because of their greater area of fetch because the eddy covariance sensors were mounted higher up on the tower than the Bowen ratio sensors; (2) local measurements of net radiation and soil heat flux used in the Bowen ratio flux derivations were not necessarily representative of the area over which fluxes were sampled; (3) for the vertically mounted one-dimensional sonic anemometers used in the eddy covariance systems, no axis-rotation correction was possible. Consequently, mean up-slope flow could affect the eddy covariance results (Fritschen *et al.*, 1992). The authors emphasize the need for further studies comparing the performance of different flux measurement systems to assure that differences measured at different sites are caused by site variations and not by the instrumentation and techniques.

1.2.1.2 **Owens Valley**

In a 1989 study, Kustas *et al.* used infrared thermometric observations collected from an aircraft to estimate surface temperatures, T_s, for a sparsely vegetated, semi-arid site in the Owens Valley of central California. Though this site receives only 100-150 mm of annual precipitation, and the vegetation, which covers 20-30 % of the ground surface, consists primarily of Nevada saltbrush and rubber rabbitbrush, these phreatophytic plants which have access to significant groundwater resources due to ample recharge from the nearby Sierra Nevada (Kustas *et al.*, 1989). Energy fluxes were measured using a Bowen ratio system and two eddy covariance systems, the latter each combining a sonic anemometer, a fine-wire thermocouple and a lyman-alpha humidity sensor. The three flux stations were spaced 100 m apart. Meteorological stations measuring mean air temperature and wind speed were paired with the eddy covariance systems. The application of the bulk transfer equation to estimate sensible heat flux provided an unsuccessful match with the observed Bowen ratio and eddy covariance measurements of sensible heat. In order to better model the resistance to heat transfer, r_{ah}, the authors introduced an added resistance term, kB^{-1} which was allowed to vary in order to better match observed sensible heat fluxes, despite the fact that there is both theoretical and experimental evidence that kB^{-1} for vegetative surfaces can be treated as constant (Kustas *et al.*, 1989). In addition, the authors state that "present data indicate that for partial canopy cover under arid conditions kB^{-1} may be a function of T_s measured radiometrically". The fact that the entire study was based on a total of only three days of flux data collected from June 2 to 5, 1986, and in the case of one of the eddy covariance systems, only relied on a single day of flux data, underscores the need for developing longer term data sets for the study of temporal surface flux variability in semi-arid regions.

1.2.1.3 **La Crau**

Kohsiek *et al.* (1993) used surface radiative temperature, air temperature and wind speed observations from a semi-arid site in the 'La Crau' region of southern France to estimate sensible heat flux with a one-layer resistance model. The study site was located in a dry, flat area of about 150 km^2. Vegetation consisted of a very sparse cover of grasses and herbs, while most of the land surface was covered with pebbles and rocks. In addition to standard synoptic measurements (temperature, humidity, wind speed and direction, air pressure, precipitation and radiation), and profile measurements of wind, temperature and humidity, surface radiative temperature was measured with a Hermann KT24 infrared thermometer. Fluxes of sensible heat, momentum, and water vapor were measured with the eddy covariance method (3-D sonic anemometer, fast-response thermometer and hygrometer; Kohsiek *et al.*, 1993). However, of the 22-day long observation period (June 2-23, 1987) only sensible heat flux measurements for two particular days were shown, making comparisons to our present study difficult. The authors conclude that it is feasible to estimate sensible heat flux of a semi-arid area by using a one-layer resistance model with temperature, wind speed, radiative surface temperature, and roughness lengths for momentum and heat as input parameters (Kohsiek *et al.*, 1993). It would clearly be valuable to investigate whether this also holds true for long-term measurements of sensible heat flux.

1.2.1.4 **San Luis Valley**

Stannard (1993) conducted a study of surface fluxes in the San Luis Valley, a semi-arid, high-altitude rift between the Sangre de Christo and San Juan Mountain ranges in southern Colorado. Though this study site was located in a region characterized as semi-arid, it is distinctly different from the site of the present study. The San Luis Valley only receives about two thirds of the amount of precipitation measured at the Tucson Mountain field site (180 mm/year vs. 275 mm/year) and vegetation is dominated by the phreatophyte species greasewood (*Sarcobatus vermiculitus*), rabbit brush (*Chrysothamnus nauseosus*), and salt grass (*Distichlis stricta*). Individual plants, spaced meters apart, grow in sandy soils above a very shallow water table (0.8 - 1.6 m below land surface during the time of the study). In contrast, vegetation at the Tucson Mountain site is denser (vegetation cover fraction ~ 40 %) and more varied, with species ranging from saguaro cacti (*Carnegia giganteus*) and various opuntia cacti (*Opuntia ssp.*) to palo verde (*Cercidium microphyllum*), velvet mesquite (*Prosopis veluntina*) and ironwood trees (*Olneya tesota*), as well as many species of smaller bushes, *e.g.* creosote (*Larrea tridentata*), brittle bush (*Encelia farinosa*) and triangular-leaf bursage (*Ambrosia deltoidea;* Unland *et al.*, in press).

In the Stannard study, measurements were taken intermittently from 1985 to 1988 (eighteen measurement periods of 2-4 day duration each), using an eddy covariance system which combined a one-dimensional sonic anemometer, fine-wire thermocouples and a lyman-alpha or krypton hygrometer to measure sensible and latent heat fluxes. The main focus of that effort was to use these measurements of sensible and latent heat flux, along with measurements of net radiation, soil heat flux and standard micrometeorological variables to compare the performance of three evapotranspiration models, namely the Penman-Monteith model, the modified Priestley-Taylor model, and the Shuttleworth-Wallace model. Surprisingly, Stannard found that the modified Priestley-Taylor model, a one-component simplified form of the Penman potential evapotranspiration model, performed as well as the rigorous Shuttleworth-Wallace model which predicted that about one quarter of the vapor flux to the atmosphere is from bare-soil evaporation (Stannard, 1993).

However, more relevant in relation to the present study is the author's remark that "a large part of the scatter in all three models is caused by erroneous measured values at times when fluxes are small, and relative errors in measured fluxes (or weather variables) are large" (Stannard, 1993). Similar measurement difficulties were encountered in the present study with the Bowen ratio system, where measurement errors were associated with exceeding the instrument's normal operating range during very hot and dry conditions in the early summer months (Unland *et al.*, in press). Such problems were not experienced with the eddy covariance system at the Tucson Mountain site. This can be attributed to the superior design of the eddy covariance system employed in the present study which combines a 3-axis ultrasonic anemometer (*Gill Instruments*, Hants, UK; Model 1012RA) to measure wind speed variations and air temperature, with an infrared gas analyzer (*Li-Cor*, Nebraska, USA; model 6262) to measure concentrations of water vapor and carbon dioxide (Unland *et al.*, in press). Due to the design of the eddy covariance system used by Stannard (1993), it was necessary to introduce a density correction (Webb *et al.* 1980) and a correction term to account for the sensitivity of the hygrometer to oxygen in the latent heat flux calculation. These corrections were not needed in calculating the fluxes from the eddy covariance system used in the present study (see Section 2.2.2 of Appendix A).

1.2.1.5 **Smith Creek Valley**

In 1992, a study of energy budgets in a sparsely vegetated rangeland at Smith Creek Valley, central Nevada, was conducted to investigate the feasibility of using one-dimensional theoretical numerical models to partition the latent heat fluxes between bare soil and canopy components (Nichols, 1992). Vegetation cover was sparse (25%). Due to a very shallow water table (less than 3 meters below land surface), the dominant plant species was phreatophytic greasewood (*Sarcobatus* ssp.). Thus conditions were very similar to those described for the Stannard study above. Nichols (1992) reported that reasonably good estimates of sensible heat flux from the soil and latent heat flux from the canopy were achieved by using these one-dimensional models, however, estimates of latent heat flux from the soil were less satisfactory.

The instrumentation used for taking flux measurements in the Nichols experiment was essentially identically to that used in the present study: a Bowen ratio system manufactured by Campbell-Scientific, Logan, UT (1988), implementing a single-cooled-mirror hygrometer. Nichols notes that during the course of the five-months measurement period (May to September 1989), data for approximately half of the 105 days for which measurements were made were rejected because of low humidity conditions that lead to incorrect vapor pressure determinations. This was attributed to operating limitations of the cooled mirror which are exceeded under conditions of high temperatures and low humidity (i.e., ambient temperature approaching 35 °C and relative humidity below 10 %), a common occurrence in central Nevada during July and August (Nichols, 1992). In addition, vapor pressure gradient data were rejected for several days when Bowen ratio values were inexplicably too large or too small. These occurrences were attributed to advection of drier air from upwind areas of non-phreatic vegetation or advection of moister air from very near convective storm precipitation. Thus, instrumental failures encountered with the Campbell Bowen ratio system and the rejection criteria applied in filtering out erroneous vapor pressure data were very similar to those described in the present study (see Sections 2.2.4 and 2.3 of Appendix A), though the latter were defined independently.

1.2.1.6 **SEBEX**

Several studies have been undertaken in the southern Sahelian zone of the Niger

Republic in the context of the Sahelian Energy Balance Experiment (SEBEX), a collaborative effort of the Institute of Hydrology (Wallingford, UK) with the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Sahelian Center (Sadoré, Niger). These experiments were initiated to address the need for incorporating energy flux observations from semi-arid regions such as the Sahel in order to achieve a more realistic representation of vegetation in the land-surface submodels of General Circulation Models (*e.g.* Wallace *et al.*, 1990, Gash *et al.*, 1991, Wallace *et al.* 1991).

Exploratory measurements were taken over a two-week period (28 September to 10 November, 1988) at the start of the dry season, in a fallow savannah bushland at the ICRISAT experimental farm (Gash *et al.*, 1991). This area had not been cultivated for six years previous to the onset of the experiment, and fuelwood collection was negligible. Approximately 80 % of the ground cover was a mixture of mainly annual leguminous and grass species, predominantly *Cassia mimosoides, Tephrosia linearis, Aristida mutabilis* and *Eragrostis tremula,* growing in sandy soils. Woody shrubs (*e.g. Guiera senegalensis*) made up the remaining ground cover. Standard synoptic variables (solar radiation, aspirated wet and dry bulb temperature, wind speed and direction) were measured with a Campbell Scientific automatic weather station; fluxes of water vapor, sensible heat and momentum were measured using a Mk2 Hydra eddy covariance system (Shuttleworth *et al.*, 1988). Measurements continued intermittently during 1989 and 1990, both at the above described site and at a nearby area of degraded natural forest, where dense strips of vegetation about 20-40 m wide by 100-200 m long were separated by areas of completely bare crusted soil ('tiger brush', Wallace *et al.*, 1991). Here vegetation was dominated by woody species (*Combretum micranthum, Combretum nigricans, Acacia pennata* and *Guiera senegalensis*). Estimated vegetation cover fraction was 40 %. Soils at the tiger brush site were much higher in clay content than those at the fallow savannah site (Wallace *et al.*, 1991).

The main objective of the SEBEX project was to obtain direct measurements of available energy, evaporation and sensible heat flux from three contrasting Sahelian land types in order to see how they might be affected by a change in vegetation. A second objective was to investigate the possibility of using satellite remote sensing to estimate energy fluxes for areas of the size required for making climate forecasts on a regional scale. The authors concluded that evaporation from this area of West Africa shows large spatial and temporal variablility. They suggest that a combination of satellite estimates of surface temperature and ground-based point measurements of sensible heat flux and evaporation may potentially determine the spatial variation of evaporation over regions of heterogeneous vegetation (Wallace *et al.*, 1991).

1.2.1.7 **Monsoon '90**

The Monsoon '90 multidisciplinary field campaign, aimed at assessing the feasibility of coupling remotely sensed and traditional ground-based measurements with energy and water balance models for large-area estimates of fluxes in semi-arid rangelands, was conducted during June-September 1990 over the U.S. Department of Agriculture's Agricultural Research Service (USDA-ARS) Walnut Gulch experimental watershed in southeastern Arizona (Kustas and Goodrich, 1994). Though the main objectives of this intensive study were related to investigating spatial energy flux variability by using remote sensing observations from a variety of ground-, aircraft- and satellite-based systems, valuable insights were also gained from the ground-based meteorological-energy flux (METFLUX) stations located throughout the Walnut Gulch watershed (Kustas *et al.*, 1991, Kustas *et al.*, 1994, and Stannard *et al.*, 1994).

Soils at Walnut Gulch varied from gravelly loamy sands to sandy loams and typically had a high rock content in the surface layers (50 % rock fraction, Kustas and Goodrich, 1994). Vegetation cover (20-60 % cover fraction) consisted of mixed grass-brush rangeland, the western half of the watershed being dominated by brush, and the eastern half primarily covered with grasses. Annual precipitation at Walnut Gulch typically varies from 250 to 500 mm, with approximately two-thirds falling during the "monsoon" season (July - September; Kustas and Goodrich, 1994). It must be noted, however, that precipitation received during June and July 1990, at the onset of the Monsoon '90 experiment, was significantly higher than in previous years, totaling 140 mm over these two months, almost double the amount usually received for this period. This led to a large increase in biomass at the start of the campaign (Kustas *et al.*, 1991).

The Walnut Gulch experimental watershed is well-instrumented, with 92 rain gages and 11 large runoff-measuring stations located in the upper 150 km^2 of the Walnut Gulch drainage basin (Kustas and Goodrich, 1994). Eight METFLUX stations were installed along two transects, covering the main vegetation biomes in the region. At each METFLUX site, continuous measurements were taken of standard weather variables, as well as surface and soil temperature, soil moisture, incoming solar and net radiation, and soil heat flux. Each station also measured components of the surface energy balance using the variance method, estimating sensible heat flux indirectly from measurements of the standard deviation of temperature, σ_T, and an estimate of friction velocity, u (Kustas *et al.*, 1994). However, during the July-August campaigns, two small subwatersheds were more intensely monitored: Lucky Hills (site 1, vegetation cover shrub-dominated), and Kendall (site 5, primarily grassland). These were also the only two sites where ground measurements were made during the June and September campaigns (Kustas and Goodrich, 1994), thus most of the Monsoon '90 surface flux studies concentrate on the Lucky Hills and Kendall subwatersheds.

In their 1994 study, Kustas *et al.* estimated latent and sensible heat fluxes using the variance method and compared them with those calculated from eddy covariance and Bowen ratio systems. The authors concluded that sensible heat flux estimates compared well under unstable conditions, however, when comparing latent heat flux estimates with eddy covariance measurements there was an increase in scatter. Based on these results, Kustas *et al.* (1994) recommended the use of the variance method because of its low cost and maintenance requirements. However, these results were not confirmed in the present study which showed the variance method to be unreliable in estimating sensible heat fluxes from the running mean of sigma-T thermocouple temperature data collected at the Tucson Mountain site. A much improved comparison with eddy covariance measurements was, however, achieved by calculating the sigma-T sensible heat flux from the linear average of sonic temperature (see Section 3.2 of Appendix A).

1.2.1.8 **Summary of Surface Flux Measurement Studies**

The surface flux measurement studies described above varied in scope and size, from point measurements at a single site (*e.g.* San Luis Valley; Stannard, 1993) to large-scale studies covering entire watersheds (Monsoon '90; *e.g.* Kustas and Goodrich, 1994) or GCM-grid squares (FIFE; Desjardins *et al.*, 1992, and Fritschen *et al.*, 1992). Most focused on comparisons with or validations of remotely sensed data which are expected to provide better descriptions of spatial flux variability than can be achieved from ground-based flux measurements alone. None of these studies, however, properly addressed the issue of temporal flux variability, as most were based on very limited data sets (on the scale of days to weeks). The present study represents a first step in developing long-term observational flux data sets for the semi-arid desert vegetation cover class which will be needed for the validation of surface-vegetation-atmosphere transfer schemes (SVATs) providing land-surface parameterizations for global climate and weather forecasting models. A discussion of the most important surface flux modeling studies concerned with the role of SVATs in global circulation models is included in Section 1.2.2 below.

1.2.2 Previous Surface Flux Modeling Studies

1.2.2.1 **Soil-Vegetation-Atmosphere Transfer Schemes**

A wide variety of land-surface models have been developed to describe the interactions of energy, momentum, and water flux between the surface and the overlying atmosphere. Some of these soil-vegetation-atmosphere transfer schemes (SVATs) are general enough to match the wide range of conditions provided by a global circulation model (GCM); others are intended for more regional or local applications (Dickinson, 1995). These models can be regarded as one-dimensional, since they only consider layers in the vertical (z) direction. When used to provide the land-surface description in three-dimensional GCMs, processes occurring in the soil-vegetation-snow-atmosphere system of one grid square are considered to be independent of the surface exchanges in the neighboring grid squares (Henderson-Sellers *et al.*, 1993).

In SVATs, vegetation is often treated as a separate layer. This is a marked improvement over earlier so-called bucket schemes (Manabe, 1969) in which a near-surface layer of soil was modeled as a bucket, which could be filled by precipitation (or snowmelt), and emptied by evaporation and runoffs - the latter occurring only when the bucket was full. In the bucket scheme, the evaporation rate is a linear function of the amount of water in the bucket below some critical value; in SVATs, evapotranspiration is a complex function dependent on meteorologic conditions, vegetation and soil parameters. SVATs usually only treat three land components (soil, snow, and vegetation) explicitly; land ice, lakes and other land components are neglected. As of yet, carbon fluxes are only included in a few SVATs (*e.g.* Sellers *et al.*, 1986), though many current ecological models deal with carbon uptake and release (*e.g.* Collatz *et al.*, 1991).

1.2.2.2 Land Surface Schemes in Global Climate Models

Previous studies of land surface schemes in global climate models have focused on predicting the effects on the atmospheric circulation and the hydrologic cycle due to imposed extreme changes to continental surfaces. Desertification experiments have been conducted by Charney (1975), who found decreases in precipitation, evaporation and net radiation and other responses involving biogeophysical feedbacks; more recent desertification simulations over the Sahel region resulted in a weakening of the tropical easterly jet over Africa and induced other climate changes at locations more distant from the original site of the perturbation (Laval and Picon, 1986; Xue and Shukla, 1993; Henderson-Sellers *et al.*, 1995a).

Other experiments simulated extremes of soil moisture, contrasting the effects of leaving the soil surface of the entire continent of Australia either totally dry or completely saturated at the onset of a model run, see Yang (1992) and Simmonds and Lynch (1992). These two studies both produced increases in evaporative flux, though only the Simmonds and Lynch experiment (1992) resulted in decreased temperature and increased surface pressure.

The effects of tropical deforestation have been widely studied (*e.g.* Henderson-Sellers and Gornitz, 1984; Lean and Warrilow, 1989; Nobre *et al.*, 1991; Dickinson and Kennedy, 1992). These studies showed decreases in precipitation, evaporation, and net radiation, and an increase in moisture convergence in response to deforestation scenarios (Henderson-Sellers *et al.*, 1995b). Bonan *et al.* (1992) showed in their boreal deforestation simulation that removal of vegetation resulted in ocean cooling, and increased sea-ice as well as land-surface albedo sufficiently in winter to induce surface cooling throughout the year.

1.2.2.3 **Land Surface Schemes in Weather Prediction Models**

SVATs have also been incorporated into numerical weather prediction models (NWP). Weather forecasts produced by models which incorporate land surface schemes with an explicit stomatal resistance parameterization show higher near-surface temperatures and lower humidities (Sellers *et al.*, 1989; Blondin, 1989). A study of forecasting models for the Sahara Desert region showed that a simple bucket scheme produced considerable overestimates of evapotranspiration when compared with a Penman-Monteith scheme (Pan *et al.*, 1989). Sellers *et al.* (1989) conducted sensitivity studies of the National Meteorological Center (NMC) general circulation model comparing the simple bucket scheme with the Simple Biosphere (*SiB*) model (Sellers *et al.*, 1986). In these experiments, implementation of *SiB* as land-surface submodel resulted in predictions of higher temperatures over tropical land masses, due to greater release of sensible heat over those regions, and, more significantly, improved the description of diurnal cycles of near-surface air temperatures and relative humidity (Henderson-Sellers *et al.*, 1995b).

1.2.2.4 **PILPS**

As described in sections 1.2.2.2 and 1.2.2.3 above, several sensitivity analyses and studies integrating SVATs into global climate and weather forecasting models have been undertaken, but clearly, there is a need for validation and systematic intercomparison of the currently available and proposed SVATs for use in global climate and weather prediction models. The Project for Intercomparison of Land-surface Parameterization Schemes (PILPS) was developed as a joint research effort sponsored by the Global and Energy Water Experiment (GEWEX) of the World Climate Research Programme (WCRP), and the Working Group on Numerical Experimentation (WGNE) to address this issue (Henderson-Sellers *et al.*, 1993). PILPS was designed as a seven-year project to be executed in five stages. The PILPS science plan is summarized in Table 1 below.

Table 1. PILPS Science plan (Henderson-Sellers *et al.*, 1993; Henderson-Sellers *et al.*, 1995b).

Phase No.	Activity
0	Documentation of existing SVATs
1	Off-line sensitivity studies and intercomparisons using synthetic forcing
2	Off-line evaluations using observed data and development of adequate observational data sets
3	Coupled intercomparisons with participating SVATs evaluated as interactive components of atmospheric GCMs participating in the Atmospheric Model Intercomparison Study (AMIP; Gates, 1992)
4	Evaluation of SVATs within fully coupled ocean-atmosphere global climate models and numerical weather forecast models

This is an ambitious science plan and, in practice, PILPS's success has been hampered by a lack of long-term observational data sets for many of the vegetation cover classes represented in GCMs. Up to now, PILPS experiments have only done simple (Phase 1) intercomparisons against model-generated data for tropical forest, mid-latitude grassland, and tundra biomes; more extensive (Phase 2) validation runs so far have only been performed for a dataset collected at Cabauw (Netherlands), a flat grassland terrain with a permanently saturated deep soil zone (Henderson-Sellers *et al.*, 1995b), and for a dataset collected at an agricultural site in France from the HAPEX-MOBILHY (Hydrology-Atmosphere Pilot Experiment - Modelisation de Bilan Hydrique) program (André *et al.*, 1986). Other observational data sets to be included in Phase 2 of PILPS should include: (1) at least one full year of forcing meteorology (including surface pressure, specific humidity, air temperature, wind speed, incident solar radiation, downward thermal infrared radiation at the surface, and precipitation); (2) validation data (including skin temperature, net radiation, evapotranspiration, sensible heat flux, runoff, and snow amount), and (3) soil thermal and hydrological characteristics and vegetative phenology (Henderson-Sellers *et al.*, 1995b).

In addition to the Cabauw and HAPEX-MOBILHY datasets described above, the following datasets have been offered to PILPS: ARME (Amazon Region Micrometeorology Experiment - Amazon, Brazil), FIFE (tall-grass prairie, Kansas), Glen Eagle (western Australia), Russian soil moisture (Russia), telegraph line data (north Australia), and Arctic tundra (Canada). It is possible that the Tucson Mountain observational data set developed in the present study will help fill the gap for the semi-arid desert vegetation cover class. Meanwhile, in the present study, these data were used successfully for calibrating and validating an off-line version of the *Biosphere-Atmosphere Transfer Scheme* (BATS; Dickinson *et al.*, 1993), one of the SVATs currently being evaluated in PILPS.

1.3 Thesis Format

The paper included as Appendix A, "Surface Flux Measurement and Modeling at a Semi-Arid Sonoran Desert Site" by Unland *et al.* (in press) presents the major results and conclusions obtained during research performed by the author for partial fulfillment of the requirements for a Master of Science degree. The author was instrumental in obtaining and analyzing field measurements of meteorological variables and surface energy fluxes, and performed quality control, analysis of raw data and derivation of the energy fluxes from the Bowen ratio system. In addition, the author performed the calibration and validation of the *Biosphere-Atmosphere Transfer Scheme (BATS)* using meteorological and energy flux measurements from the Tucson Mountain field site.

2. PRESENT STUDY

2.1 Summary of Paper.

The methods, results, and conclusions of this study are presented in the paper entitled "Surface Flux Measurement and Modeling at a Semi-Arid Sonoran Desert Site" accepted for publication by the Journal of Agricultural and Forest Meteorology and included as Appendix A. Also included as Appendix B is the field site manual for the Tucson Mountain field site. This was developed by the author, with substantial support from Paul Houser, and provides a detailed description of the experimental systems, and of their operation and maintenance. The following is a summary of the methodology and the most important findings presented in the paper.

Continuous measurements of standard meteorological variables using an automatic weather station and intermittent measurements of the surface energy balance, carbon dioxide flux, and momentum flux using Bowen ratio, eddy covariance, and sigma-T instrumentation were made for 13 months at a semi-arid Sonoran Desert site just west of Tucson, Arizona (see Figure 1). Weather observations demonstrate typical semi-arid Sonoran desert conditions:

i. Frequent clear skies.

ii. High radiation.

iii. Large seasonal and diurnal temperature range.

iv. Low relative humidity

v. Intermittent, mainly convective precipitation during a summer monsoon season.

Substantial observational problems associated with surface flux measurements in this extreme environment were reported. Comparisons between flux measurements made simultaneously with different instrumental systems show acceptable agreement. Most of the incoming radiant energy leaves as sensible heat, and latent heat fluxes are always low, but transpiration is enhanced for about ten days after a rain event. To investigate the influence of Crassulacean Acid Metabolism plants on carbon dioxide flux, eddy covariance measurements were sustained through the night. Carbon dioxide uptake is very low, typically with peak daytime uptake in the order of only 0.25-1.0 μmol m^{-2} s^{-1} for the period for which data are available, and some carbon uptake persists even at night.

The observations were used to validate and calibrate the surface energy balance simulated by the *Biosphere-Atmosphere Transfer Scheme (BATS),* with the following results:

i. Using default "*semi-desert*" soil and vegetation parameters specified in the National Center for Atmospheric Research *Community Climate Model version 2 (CCM2)* resulted in a poor simulation of observations.

ii. Model performance was substantially improved by using a combination of site-specific soil and vegetation parameters, and a simple optimization to modify the value of minimum surface resistance and plant wilting parameters.

iii. These site-specific parameters reflect the fact that the vegetation fraction is greater than assumed in the default parameter set, that leaf area index and minimum stomatal resistance are less, soils at the study site contain more clay, but that the plants' wilting point is lower than this clay fraction would imply.

iv. The modified, site-specific parameters more accurately describe the conservative character of the semi-desert vegetation and the moderate nature of its response to the seasonal water cycle.

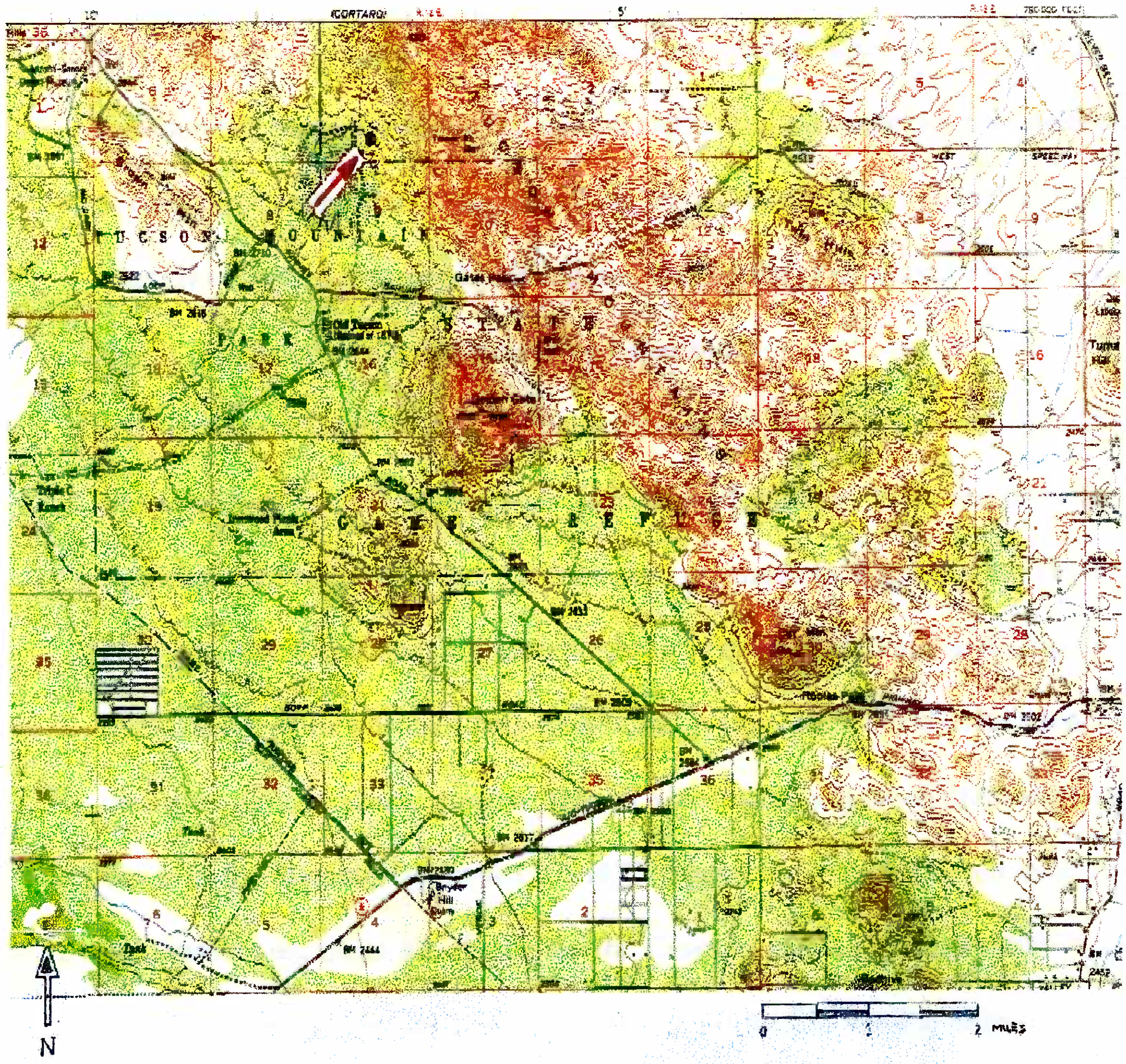

Figure 1. Location of study site.

2.2 Conclusions of Study.

The following conclusions can be made on the basis of this study:

i. Energy available for return to the atmosphere largely leaves in the form of sensible heat. Precipitation is the most important forcing mechanism in this semi-arid environment, controlling both evaporation and carbon exchange, for both daily and seasonal time scales. The magnitude of the latent heat and carbon dioxide fluxes are strongly correlated with magnitude and timing of precipitation events and latent heat flux is only weakly linked to atmospheric demand.

ii. Measurements of carbon dioxide uptake made in this study are exploratory, and are restricted to a growth phase in the semi-arid vegetation. The data show a net assimilation of carbon. Carbon dioxide uptake continues (at a reduced rate) through the night, something rarely if ever reported in other field studies (*e.g.* Verma *et al.*, 1989), which show a distinct daily cycle of much greater amplitude with CO_2 uptake during the day and release at night. Though a substantial proportion of the vegetation cover in the Sonoran Desert is C3 and C4 plants, some of the desert vegetation consists of succulents which employ the Crassulacean Acid Metabolism (*CAM*) photosynthetic mechanism (Larcher, 1994). If a sufficient fraction of the plants are of the succulent type, it is plausible that there should be a net uptake of carbon dioxide sustained throughout the night during a period of growth in desert vegetation.

iii. Micrometeorological measurements are feasible in the semi-arid conditions of this study, but it proved difficult to achieve consistent reliability and accuracy under exacting field conditions which involve extremely high temperatures and low relative humidity. The sigma-T measurements were of little use in this study, because they were of marginal and unpredictable accuracy and are only valid for unstable atmospheric conditions – which excludes their use between dusk and dawn and during and immediately after rain. It was ultimately proven easier to obtain a reasonably reliable record of surface energy fluxes using the Bowen ratio method rather than the eddy covariance method, primarily because using the Bowen ratio method required less data analysis, less computational resources, and substantially less in-field maintenance and calibration. Nonetheless, the eddy covariance system is likely to have greater accuracy and is therefore preferable when greater accuracy is required over short measurement periods.

iv. Using the set of default vegetation and soil related parameters used in the *CCM2*, the *BATS* model was unable to capture the observed rapid increase in the outgoing latent heat in response to precipitation and the gradual falloff during subsequent dry-down. An excellent description was achieved using a modified, site-specific set of parameters based on a few simple observations and some optimization of key vegetation-related parameters. This modified set of parameters more realistically reflected the fact that there is a sparse but fairly constant vegetation cover of around 40% at the study site and that the soil contains a significant amount of clay. These parameters suggest that the vegetation responds quickly when it receives water, with a substantial and rapid increase in photosynthesis and transpiration. Ultimately the soil dries and the plants reach a wilting point which, in the *BATS* model, is assumed to be determined by soil porosity. In practice the desert plants then seem able to sustain transpiration by accessing water from soil in the root zone longer than might be expected on the basis of the soil's high porosity alone.

2.3 Recommendations

Because precipitation controls both evaporation and carbon exchange, accurate measurement and characterization of the distributed precipitation field are essential to assure an accurate water balance and provide a realistic model simulation of the surface exchanges. Fulfilling this need is complicated by the large spatial variability of precipitation associated with convective storms, which are the primary mechanisms responsible for generating precipitation in semi-arid regions. The uniqueness of the photosynthetic processes employed by many desert plants and the effectiveness of the transpiration process revealed by this exploratory study argue for further measurement and modeling studies in this unusual and interesting environment.

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APPENDIX A: PUBLICATION PAPER

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Surface Flux Measurement and Modeling at a Semi-Arid Sonoran Desert Site

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Abstract

Continuous measurements of standard meteorological variables using an automatic weather station and intermittent measurements of the surface energy balance, carbon dioxide flux, and momentum flux using Bowen ratio, eddy covariance, and sigma-T instrumentation were made for 13 months at a semi-arid Sonoran Desert site just west of Tucson, Arizona. Weather observations demonstrate typical semi-arid Sonoran desert conditions, with frequent clear skies, high radiation, a large seasonal and diurnal temperature range, low relative humidity, and intermittent precipitation mainly of convective origin during a summer monsoon season. The substantial observational problems associated with surface flux measurements in this environment are reported. Comparisons between measured fluxes made simultaneously with different instrumental systems show acceptable agreement. Most of the incoming radiant energy leaves as sensible heat, and latent heat fluxes are always low, but transpiration is enhanced for about 10 days after rain. To investigate the influence of

Crassulacean Acid Metabolism plants on carbon dioxide flux, measurements were sustained through the night. Carbon dioxide uptake is low, typically with peak daytime uptake in the order 0.25-1.0 μmol m^{-2} s^{-1} for the period for which data are available, and some carbon uptake persists even at night. The observations were used to validate and calibrate the surface energy balance simulated by the *Biosphere-Atmosphere Transfer Scheme*. Using the default "*semi-desert*" soil and vegetation parameters specified in the National Center for Atmospheric Research *Community Climate Model version 2* resulted in a poor simulation of observations. However, using a set of site-specific parameters, including on-site observations to specify more realistic soil and vegetation characteristics, and optimized minimum surface resistance and plant wilting parameters, resulted in a substantial improvement in model performance. The site-specific parameters reflect the fact that the vegetation fraction is greater than assumed in the default parameter set, that leaf area index and minimum stomatal resistance are less, soils at the study site contain more clay, but that the plants' wilting point is lower than this clay fraction would imply. The modified, site-specific parameters more accurately describe the conservative character of the semi-desert vegetation and the moderate nature of its response to the seasonal water cycle.

1. INTRODUCTION

Semi-arid environments cover 40% of the Earth's land surface and therefore are a significant component of the Earth's climate system (Moran *et al.*, 1994). The dominant forcing in semi-arid regions is precipitation, which can be extremely variable in both time and space, resulting in great variability in soil moisture and in latent and sensible heat fluxes (Stewart *et al.*, 1994). The extreme seasonality of precipitation in semi-arid regions, such as the July-August Sonoran desert monsoon has a profound effect on seasonal patterns of surface water and energy exchange. In fact, the seasonal patterns in surface fluxes caused by monsoon precipitation greatly exceed those caused by the seasonal differences in solar forcing.

During long dry periods, the surface-atmospheric exchanges of water and energy are controlled by a complex combination of soil water availability and perhaps unique plant physiology. During short wet periods, evapotranspiration approaches its potential, and is not limited by soil water availability, but during dry periods, low soil water availability limits surface evaporation severely. Soil water availability also limits plant transpiration, but several different metabolic pathways exist in semi-arid plants that allow them to sustain photosynthesis when soil water is very low. Succulent plants use the Crassulacean Acid Metabolism (*CAM*) pathway that conserves water by only transpiring at night and utilize in-plant water storage to become independent of soil water availability, others develop extremely deep roots that tap groundwater reservoirs, while others shed leaves and continue photosynthesis in their stems. Understanding the complex interactions between plant physiology, extreme seasonality in precipitation and solar forcings, and large diurnal temperature variations in semi-arid environments is crucial for assessing their role in the Earth's climate system. Further, semi-arid regions are climatologically sensitive because slight shifts in global climate could potentially result in major changes in local surface conditions. Despite this, surprisingly little is known about the spatial and temporal variation in energy and water fluxes and how these are influenced by vegetation and soil properties in semi-arid environments.

In order to understand the complexities of the semi-arid soil-vegetation-atmosphere system which determines exchanges of water, energy, and carbon dioxide and eventually predict the interrelationship between this fragile land cover and climate, several field experiments, including the Sahelian Energy Balance Experiment (SEBEX; Wallace *et al.*, 1991), *MONSOON-90* (Kustas *et al.*, 1991), the Owens Valley study (Kustas *et al.*, 1989), the Smith Creek Valley, the Smoke Creek Desert studies (Nichols, 1992), and the La Crau observational study (Kohsiek, *et al.*, 1993) were undertaken. These experiments provided valuable insight, but have generally been of short duration and have focused mainly on investigating spatial, as opposed to temporal, variability. This study focuses on measuring and modeling the surface fluxes from a pristine semi-arid environment over a year, in order to better characterize the climate-related signals in the surface fluxes.

Soil-Vegetation-Atmosphere Transfer Schemes (*SVATS*) are one-dimensional submodels used in Global Circulation Models (*GCMs*) to describe the interaction between the overlying atmosphere and the vegetation and soil. The validity of the description provided by *SVATS* has not been fully explored in semi-arid regions. In response to this need, the performance of one of the most commonly used *SVATS*, the Biosphere-Atmosphere Transfer Scheme (*BATS*; Dickinson *et al.*, 1993) is evaluated using the surface energy and water fluxes collected in this study.

2. Materials and Methods

2.1 Experimental Site

Field data were gathered at a site located at 32°13' N, 111°5' W in the semi-arid, alluvial Sonoran Desert near Tucson, Arizona, on gently sloping terrain at an elevation of 730 m. There are uninterrupted fetches of many kilometers in all directions except 1 km to the northeast, where the 1340 m high Tucson Mountain range lies. Total precipitation measured over the year-long sampling period starting on May 12, 1993 was 275 mm.

Vegetation was interspersed with patches of exposed rocky soil, giving a fractional vegetation cover of 40%, estimated from four linear 30-m transects within the fetch of the Bowen ratio instrument (Woodhouse and Zeng, 1993). Key species include creosote bush (*Larrea tridentata*), brittle bush (*Encelia farinosa*), triangular leaf bursage (*Ambrosia deltoidea*), velvet mesquite (*Prosopis velutina*), palo verde (*Cercidium microphyllum*), ironwood (*Olneya tesota*), jojoba (*Simmondsia chinensis*), ocotillo (*Fouquieria splendens*), non-native agave (*Agave americana*), as well as various cacti including saguaro (*Carnegia giganteus*), Staghorn, chainfruit and teddybear cholla (*Opuntia versicolor, O. fulgida and O. bigelovii*, respectively), and Englemann's prickly pear (*Opuntia phaeacantha*). Of these, all the succulent species (cacti and agaves) employ the Crassulacean Acid Metabolism (CAM) while the other species employ the more common C3 pathway for photosynthesis. For short periods in the spring and after the summer monsoons, a sparse cover of short black gramma grass (*Bouteloua eriopoda*; C4) and flowering annuals developed on the otherwise exposed soil. Vegetation heights range from a few tens of centimeters for low grasses and bushes up to 7 m for the tallest saguaro cacti; mean vegetation height was estimated as 1.2 m.

Soil samples were obtained at depths of 1 cm and 15 cm from a bare soil area, a vegetated area (under a bush), and a stream bed. These samples were sifted through a D_{10} mesh sieve, and the fine fraction was analyzed for soil texture and albedo. The coarse fraction, consisting mainly of rocks, had a similar color to the fine fraction taken from the same sample. In fact, samples taken from the bare and vegetated surfaces are more representative of the average soil parameters for the field site than those from the stream bed, because the latter constitute just a small fraction of the surface area. All sites had a significant fraction of clay, with the least clay fraction in the stream bed samples. The soil texture was assigned to one of the *BATS* soil classes (see Dickinson *et al.,* 1993, Table 3) on the basis of porosity; overall, the *BATS* soil texture class 9 was the most representative of the soil at the field site. For the near-surface samples, soil albedo measurements for wavelengths $\lambda < 0.7$ μm indicated albedo ranges of 0.19 to 0.21 and 0.093 to 0.11 for dry and wet samples, respectively, corresponding to *BATS* soil color index 3 (see Dickinson *et al.,* 1993, Table 3).

After several weeks without precipitation, on September 23, 1993, a bulk soil density of 1700 kg m^{-3} was determined from soil samples taken at the field site, when the gravimetric soil water content was 0.08 kg water per kg soil (volumetric water content, 0.136 m^3 of water per m^3 of soil).

2.2 Micrometeorological Instrumentation and Methods

The instrumentation used in this study is shown in Figure 1 and includes a Bowen ratio system, sigma-T systems, an eddy covariance system, and a standard meteorological station. The Bowen ratio system measures the height-dependent difference in temperature and humidity at two levels and derives the sensible and latent heat fluxes via an energy balance calculation. The sigma-T system measures the standard deviation of air temperature using fast response thermocouples to provide an alternative estimate of sensible heat flux. The eddy covariance system uses an infrared gas analyzer and a sonic anemometer to provide direct measurements of sensible and latent heat, momentum, and carbon dioxide fluxes. Finally, the automatic weather station provides routine measurements of precipitation, net radiation, incoming short-wave radiation, soil heat flux, air temperature, relative humidity, and wind speed and direction.

2.2.1 Automatic Weather Station

Standard meteorological measurements were taken using an automatic weather station (*Campbell Scientific*, Utah, USA) from May 12, 1993 to June 5, 1994. Measurements of net radiation, incoming short-wave radiation, air temperature, relative humidity, wind speed and direction, precipitation, soil temperatures, and soil heat flux were recorded on a data logger, initially as average values over 10-minute intervals. These were subsequently combined to provide time averages over longer intervals, as required. Recognizing that about half the land surface is vegetated, net radiation was taken as the arithmetic average from two net radiometers (*R.E.B.S.*, Washington, USA; model Q-6), situated to sample the extremes of net radiation variability due to vegetation. One was mounted at a height of 3.4 m above a palo verde bush, and the second at a height of 2.9 m above a mixture of bare soil and small sagebrush plants. The instrumental error associated with these net radiometers is estimated as 5%, while the systematic difference associated with the underlying ground cover was greater than this, the daytime measurement over the short vegetation and soil being typically 10-12% less than that over the bush.

The pyranometer (*Li-Cor*, Nebraska, USA; model LI-200SZ) and a combined thermometer and hygrometer (*Campbell Scientific*, Utah, USA) were respectively mounted 8.3 m and 6.7 m above the ground. Factory calibration specifies a maximum absolute error of 5% for the pyranometer, but suggests typical values of 3% under natural daylight conditions. At 20 °C, the accuracy of the hygrometer quoted by the manufacturer is 2% for the relative humidity (*RH*) range 0-90% or 0.3 g/kg for the specific humidity (q) range 0-14.5 g/kg, and 3% for the *RH* range 90-100% or 0.5 g/kg for the q range 14.5-16.1 g/kg. Temperature measurement accuracy is 0.4 °C for the temperature range -33 to +48 °C. The anemometer and the wind vane, with estimated measurement accuracies of 2% and 5°, respectively, were installed on top of the 9-m tower. Precipitation was measured using a tipping bucket rain gage (with funnel top 31 cm above the ground), which had a quoted accuracy of 1% at rainfall rates of 50 mm h^{-1} or less.

Following the same methodology used for averaging the net radiation measurements, the areal average soil heat flux was obtained as an average of fluxes measured at two bare-soil and two vegetation-covered sites, recognizing that about half the land surface is vegetated. Four soil heat flux plates were buried 8 cm below the soil surface, two beneath vegetation and two under bare soil. The average soil temperature above the heat flux plates was determined by averaging soil thermocouple measurements at 2 cm and 6 cm above the plates. The surface heat flux was calculated by adding the measured heat flux to the energy stored in the layer above the heat flux plates, the latter being proportional to the rate of change of soil temperature. The estimates of the thermal capacity of the soil required for this calculation (Woodhouse and Zeng, 1993) were based on fairly dry soil samples obtained on September 23, 1993 (see Section 2.1 above). This estimate of thermal capacity is valid throughout most of the measurement period, except during some short wet periods where the lack of soil moisture information may lead to errors in soil heat flux. Sensitivity tests revealed that likely changes in the thermal capacity for moist soil during and immediately after rainstorms give only a small (~ 2%) error in the measured surface heat fluxes.

2.2.2 Eddy Covariance System

The eddy covariance system used in this study was assembled following the design of Moncrieff *et al.* (1995) and implemented to operate in an isolated field environment using solar energy. It used a 3-axis ultrasonic anemometer (*Gill Instruments*, Hants, UK; Model 1012R2A) to measure wind speed variations and air temperature, a carbon dioxide and water vapor infrared gas analyzer (*Li-Cor*, Nebraska, USA; model 6262) to measure variations in concentration, and a high-speed laptop computer for system control and data processing, together with an air ducting system (including high-speed pumps and chemical air scrubbers), and other assorted data handling and power-related hardware. The computer made measurements of fluctuating variables 20 times per second.

The sonic anemometer and gas analyzer intake were situated well above the vegetation on top of a 6-meter tower. Because the sonic anemometer was of a 3-axis design, it allowed measurement of the three-dimensional wind vector, and it was deployed in an operational mode in which it makes manufacturer-provided real-time corrections for the flow distortion and wind shadowing generated by the anemometer structure. The anemometer was linked to the portable computer through a serial port and had the option of monitoring additional voltage inputs. These were used to collect the concentration measurements from the infrared gas analyzer.

The gas analyzer measured carbon dioxide and water vapor concentrations at high speed by using the differential absorption of infrared light by these two gases. It uses a light chopper to allow rapid, alternate samples of the light absorption by a zero concentration reference gas to correct for detector drift. The gas analyzer was calibrated at least once each week against gases with known concentrations of water vapor and carbon dioxide, these being derived from a dew-point generator (*Li-Cor*, Nebraska, USA; model LI-610), a compressed reference gas (400 ppm CO_2 accurate to 1% of the National Institute of Standards standard), and "scrubbing" chemicals to provide air samples with zero concentrations. During measurements, air was ducted 10 meters (using "*Bev-a-Line IV*" polyethylene tubing) from the vicinity of the sonic anemometer, down the tower and into the infrared gas analyzer, using a high-speed pump operating at a flow rate sufficient to assure turbulent flow in the ducting tubes. A pressure sensor was included in the gas flow path adjacent to the sampling chamber to allow correction for pressure changes associated with air movement through the ducting system.

The eddy covariance system consumed approximately 60 W of power, mostly by the pumps and the infrared gas analyzer. This power was supplied by ten (46 by 91 cm) solar panels regulated to charge ten 105 amp-hour deep-cycle marine batteries. Power supplied to the gas analyzer and pumps was regulated by DC-DC converters, use of which also helped to prevent "ground loop" problems. In this application a DC-AC inverter was used to supply the computer, tape drive, and sonic anemometer with 110 volts AC because the DC-DC converters suffered momentary power interruptions which stopped data collection. Solar power was plentiful at this site, but high daytime air temperatures and heat produced by instrumentation lead to instrument damage, necessitating the development of an instrumentation enclosure with enhanced air circulation, and high reflectance properties.

The process of ducting an air sample from the intake near the sonic anemometer on top of the tower to the gas analyzer introduces a delay of several seconds between the wind vector and concentration measurements. This must be allowed for during data analysis. The on-line computer was not powerful enough to do the required processing in real time, so the raw wind vector and concentration data were saved for retrospective analysis. About 20 megabytes of data were stored per day, then transferred and reprocessed. Ultimately, the volume of data and the complexity of retrospective data processing (see below) associated with the prolonged use of this eddy covariance system provoked a decision to choose the alternative Bowen ratio system for the year-long routine flux measurements undertaken in this study.

Retrospective processing of the stored eddy covariance measurements was a two-step process. The air-ducting delay time was determined using a cross-correlation analysis between the measurements of carbon dioxide and water vapor and air temperature as measured by the sonic anemometer. However, in this environment where measured fluxes are often low (especially at night), the delay time is not always easily identifiable from an individual cross-correlation analysis made at a particular time, and a process of manual interpolation was required to select the delay times (so justifying the storage and retrospective processing of the data). This re-analysis involved plotting the time series of cross correlation spectra for each 20-minute sampling time and assuming that delay time was fairly consistent from one time period to the next. Delay times were relatively uniform, with changes typically of less than about one second in a day but sometimes with changes up to several seconds in a week.

The second step in the analysis was to apply calibration to the raw voltages and to calculate the covariances, variances, and means from the several variables using the time alignment between the data streams associated with flow down the ducting tubes derived as above. The "*EDDYFLUX*" software (Verhoef, 1992) was used for this purpose. This software performs a coordinate rotation analysis as well as making corrections for sensor response, path length averaging, sensor separation, dampening of fluctuations and contamination of CO_2 flux by latent heat flux (Moore, 1986; Philip, 1963: Leuning and King, 1991; Webb *et al.*, 1980), for all of which a correction exceeding 5% is rarely needed. Finally, a correction to account for the change in carbon dioxide storage below the sensor was made, where it was assumed that the carbon dioxide concentration below the sensor was equal to the concentration measured at the sensor.

2.2.3 Sigma-T Measurements

Tillman (1972) proposed a simple procedure for estimating sensible heat flux which is based on Monin and Obukhov's (1954) similarity theory applied in unstable atmospheric conditions and which has become known as the "*Sigma-T*" method. In very unstable conditions well above the ground, it requires measurements only of the standard deviation of temperature, σ_T, and the mean air temperature, θ, at height, z, together with an estimate of the zero plane displacement height, d. The sensible heat flux is estimated from:

$$H=\rho_a c_p\left[\left(\frac{\sigma_T}{C_1}\right)\frac{kg(z-d)}{\theta+273.2}\right] \tag{1}$$

where k is the von Karman constant (~ 0.4), and C_1 is a constant which is often set to 0.95 following Tillman (1972). Because this method is only valid during unstable atmospheric conditions, it cannot be applied between dusk and dawn (*i.e.,*during the night), or during rain, because the atmosphere is usually neutral or stable at these times, or during rain because evaporation from the sensors produces invalid standard deviations.

In this study, the measurements required to apply this technique were made using fine-wire (76 μm diameter) thermocouples. These were installed on arms extending 0.75 m from the tower, at a height of 7 m from June 9, 1993, and also at 5 and 10 m between November 1 and December 31, 1993. The standard deviation relative to a running mean and the arithmetic average of air temperature were recorded on a data logger over 20-minute intervals, with a resolution equivalent to 0.006 °C at a frequency of 10 Hz.

2.2.4 Bowen Ratio Measurements

The Bowen ratio-energy balance method relies on measuring the components of the surface energy budget:

$$H+L_e=R_n-G \tag{2}$$

Here the net radiation, R_n, and the soil heat flux, G, are directly measured; while the ratio of L_e and H are estimated from measurements of the difference in vapor pressure, *de*, and potential temperature, *dT*, between two levels above the ground. The Bowen ratio, β, the ratio of the sensible to the latent heat flux, is assumed to be proportional to these differences, thus:

$$\beta = \left(\frac{c_p p}{\varepsilon \lambda} \right) \left(\frac{dT}{de} \right) \tag{3}$$

where:

p = Atmospheric pressure (kPa)

c_p= Specific heat of air (kJ kg^{-1} $°C^{-1}$)

λ = Latent heat of vaporization (kJ kg^{-1})

ε = Ratio of molecular weight of water to that of air.

Combining the definition of the Bowen ratio with the energy-balance equation gives:

$$L_e = \frac{(R_n - G)}{(1 + \beta)} \tag{4}$$

with the sensible heat flux then derived as the residual in the energy-balance equation as:

$$H = R_n - G - L_e \tag{5}$$

Net radiation and ground heat flux were measured for the period May 12, 1993 to June 5, 1994, with measurements of the Bowen ratio also attempted over this same period using a proprietary hardware system (*Campbell Scientific*, Utah, USA). Temperature and humidity sensing was carried out near the end of two 1.5-m long arms, one mounted near the top of the 10-m high tower and the other 3 m above the ground. Air temperatures were measured using 76 μm diameter chromel-constantan thermocouples, with the differential voltage output between the two levels monitored with a data logger resolution equivalent to 0.006 °C. The vapor pressure was measured with a cooled dew-point hygrometer (*General Eastern Corp.*, Massachusetts, USA; model DEW-10). This hygrometer alternately sampled air ducted from intakes adjacent to these two thermometers every two minutes, via (1 μm pore size) Teflon filters and (Bev-A-Line IV) polyethylene tubing, with a 2-liter buffering container in each air line. Dew-point measurement errors are estimated as 0.5 °C, corresponding to better than 0.01 kPa in vapor pressure resolution over most of the range -10 °C to 70 °C ambient temperature. The difference in humidity between the two levels is small in the semi-arid environment, and the original separation of the two arms (3 m) proved inadequate to resolve the (humidity) gradients. Even the greater separation (7 m) used after July 6, 1993 provided only marginally adequate resolution, as described below.

In practice, the Bowen ratio system provides only intermittent measurements because of hardware problems, these being particularly severe at the outset of the study. These problems are outlined here for the guidance of others planning to operate such a proprietary system in a similarly exacting semi-arid environment. Although equipment maintenance was reasonably simple, substantial data were lost due to small air leaks produced by ultraviolet degradation of the polyethylene ducting tubes which can subtly compromise the measurement. Such tubing exposed to intense sunlight should be changed periodically to prevent leakage. Other hardware problems encountered in this study include the occasional sticking of the solenoid valve used to switch the air flow sampled by the dew point sensor and damaged thermocouple junctions due to bird activity and hailstones.

However, the most troublesome aspects of this particular Bowen ratio measuring system when operating in a semi-arid environment are associated with the cooled dew-point mirror. Under conditions of very low humidity, and with dew point commonly well below 0 °C, the normal operating range of this mirror is easily exceeded. The device then sometimes fails to sense that the proper dew-point had been reached during a cooling cycle, and the heat pump continues cooling the mirror, causing persistent ice formation. This condition, if not detected in time, may cause the mirror to chip or scratch and, if the ice is allowed to build up for more than a few days can (and in our case did) cause heat pump failure. Ready access to a spare dew-point mirror and cooling system is therefore advisable when using this proprietary system in semi-arid environments. A heat source (an automotive light bulb connected to a thermostat set to turn on when the temperature in the box dropped to 10 °C) was installed near the dew-point mirror block in the enclosure box. This alleviated the freezing problem to some extent by speeding recovery from persistent icing.

2.3 Analysis Procedures and Quality Control

The near-surface weather variables obtained from the automatic weather station (*AWS*) for the first 365 days of the study (from 12 May 1993 to 11 May 1994) were used in the modeling component of this study. There were no missing data in the *AWS* record;

however, occasional measurements from one of the two net radiometers were unreliable because of bird damage to radiometer domes. Normally the preferred value of net radiation is the average value from the two net radiometers, but when one was unavailable, a value for the missing measurement was derived from the other using the linear regression between the two radiometers established at other times. Soil heat flux was also normally calculated as the average of the two sets of soil heat flux instruments, but again, occasionally missing data records were allowed for by exploiting the linear regression derived when both systems were available.

Only a proportion of the original raw Bowen ratio data were considered reliable enough for use in the *BATS* validation exercise due to various mechanical failures and other system limitations, which were most severe during initial data collection. Of the 389-day period for which data collection was attempted (from May 12, 1993 to June 5, 1994), only 170 days were determined to contain some valid data, these falling within the period August 10, 1993 to March 27, 1994. However, even within this subset of days, not every 20-minute sampling period was considered acceptable; in fact, only 30% of the measured vapor pressure and temperature differences were considered reliable.

A deliberately exacting set of criteria was applied to select among these Bowen ratio data to ensure their credibility, the primary exclusion being to ignore data when the observations were considered beyond the instrumental accuracy of the Bowen ratio system as a whole or the individual sensors involved in that system. Accordingly, observations in which the absolute value of the vapor pressure difference between the two measurement levels, $|de|$, was less than 0.005 kPa were excluded, as were observations for which the Bowen ratio was close to -1, specifically for the range $|1+ \beta | < 0.3$. The latter occurs when sensible and latent heat fluxes are in opposite directions and approximately equal, when the Bowen ratio method cannot determine the size of the surface fluxes. This condition routinely occurs for short periods around dawn or dusk when the energy available for evaporation (and both surface energy fluxes) is low and the time rate of change of R_n is large. For short periods of less than an hour for which no reliable data were available, the missing values of energy fluxes were interpolated from the preceding and subsequent values.

In addition, some simple plausibility tests on the calculated latent heat flux were effective in removing spurious data associated with settling periods after instrumental servicing or with one or more of the several modes of instrumental failure described above. Hence, data with calculated latent heat fluxes greater than 400 W m^{-2} were also considered invalid, as were data for which the latent heat flux was negative when the relative humidity was less than or equal to 80%.

2.4 Fetch Analysis

An estimate was made of the surface area contributing to the micrometeorological flux measurements using the approach of Schuepp and Desjardins (Schuepp *et al.*, 1990; Desjardins *et al.*, 1992), applied with aerodynamic parameters and instrument heights appropriate for the study site. Figure 2(a) gives the result of an example calculation relevant to the eddy covariance system for a wind speed of 3.5 m s^{-1} (at a height of 6.4 m), a friction velocity of 0.38 (m s^{-1})^2 and a sensible heat flux of 300 W m^{-2} which shows that 80% of the flux originates within 282 m of the micrometeorological tower, with the maximum contribution at 50 m and areas 1 km away making marginal contributions. The calculated fetch has some sensitivity to the prescribed wind speed and sensible heat for which calculation is made, but this is not significant in this experimental context.

Estimates of flux contributing surface area are more complex for the Bowen ratio instrument, due to measurements at multiple heights. Figure 2(b) shows flux contributing surface area estimates for the Bowen ratio sensors mounted at heights of 3 m and 10 m. For the 3 m height, 80% of the flux measured originates within 67 m of the tower, with the maximum contribution at 20 m, while at a height of 10 m, 80% of the flux measured originates within 544 m of the tower, with a maximum contribution at 80 m. Since the vegetation within about 1 km of the tower is relatively evenly distributed, the differences in the fetch between the two Bowen ratio measurement points is not significant.

The above calculations suggest that differences in surface vegetation cover are not an issue, because the site has a fairly uniform mix of Sonoran Desert vegetation extending at least one, and more typically several kilometers, in all directions. However, available water from precipitation is an important aspect of the surface energy balance in this environment, as the summer Arizona monsoon season is commonly associated with highly localized, convective precipitation. For example, exploratory measurements with simple non-recording rain gages deployed on a 10-m grid over a 50 m by 40 m area at this site showed that the rainfall measured in individual storms could vary by as much as 20% for convective storms and 5% for frontal storms. Thus, it is possible to receive a certain amount of precipitation within the source area from which the measured fluxes originate, but to measure a significantly different amount of precipitation in the rain gage at the study site and *vice versa*. Clearly this possibility needs to be remembered, because in principle, it has the potential to compromise the match between the measured surface energy and water budgets, at least in the short term, and so could provide a limitation on the capability to validate model calculations of surface exchanges based on single point measurement against measured fluxes from a sampled area some distance upwind.

3. Observational Results

3.1 Climate Characteristics

Measurements of the near-surface weather variables provided by the *AWS* confirm that the climate at the study site exhibits characteristics typical of the semi-arid Sonoran Desert climate. Figure 3 shows daily average weather variables for the year starting May 12, 1993. Daily average solar radiation ranges from 350 W m^{-2} in summer to 150 W m^{-2} in winter, with net radiation always significantly lower, because the largely cloudless skies ensure significant energy loss as long-wave radiation. Daily average air temperature varies from around 30 °C in July to about 10 °C in January, but the diurnal cycle in air temperature is always high, and maximum daytime temperatures in the summer commonly reach 45 °C.

Precipitation is largely convective in nature, with short storms concentrated in the summer monsoon season – mainly in July and August – but the frequency of monsoon rains was lower than usual in the year for which data are available. Frontal storms contribute smaller amounts of precipitation, primarily in the winter months from December to February. The total measured precipitation at the study site over the year for which results are reported was 275 mm. Specific humidity was normally very low, about 4 g/kg for daily averages, but increases to 9 g/kg during the July-September monsoon season. Wind speeds are also fairly low, averaging about 5 m s^{-1}, again with some increase associated with storms.

3.2 Flux Comparisons

In principle, three independent measurements of surface energy fluxes were made simultaneously at the study site using the eddy covariance, Bowen ratio and sigma-T methods. Unfortunately, when these data were subsequently analyzed, and a careful quality control applied to each, the time period for which simultaneous data were available from all three systems was very limited. In particular, data collection with the eddy covariance system was only made early in the study year and only during the period when there were successive instrumental failures in the Bowen ratio measurement system, *i.e.*, prior to August 10, 1993, when routine data collection from the Bowen ratio system was finally established.

Consequently, it is only possible to present worthwhile comparisons between the surface fluxes measured with the eddy covariance method and the sigma-T method for the early period of data collection and comparisons between the Bowen ratio method and the sigma-T method for the longer, later period. Figure 4 shows comparisons between the measured sensible heat given by the thermocouple-based sigma-T method and those from the eddy covariance system in Figure 4(a) and the Bowen ratio method in Figure 4(b). Although there is a reasonable level of agreement between the measured fluxes in these two figures, there is substantial scatter and, in the case of the comparison with the eddy covariance data, evidence of a significant systematic difference at lower values of sensible heat. To isolate the cause of this systematic difference, sigma-T was recomputed using a linear average of sonic temperature, rather than a running mean of thermocouple temperature. The sensible heat flux based on eddy covariance and that based on the standard deviation of sonic temperature in Figure 4(c) compares favorably (97% correlation). This implies that the agreement between sigma-T and eddy covariance sensible heat fluxes is better when it is possible to calculate standard deviation with a linear average.

The Bowen ratio systems' decreased reliability in detecting small latent heat fluxes is important and relevant to the *BATS* model validation studies described later. Further, in such low flux conditions, the quality control restriction applied within these data, namely that the measured difference in atmospheric humidity between the two air intakes should be within instrumental accuracy, introduces a bias towards allowing only the highest values of latent heat in the accepted subsample. For this reason, our eddy covariance flux measurements are likely to be the more reliable of the two primary latent heat measurements made in this study, but only for the limited period for which they are available. Flux measurements from the Bowen ratio system, which were available for a much greater fraction of the time, are most credible for periods when latent heat fluxes are reasonably large. In the comparisons between modeled and measured fluxes made later, comparisons are made against data taken with both the eddy covariance and the Bowen ratio systems, but the eddy covariance data are given greater credence when the latent heat is low.

3.3 Eddy Covariance Measurements

The ability to close the energy balance is a measure of the reliability of the eddy covariance measurements. Figure 5 shows a comparison between the hourly average sum of the latent and sensible heat fluxes and net radiation minus soil heat flux. A 96%

correlation between energy received and imparted by the land surface shows that an approximate energy balance is achieved, with the sum of latent and sensible heat fluxes (L_e + H) being, on the average, 22 W m^{-2} larger than (R_n-G), the measured available energy.

The diurnal pattern of eddy covariance energy fluxes are shown in Figure 6(a) for a typical dry day (July 22, 1993) with clear skies, and in Figure 6(b) for a day with substantially more cloud cover and a late afternoon storm (August 7, 1993). Typically, during dry periods, sensible heat rises to a peak in the middle of the afternoon, while ground heat flux peaks in the morning and then decreases to reach a minimum value just after dusk. The latent heat rises during the day, but remains very low, reflecting the lack of available water. The behavior on the day with cloud cover and rain is markedly different, with substantially less net radiation and sensible heat flux, but much higher values of latent heat flux after the afternoon storm and well into the night, supported by negative ground and sensible heat fluxes.

Figure 7(a) shows hourly averaged, storage-corrected carbon dioxide flux measured with the eddy covariance system for the period between July 19 and August 9, 1993. A 5-hour running mean has also been applied to these data to improve the signal-to-noise ratio; these data are otherwise very "noisy" (Note: by comparing hourly fluctuations with this 5-hour running mean, we estimate random errors of order 0.25 μmol m^{-2} s^{-1} for hourly average measurement, but anticipate that some of this error will average out in longer-term total fluxes). For the period when carbon exchange measurements were available, carbon dioxide fluxes were always very low, averaging only about 0.25 μmol m^{-2}s^{-1} for the drier period (July

19-31, 1993) and about 1 μmol m^{-2} s^{-1} in wetter conditions (August 3 to 9, 1993). Figure 7(b) shows the diurnal CO_2 flux pattern from a typical dry day (July 22, 1993) and a typical wet day (August 7, 1993), while Figure 7(c) shows a comparison between this same wet day and the CO_2 uptake pattern for an unexceptional day during the First *ISLSCP* Field Experiment (*FIFE*, August 10, 1987; Kim and Verma, 1990). Table 1 summarizes the meteorological conditions for the wet and dry days referred to in Figures 6 and 7(b) and (c). The measured diurnal cycle of carbon dioxide exchange was about ten times larger at the *FIFE* site: very interestingly, the carbon uptake by the plants at this semi-arid study site continues through the night, while the prairie grasses at the FIFE site show a more typical daily cycle, with downward fluxes during the day and upward fluxes at night. We return to this interesting result in Section 5.

4. Modeling Results

4.1 BATS Model Description

The Biosphere-Atmosphere Transfer Scheme (*BATS*) is a parameterization of the current understanding of ecohydrological processes at the scale of individual (50-1000 m) plots of vegetation. The processes incorporated are those associated with the exchange of solar and long-wave radiation, water input as rain, snow, and dew, water loss as runoff, and the surface transfer of momentum and sensible and latent heat exchanges.

The *BATS* uses separate model components in its radiative and hydrological description. Three layers of soil are used to calculate the water budget, all having a top surface at the soil-air interface, but with the lower surface at increasing depths. The soil is considered as a 0.1 m surface layer, a 0.5 to 2-m root layer with a total depth of 3 m. Soil temperature calculations are based on the *"force-restore"* method (Deardorff, 1978; Dickinson *et al.*, 1993), in which two soil layers are considered, with the upper 20-cm layer affected by the diurnal cycle and heat flux from deep soil tending to "restore" the temperature of that surface layer.

The parameterization of the vegetation canopy is based on the "*single big leaf*" concept, the processes considered being sensible and latent heat exchanges with the atmosphere, absorption of solar radiation and shading of the ground, and the presence of surface moisture on the canopy as a result of dew or rainfall. Excess moisture on leaves drips to the ground as throughfall. The vapor pressure over the dry area of the canopy is parameterized using stomatal resistance, which controls the escape of water from saturated conditions within the leaf to the adjacent external air. The *BATS* considers four layers of canopy in order to calculate the dependence of stomatal resistance on solar radiation. The transpiring part of plants is specified using leaf area index *(LAI)*, while non-transpiring parts and dead matter are described with stem area index *(SAI)*. In general, seasonal variation in *LAI* is determined by a quadric function of deep soil temperature, while the *SAI* is constant for each cover type.

The *BATS* allows for partial wetting of the canopy by rainfall, with transpiration suppressed over the wet portion of the canopy. Snow is also intercepted by leaves, and the treatment of solid water storage on the canopy is the same as for liquid water. The water stored per unit area of land surface is calculated from the difference between precipitation and evaporation from the plant surface. Two transfer phases are considered in the movement of water and heat flux from the canopy to the atmosphere: first, exchange with the air within the canopy, and second, exchange between the canopy air and the atmosphere overlying the canopy. There is no description of heat or moisture storage in the canopy air, and photosynthetic and respiratory energy transformation in the canopy are neglected. Separate temperature, humidity, and wind speed calculations are made for the canopy layer, and heat and moisture fluxes exchanged between leaves and atmosphere are transferred through this canopy layer.

The *BATS'* treatment of the Earth's surface includes bare soil, soil with vegetation cover, snow-covered soil, frozen soil, inland water, sea, and sea ice. Within each land grid square, three types of surface conditions can exist, namely bare soil, vegetated soil, and snow. In this study, the land surface without snow cover is the focus of attention. The location of canopy and bare soil is not specified within an individual grid square, and soil properties and overlying atmosphere are both assumed uniform across the square. Soil textural properties are also assumed constant with depth.

Each grid square modeled by the *BATS* is described by one of 18 land cover classes, namely mixed crop, irrigated crop, short grass, long grass, four types of forest, two types of shrubs, mixed woodland, two types of desert, tundra, glacier, marsh, ocean, and inland water. Specifying one of these cover types then selects a "*standard*" set of values of the surface parameters, which are then used in running the model. The *BATS* also allows specification of one of 12 standard soil texture classes which determine the hydraulic and thermal properties of the soil and eight soil color classes which determine the soil albedo.

In this study, the initial model validation run used parameters appropriate for the southwestern USA within the National Center for Atmospheric Research's (*NCAR*) Community Climate Model version 2 (*CCM2*), specifically standard parameters for vegetation type 11, *i.e.*, "*semi-desert*" (see Dickinson, 1993, Table 1), soil color index 2, and soil texture class 3. To investigate whether these standard *CCM2* parameters adequately characterize exchanges for the Sonoran Desert, field measurements of some of the vegetation and soil parameters were made. These measurements, together with an optimization of certain key vegetation parameters, then formed the basis of a modified set of parameters.

4.2 BATS Model Forcing Data and Initialization

The continuous set of near-surface weather variables from the *AWS* were expressed as 20-minute averages for the year from 12 May 1993, and were used as "*forcing variables*" for the *BATS* validation studies carried out with a stand-alone version of the *BATS* model, *i.e.*, they were used as the time series of input variables required by the model to make calculations of surface flux exchange. The measured incoming short-wave radiation, air temperature and specific humidity, wind speed, and precipitation are variables used directly by the model, but the required value of downward long-wave radiation was not available from direct measurement. It was therefore derived for each time period from the surface radiation balance using measured incoming short-wave radiation and measured net radiation, together with the model-calculated surface temperature from the previous modeled time period. [Note: For this reason, model-calculated estimates of net radiation are necessarily always close to measured values in this study]. The model also requires atmospheric pressure, though in fact the sensitivity of calculated surface fluxes to variations in air pressure is small. Because routine atmospheric pressure measurements were not made, air pressure was assumed constant at 91.29 kPa, this being the average air pressure measured at nearby Tucson International Airport, with a hydrostatic correction made for the elevation difference.

In order to run the *BATS* model, it is necessary to designate certain initial conditions, specifically the temperatures of the canopy and soil layers and the moisture stored on the canopy and in the soil. Canopy and soil temperatures change rapidly in the model, and their initiation is therefore less critical. The initial values were specified as equal to the most appropriate measured air and soil temperatures. Unfortunately, no soil moisture measurements were available for the beginning of the *BATS* model validation run (on May 12, 1993). However, precipitation and temperature records suggest that soil moisture conditions for that date were similar to those for September 23, 1993 when measurements were available (both days fall at the end of extended dry periods with similar atmospheric demand). The volumetric water content of 0.136 m^3 of water per m^3 of soil measured on September 23, 1993 was therefore used to initialize the soil water storage in all three soil layers in the *BATS* model runs. In fact, the *BATS* was always run with 20 years "*spin-up*", *i.e.*, recycling the one-year forcing data set 20 times to allow the model sufficient time to equilibrate, so the particular values used for the initiation are not critical.

4.3 BATS Parameterization

In the model calibration, a stand-alone version of the *BATS* was run with two sets of parameters. The first set consisted of the standard vegetation and soil-related parameters assigned to the *BATS* when it was used to describe the semi-arid southwestern USA in the *CCM2*. In the second set of parameters a set of site- and location-specific parameters was determined in part from on-site measurements and in part by optimization, as described below. These two sets of parameters are given in Tables 2 and 3; vegetation-related parameters are given in Table 2 and soil-related parameters in Table 3.

The fractional vegetation cover at the study site, which is estimated as 40% (see

Section 2.1), is significantly higher than the 10% cover fraction specified for "*semi-desert*", *i.e.*, specified for the *BATS* land cover type 11, in the *CCM2*. Vegetation cover fraction was therefore set to a fixed value of 40% in the site-specific parameter set. No direct leaf area index (*LAI*) measurements were made at the site. Nonetheless, it is clear that the standard specification used in the *CCM2*, namely a seasonal variation between leaf area indices of 0.5 and 6.0, is unrealistic. In the absence of actual measurements, but on the advice of an ecologist with local expertise (Weltz, 1995), *LAI* was prescribed to have a fixed value of 1.0 in the site-specific parameter set. In practice, as we will show later, the precise value of *LAI* has little impact on modeled surface energy fluxes.

The fraction of roots in the upper soil layer is also a morphological aspect of semi-arid vegetation which is implausible in the *CCM2* parameter set. In the *CCM2*, it is assumed that 80% of transpiration is extracted from the upper soil layer, despite the fact that this layer is only 10% of the overall rooting depth. Typically, roots are much more evenly distributed in Sonoran Desert vegetation (Weltz, 1995) because they need to acquire water from soil storage at depth. Accordingly, the fractional extraction from the upper soil layer was reduced to 30% which corresponds to the optimized value of the rooting fraction from the sensitivity study (discussed in Section 4.5 below), and a more even distribution of roots throughout the rooting zone (see Figure 10(c) and Table 2). The estimated vegetation height at the field site was 1.2 m (see Section 2.1). In the site-specific parameter set, zero-plane displacement height and roughness length were specified as 75% and 10% of this estimated vegetation height, *i.e.*, $d = 0.9$ m and $z_0 = 0.12$ m, respectively. Again, we will show later that surface fluxes calculated by the *BATS* are in fact not sensitive to the precise value of these two parameters.

Soil albedo measured at the field site for near-surface soil samples is reasonably constant (see Section 2.1). Suitable values of albedo, biased towards the results for the bare soil and vegetated sites which are most representative of average conditions, are 0.20 and 0.10 for dry soil and wet soil, respectively. These values closely correspond with the *BATS* soil color index 3 (Dickinson *et al.*, 1993; Table 3), and were therefore used for the site-specific soil parameters. In practice, color index 2, which is that used in the *CCM2* (see Table 3), is also in good agreement with the measured albedo at the site.

On the basis of the observed soil porosity (see Section 2.1), the *BATS* soil texture class 9 is the most representative of the soil at the field site. This soil class has a significantly higher porosity and clay content and has an order of magnitude lower hydraulic conductivity than a texture class 3 soil, the latter being the class assumed for the "*semi-desert*" land cover of the southwestern USA in the standard *CCM2* parameter set. Thus, soil parameters in the modified *BATS* parameter set were initially chosen as class 9, but some parameters were later modified as explained below.

In early validations runs, the calculated latent heat flux when water was readily available in the soil after rain was low compared with observations, and the rate at which the calculated latent fluxes subsequently declined as soil water availability fell was much too rapid. The non-field specified parameters responsible for controlling the behavior of vegetation are minimum stomatal resistance, r_{smin}, and the two parameters (s_w and B) which control the "wilting" behavior of vegetation cover in response to drying soils. Because these parameters are not amenable to field measurement on a whole-canopy, area-average basis, their preferred values were determined by optimizing the correspondence between modeled and observed surface fluxes. However, in specifying the required optimum values, it was considered realistic and reasonable to place constraints on the numerical values allowed. In the case of s_w and *B*, the selection was restricted only to pairs of values which corresponded to the *BATS* soil texture classes.

The optimum value of r_{smin} so determined was 6 s m^{-1}, which is considerably less than the standard value of 200 s m^{-1} used in the *CCM2*. In practice, the effective value of stomatal resistance calculated and applied by the *BATS* during a model run is always substantially greater than this minimum value due to the assumed effect of stress factors linked to environmental (mainly meteorological) variables. In the semi-arid environment the air is usually hot and dry, which enhances the calculated effect of such environmental stress within the model. It seems that a comparatively low optimum value of minimum stomatal resistance is required to accommodate these strong environmental stress factors in the semi-arid environment, so that the calculated latent heat fluxes can agree with the transpiration rate observed when vegetation has ready access to water in the soil.

Within the *BATS*, the effect of soil drying on the maximum transpiration flux, E_{trmax}, is described by a "*plant wilting factor*", W_{LT}^i, through the equation:

$$E_{trmax} = \gamma_{r0} \sum_i R_{ti}(1 - W_{LT}^i) \qquad (6)$$

where γ_{r0} is the maximum total transpiration that can be sustained, with a summation over contributing soil layers each denoted by *I*, where R_{ti} is the fraction of roots in a given soil layer. W^i_{LT} is zero at saturation and unity at permanent wilting point, and is calculated by:

$$W^i_{LT} = \frac{(s_i)^{-B} - 1}{(s_w)^{-B} - 1} \tag{7}$$

where s_i is the ratio of actual soil water present to that at saturation for the i^{th} soil layer, and s_w is the ratio of soil water for which transpiration essentially ceases to that at saturation in the i^{th} soil layer. *B* is the Clapp and Hornberger (1978) exponent for the specified soil class. In this way, the two parameters s_w and *B* (which are linked) control the onset of plant wilting through the above equations.

In the 12 *BATS* soil-related parameter sets, the values of s_w and *B* are explicitly tied to the values of other soil-related parameters through the assumption that there is a maximum soil water tension (of 15 mbar) against which plants can obtain water. Plant wilting behavior is thus formulated as a soil property, with a fixed relation to other soil properties (such as hydraulic conductivity); and in this way, a set of soil classes is determined by the porosity of the soil. On this basis, the soil at the field site was assigned to be the *BATS* soil texture class 9, as described above.

During the optimization to determine the plant wilting parameters, the other porosity-determined soil parameters such as hydraulic conductivity were held fixed, *i.e.*, they were defined to correspond to those of the *BATS* soil texture class 9 as described above. However, the two parameters controlling wilting behavior (s_w and B) were allowed to take on values corresponding to any of the other allowed *BATS* soil texture classes. The resulting optimum values of these two parameters correspond to soil texture class 4, *i.e.*, a soil class intermediate to that expected on the basis of observed soil porosity, and that (appropriate to a fairly sandy soil) assumed in the *CCM2* parameter set. It is not clear whether the need to redefine these plant wilting parameters is linked to the possibility that semi-arid vegetation has evolved the ability to extract water against higher soil water tensions than other plants or whether it is of more complex reasons, perhaps because a significant proportion of the plants at the site use the Crassulacean Acid Metabolism (*CAM*) mechanism for carbon dioxide assimilation (see Section 5).

4.4 Model Comparisons with Observations

Hourly average latent heat flux observed using the Bowen ratio system for the period between August 26 and September 9, 1993 (day of year 238-252) is compared with that calculated by the *BATS* using the parameters used in the *CCM2* in Figure 8(a) and using site-specific parameters in Figure 8(b). These figures illustrate observed and modeled behavior during a dry-down period after a monsoon rain in late August and are typical of the observed behavior in response to rain throughout the year. The observed latent heat fluxes show an immediate increase after each rain event (on days 238-242), followed by a steady decline during the dry-down (on days 243-252). The site-specific set of parameters captures this behavior very accurately (see Figure 8(b)), while the parameter set used in the *CCM2* results in an over-rapid decline of latent heat flux after the rainy period and also does not capture the daily latent heat cycle, except for days where peak values exceed 200 W m^{-2}.

The modeled surface energy balance is significantly improved over that calculated with the parameter set used in the *CCM2*, which is a general result. Figure 9 shows the correlations between modeled and observed hourly average latent and sensible heat fluxes over the entire period for which Bowen ratio data are available (August 10, 1993 to March 26, 1994) and, in the case of the site-specific parameters, also shows a comparison of fluxes with measurements made with the eddy covariance system for the period between July 19 and August 9, 1993. The correlation coefficients relevant to each comparison shown in Figure 9 are higher when the site-specific parameters are used; except for Bowen ratio sensible heat fluxes where the correlation coefficients are essentially the same when the *CCM2* or the modified parameter set is used (see Figures 9(b) and (d)).

In comparison with the Bowen ratio observations, the latent heat flux is generally underestimated relative to measurements when the *CCM2* parameters are used (see Figure 9(a)), but there is no significant bias with the site specific parameters (see Figure 9(c)). In the case of sensible heat flux shown in Figures 9(b) and 9(d), using the *CCM2* parameters tends to overestimate large fluxes, while the site-specific parameters do not. As we observed in Section 3.2, fluxes measured with the eddy covariance system are arguably more reliable than those made with the Bowen ratio system especially when latent heat is low. Figures 9(e) and 9(f) show that calculated sensible and latent fluxes made with site-specific parameters compare well with measurements from the eddy covariance system within experimental error. In the case of observations made with the Bowen ratio system, the root mean square errors between modeled and observed sensible heat fluxes are 42 W m^{-2} and 39 W m^{-2} for the *CCM2* and site-specific parameter sets, respectively; while the equivalent root mean square errors for the latent heat fluxes are 39 W m^{-2} and 24 W m^{-2}. For the eddy covariance data and the site-specific parameters, the root mean square errors between the modeled and observed sensible and latent heat fluxes are 50 W m^{-2} and 16 W m^{-2}, respectively.

4.5 Sensitivity Checks on Modified Parameters

Because the values of several parameters were redefined in part from on-site measurements and in part by optimization in the site-specific data set, it is valuable to investigate the sensitivity of modeled latent heat fluxes to these parameters.

The *BATS* parameters modified in response to on-site observations were fractional vegetation cover, leaf area index, the proportion of roots in the upper soil layer, zero-plane displacement, and roughness length. Figures 10(a) to 10(f) sequentially show the variation in the root mean square error and the correlation coefficient between measured and modeled latent heat fluxes calculated over the complete observational data set for a range of parameter values. In each case, the full circle shown in each of these figures is the preferred value of the parameter assigned through this study. In all cases, the root mean square error and correlation coefficient are close to their optimum with the field-specified parameter value and, in the cases of leaf area index, zero-plane displacement, roughness length, and *BATS* soil texture class (wilting parameters fixed to correspond to soil texture class 4) show limited parameter sensitivity.

Minimum stomatal resistance, r_{smin}, and the two parameters (s_w and B) which control the behavior of vegetation cover response to drying soils merit particular attention, since they were selected not on the basis of field knowledge, but rather by parameter optimization based on the observed surface fluxes. Figures 11(a) and 11(b) show the variation in the root mean square error and the correlation coefficient between measured and modeled latent heat fluxes calculated over the complete observational data set in these two cases. They demonstrate that the preferred selections are indeed the values with minimum root mean square error and maximum correlation, but also show that selecting a values of r_{smin} in the range 4 to 10 s m^{-1} and values of s_w and B for soil classes 2 to 6 do not have a major impact on the quality of fit.

4.6 Seasonal Water Balance

Table 4 shows the components of the annual water balance calculated from the *BATS* run using the *CCM2* and site-specific parameter sets for the year from 12 May 1993. With the *CCM2* parameters, *BATS* calculates an unreasonably large drainage to groundwater (31 mm); with the site-specific parameters, drainage to groundwater is zero, and the runoff ratio is around 5%, which is known to be a plausible value for local runoff in this region.

Table 5 gives the monthly budgets of water balance components. With site-specific parameters, the *BATS* is able to enhance evaporation following precipitation, and capture the observed gradual decline during subsequent dry-down. This was associated with a lower root-zone soil moisture content and zero baseflow throughout the year. Although the annual total surface runoff for both *CCM2* and site-specific parameters is essentially the same (Table 4), the monthly patterns are different, with more surface runoff during the summer monsoon season and less runoff resulting from winter and spring storms for the run with site-specific parameters. In summary, the modified parameters promote the efficiency of soil water use by plants and soil evaporation, and retard the gravitational drainage out of the model soil column.

5. Discussion and Conclusions

This study, in common with other studies of surface energy balance in the southwestern USA (*e.g.*, Kustas *et al.*, 1989; Kustas *et al.*, 1991; Nichols, 1992), confirms the fact that the energy available for return to the atmosphere largely leaves in the form of sensible heat. When viewed at both the daily and seasonal time scales, the magnitude of any latent heat flux is related strongly to the current or recent occurrence of precipitation and is less dependent on atmospheric demand. Precipitation is the most important forcing mechanism in semi-arid environments; it controls both evaporation and carbon exchange and therefore it is essential to accurately measure and characterize the distributed precipitation field to assure an accurate water balance and provide a realistic model simulation of the surface exchanges. Fulfilling this need is complicated by the large spatial variability of precipitation associated with convective storms, which are the primary mechanisms responsible for generating precipitation in semi-arid regions.

The measurements of carbon dioxide uptake made in this study are exploratory. The restricted period for which data are available correspond to a growth phase in the semi-arid vegetation, and the data do indeed show a net assimilation of carbon as expected, albeit with uptake rates much less than those commonly observed during the growth cycle of other crops in temperate regions. Arguably, the most interesting feature of these data is that they indicate that carbon dioxide uptake continues (at a reduced rate) through the night, something rarely if ever reported in other field studies. Usually a daily cycle is observed which involves uptake during the day and release at night, as in the case of the FIFE study (Verma *et al.*, 1989).

The C3 and C4 plants found at the FIFE site use a carbon dioxide assimilation mechanism which involves CO_2 entering the leaf through the open stomata during the day, with the CO_2 first converted to dicarbonic acid (malate) inside the vacuoles, followed by rapid decarboxylation of the acid to carbohydrates in the chloroplasts through photosynthesis. Though a substantial proportion of the vegetation cover present in the Sonoran Desert (and at the field site) are C3 and C4 plants, a significant percentage of the desert vegetation consists of succulents, *i.e.*, cacti (family *cactaceae*), agaves (*agavaceae*), and members of the *euphorbiaceae* family. The photosynthetic mechanism employed by these plants, the Crassulacean Acid Metabolism (*CAM*), is a two-step process (Larcher, 1994). Succulent plants open their stomata only at nighttime and assimilate CO_2 by first fixing it in the form of dicarbonic acid in the vacuoles, with the concentrations of this acid increasing throughout the night. The stomata are then closed at the onset of daylight to retard transpiration and desiccation of the plant, while the conversion of the stored acids to carbohydrates proceeds by photosynthesis. In the special case of "deciduous" plants such as the ocotillo (*fouquieria splendens*), this process of is further complicated, because this plant employs normal C3 pathway of CO_2 fixation. However, when the soil moisture drops, the leaves of the ocotillo are shed to reduce transpiration losses to a minimum, but the plant continues photosynthesis via the stems near the leaf axles. If a sufficient fraction of the plants at the study site are of the succulent type, it is entirely plausible that there should be a net uptake of carbon dioxide sustained throughout the night during a period of growth in desert vegetation.

Micrometeorological measurements are feasible in the semi-arid conditions of this study, but it proved difficult to achieve consistent reliability and accuracy under exacting field conditions which involve extremely high temperatures and low relative humidity. The sigma-T measurements were of little use in this study, because they were of marginal and unpredictable accuracy and are, in any case, only valid for unstable atmospheric conditions – which excludes their use between dusk and dawn and during and immediately after rain. After some substantial initial problems, it was ultimately proven easier to obtain a reasonably reliable record of surface energy fluxes using the Bowen ratio method rather than the eddy covariance method, primarily because using the Bowen ratio method required much less time for data analysis, less computational resources, and substantially less in-field maintenance and calibration. Nonetheless, we believe measurements made with the eddy covariance system are likely to have greater accuracy and are therefore preferable when greater accuracy is required over short measurement periods.

Using the set of vegetation and soil related parameters used in the *CCM2*, the *BATS* model was unable to capture the observed rapid increase in the outgoing latent heat in response to precipitation and the gradual falloff during subsequent dry-down. Using these parameters gave a poor description of daily, day-to-day, and seasonal behavior of the surface energy balance. In contrast, an excellent description was achieved using a modified, site-specific set of parameters which was based on a few simple observations and some optimization of key vegetation-related parameters. This modified set of parameters more realistically reflected the fact that there is a sparse but fairly constant vegetation cover of around 40% at the study site and that the soil contains a significant amount of clay. Further, these parameters suggest that the vegetation responds quickly when it receives water, with a substantial and rapid increase in photosynthesis and transpiration. Ultimately the soil dries and the plants reach a wilting point which, in the *BATS* model, is assumed to be determined by soil porosity. In practice the desert plants then seem able to sustain transpiration by accessing water from soil in the root zone longer than might be expected on the basis of the soil's high porosity alone. The uniqueness of the photosynthetic processes employed by many desert plants and the effectiveness of the transpiration process revealed by this exploratory study argue for further measurement and modeling studies in this unusual and interesting environment.

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Table 1. Meteorological conditions at the study site for the typical dry and wet days shown in Fig. 6(a), 6(b) and Fig. 7(b), 7(c)

Meteorological Variables	Typical Dry Day (July 22, 1993)	Typical Wet Day (August 7 , 1993)
Min. Air Temperature (°C)	24.9	19.5
Max. Air Temperature (°C)	34.9	33.0
Min. Soil Temperature (°C)	29.2	25.1
Max. Soil Temperature (°C)	45.1	40.3
Min. Relative Humidity (%)	16.4	35.9
Max. Relative Humidity (%)	44.5	84.1
Min. Wind Speed (m s^{-1})	0.20	0.75
Max. Wind Speed (m s^{-1})	4.5	9.9
Total Daily Precipitation (mm)	0.0	17.5

Table 2. The *BATS* vegetation-related parameters as used in the National Center for Atmospheric Research Community Climate Model version 2 (*CCM2*) for "*semi-desert*" (*BATS* land cover class type 11) and the modified site-specific parameters which produced improved model description of the observed data

Parameter Name	Standard *CCM2* Parameters	Improved, Site-Specific Parameters
Maximum fractional vegetation cover	0.1	0.4
Seasonality factor (*i.e.* difference between maximum fractional vegetation cover and fractional cover at a temperature of 269 K)	0.1	0.0
Roughness length (m)	0.1	0.12
Zero-plane displacement height (m)	0.0	0.9
Minimum stomatal resistance (s m^{-1})	200.0	6.0
Maximum leaf area index	6.0	1.0
Minimum leaf area index	0.5	1.0
Stem and dead matter area index	2.0	2.0
Inverse square root of leaf dimension ($m^{-1/2}$)	5.0	5.0
Light sensitivity factor (m^2 W^{-1})	0.02	0.02
Vegetation albedo for $\lambda < 0.7$ µm	0.17	0.17
Vegetation albedo for $\lambda >= 0.7$ µm	0.34	0.34
Depth of upper soil layer (m)	0.1	0.1
Depth of rooting zone soil layer (m)	1.0	1.0
Depth of total soil layer (m)	3.0	3.0
Fraction of water extracted by upper layer roots (saturated)	0.8	0.3

Table 3. The *BATS* soil-related parameters as used in the National Center for Atmospheric Research Community Climate Model version 2 (*CCM2*) for the "*semi-desert*" areas of southwest USA (*BATS* soil texture class 3) and the modified site-specific parameters which produced an improved model description of the observed data

Soil Parameter	**Standard *CCM2* Parameters (soil texture class 3)**	**Soil Texture Class 9**	**Modified Tucson Parameters (modified from soil texture class 9)**
Porosity (volume of voids to volume of soil)	0.39	0.57	0.57
Minimum soil suction (mm)	30.0	200.0	200.0
Saturated hydraulic conductivity (mm s^{-1})	0.032	0.0022	0.0022
Moisture content relative to saturation at which transpiration ceases	0.151	0.455	0.266
Exponent "B" defined in Clapp & Hornberger (1978)	4.5	8.4	5.0
Ratio of saturated thermal conductivity to that of loam	1.3	0.85	0.85
Soil color index	2	3	3

Table 4. Components of the annual water balance and net radiation for the year from 12 May 1993, as calculated with the *BATS* using measured weather variables. Two model parameter sets are used:
(1) the National Center for Atmospheric Research Community Climate Model version 2 (*CCM2*) parameters for the "*semi-desert*" areas of the southwestern USA, and
(2) a set of modified site-specific parameters which produced an improved model description of the observed data

Component	***BATS* Model Using Standard *CCM2* Parameters**	***BATS* Model Using Modified Tucson Parameters**
Net Radiation (mm)	1181	1180
Precipitation (mm)	275	275
Evaporation (mm)	230	262
Surface Runoff (mm)	14	14
Baseflow (mm)	31	0

Table 5. Monthly water balance and root-zone soil moisture content (*RSW*) as calculated with the *BATS* using measured weather variables. Values shown are for the set of modified site-specific parameters; values in parentheses are for *CCM2* parameters for the "*semi-desert*" areas of the southwestern USA.

Month	Precipi-tation (mm/month)	Evapo-transpiration (mm/month)	Surface Runoff (mm/month)	Baseflow (mm/month)	Monthly Mean *RSW* (mm)
Jan.	0.3	11.6 (6.5)	0.0 (0.0)	0.0 (2.6)	137.7 (162.9)
Feb.	35.7	18.8 (19.4)	1.2 (2.2)	0.0 (2.8)	149.9 (172.7)
March	30.6	28.6 (26.3)	1.1 (0.9)	0.0 (3.1)	150.8 (171.1)
April	3.2	21.8 (11.4)	0.0 (0.0)	0.0 (2.5)	138.0 (163.0)
May	14.9	14.9 (16.5)	0.1 (0.2)	0.0 (2.4)	101.8 (125.2)
June	0.1	1.2 (8.9)	0.0 (0.0)	0.0 (2.0)	129.8 (158.1)
July	14.7	14.3 (16.9)	0.1 (0.2)	0.0 (1.9)	133.4 (159.3)
Aug.	100.9	36.4 (46.7)	8.2 (6.9)	0.0 (2.3)	148.3 (170.0)
Sept.	15.0	51.7 (27.8)	1.1 (0.5)	0.0 (3.1)	164.5 (178.6)
Oct.	16.0	25.0 (17.6)	0.3 (0.3)	0.0 (2.9)	146.3 (169.0)
Nov.	35.9	20.9 (20.7)	1.3 (2.4)	0.0 (3.0)	149.5 (171.9)
Dec.	8.1	16.4 (11.5)	0.2 (0.1)	0.0 (3.0)	147.9 (168.3)

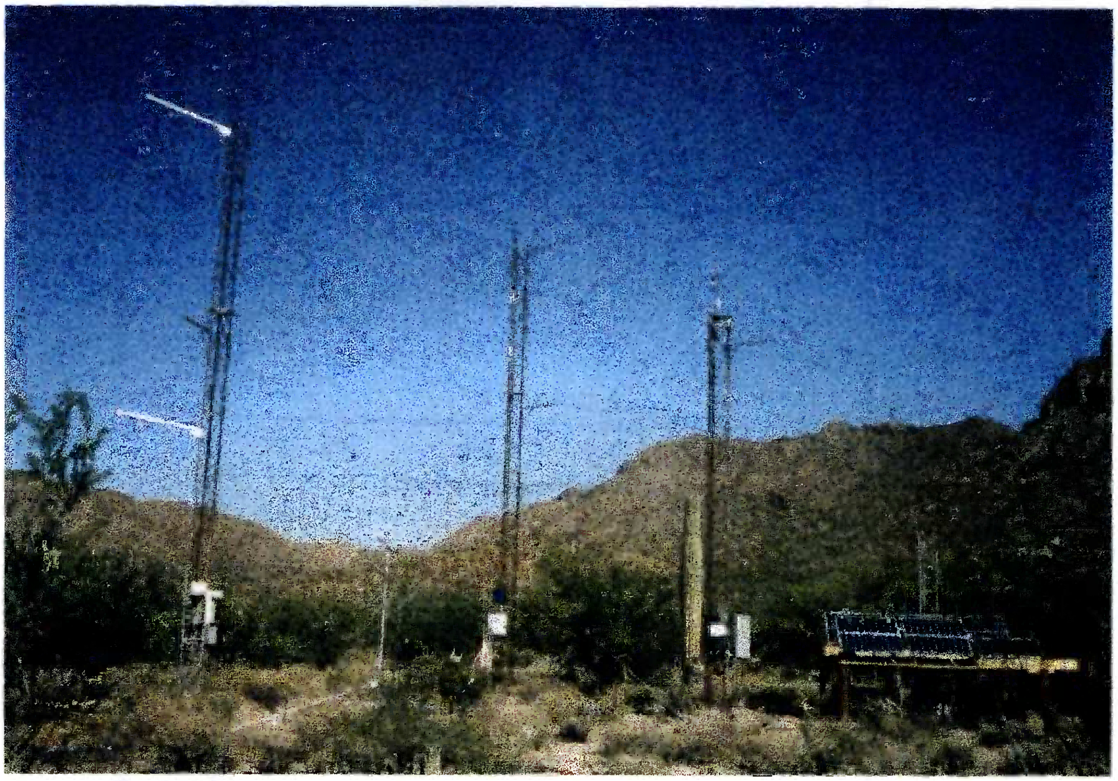

Figure 1. Micrometeorological instruments at the field site west of Tucson, Arizona, viewed from the direction of the prevailing winds and longest fetch towards the Tucson mountains, which are approximately 1 km distance towards the northeast. The Bowen ratio system is shown mounted on the tower on the left, the automatic weather station and sigma-T systems are mounted on the center tower, and the eddy covariance sensors are mounted on top of the tower on the right. The remainder of the eddy covariance system, including the photovoltaic array used to provide power, are mounted on the ground to the right.

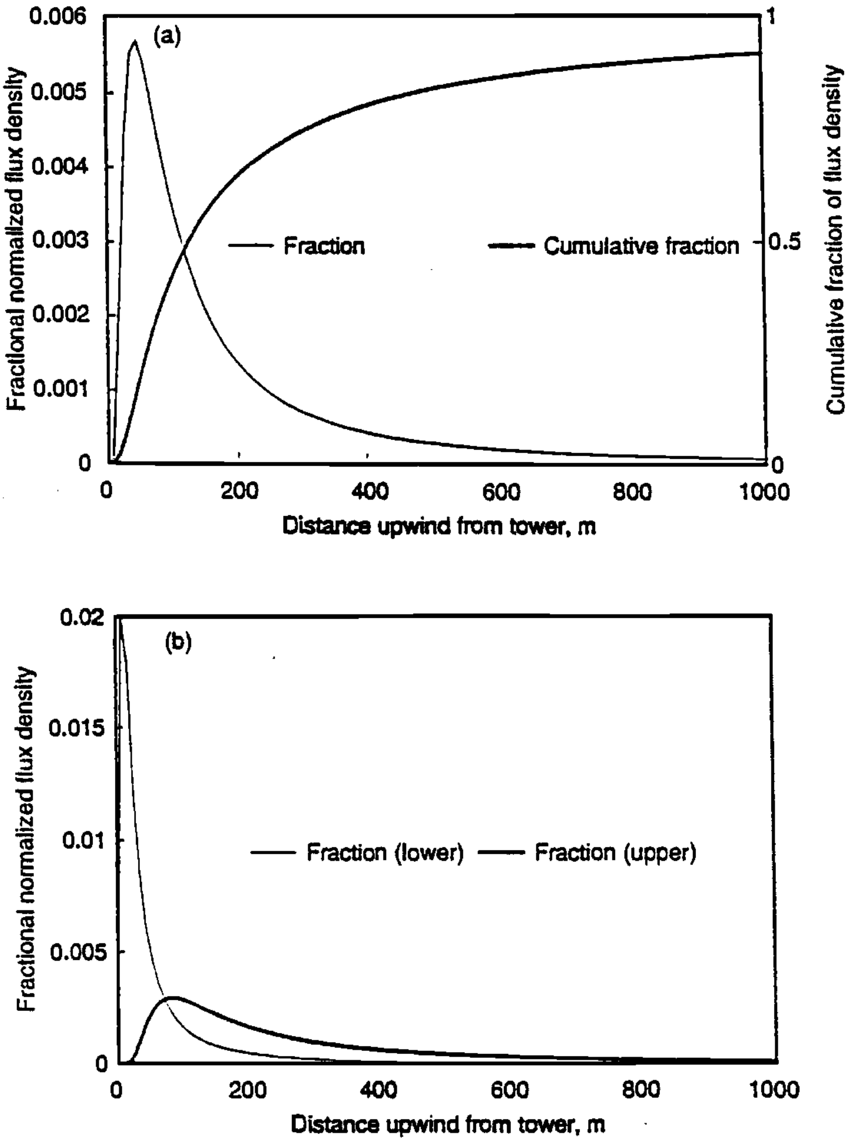

Figure 2. (a) The calculated fractional flux density versus distance upwind of the field site for eddy covariance observations made at 6.4 m based on the method of Schuepp *et al.*, (1990). The calculations assume a zero plane displacement of 0.9 m and a roughness length of 0.12 m and are made for a wind speed of 3.5 m s^{-1}, a friction velocity of 0.38 (m $s^{-1})^2$ and a sensible heat flux of 300 W m^{-2}. (b) The calculated fractional flux density versus distance upwind of the field site for Bowen ratio observations made at 3 m and 10 m.

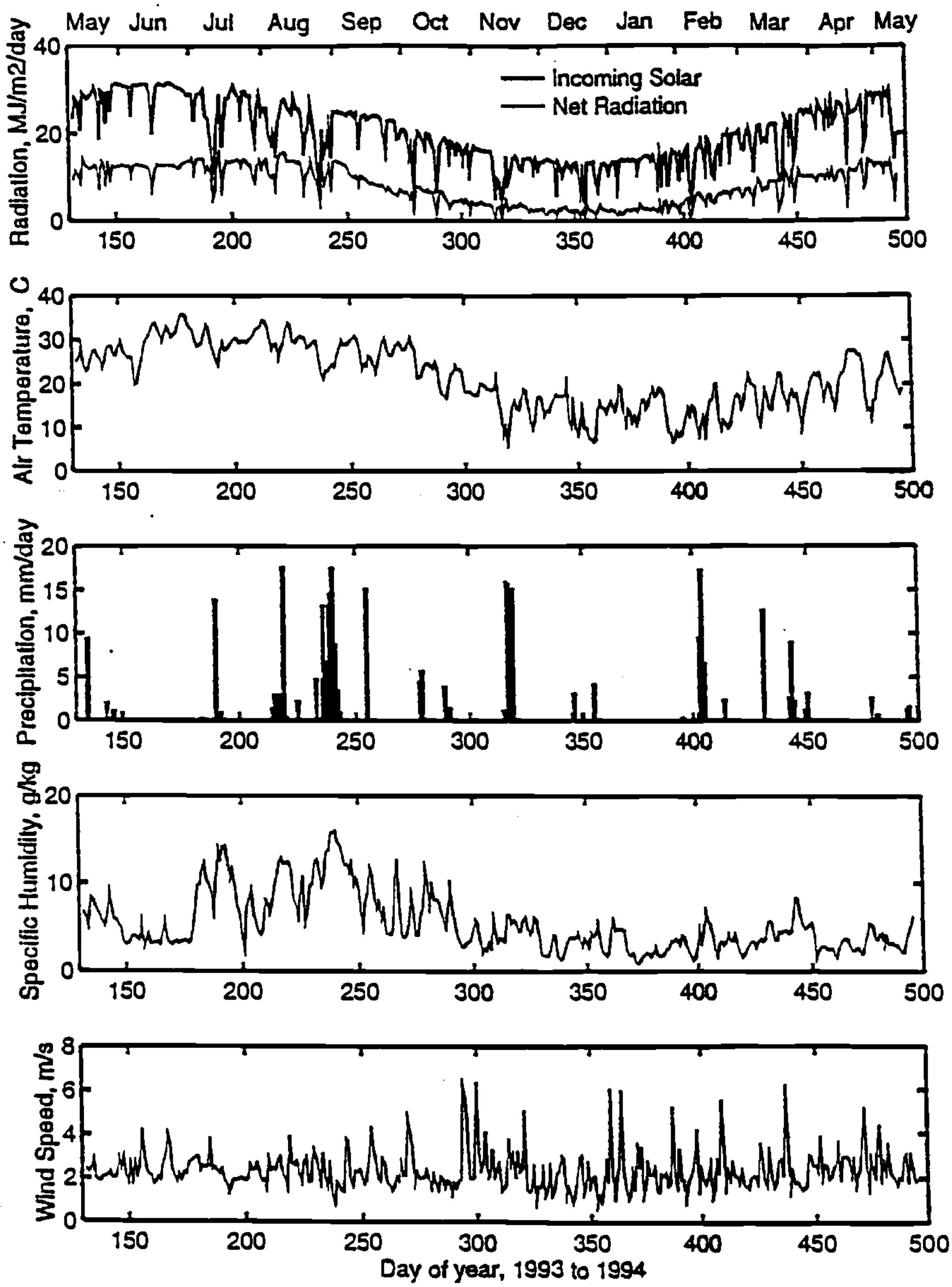

Figure 3. Daily total values of precipitation, solar and net radiation, and daily (24-hour linear average) values of air temperature, specific humidity and wind speed measured at the field site for the year from 12 May 1993.

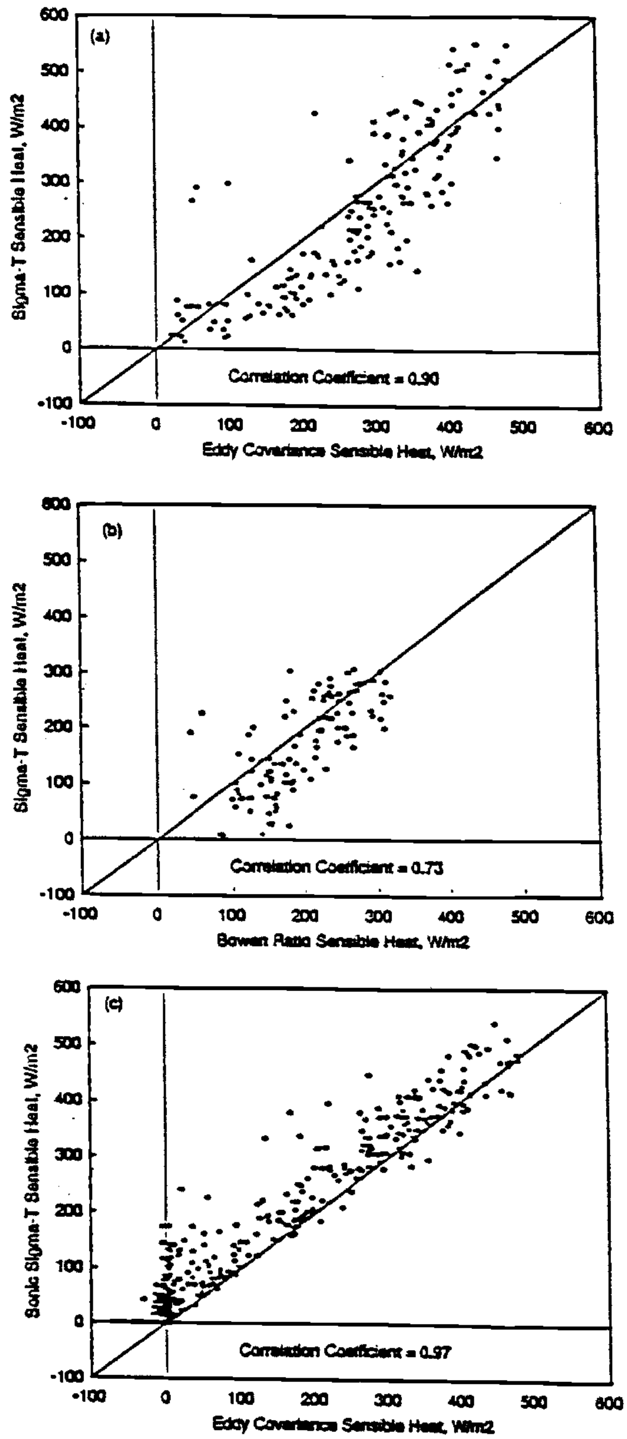

Figure 4. Measured flux comparisons of sensible heat given by the sigma-T method and those from (a) the eddy covariance system, and (b) the Bowen ratio method. (c) Measured flux comparisons of sensible heat given by the eddy covariance and sigma-T based on sonic temperature.

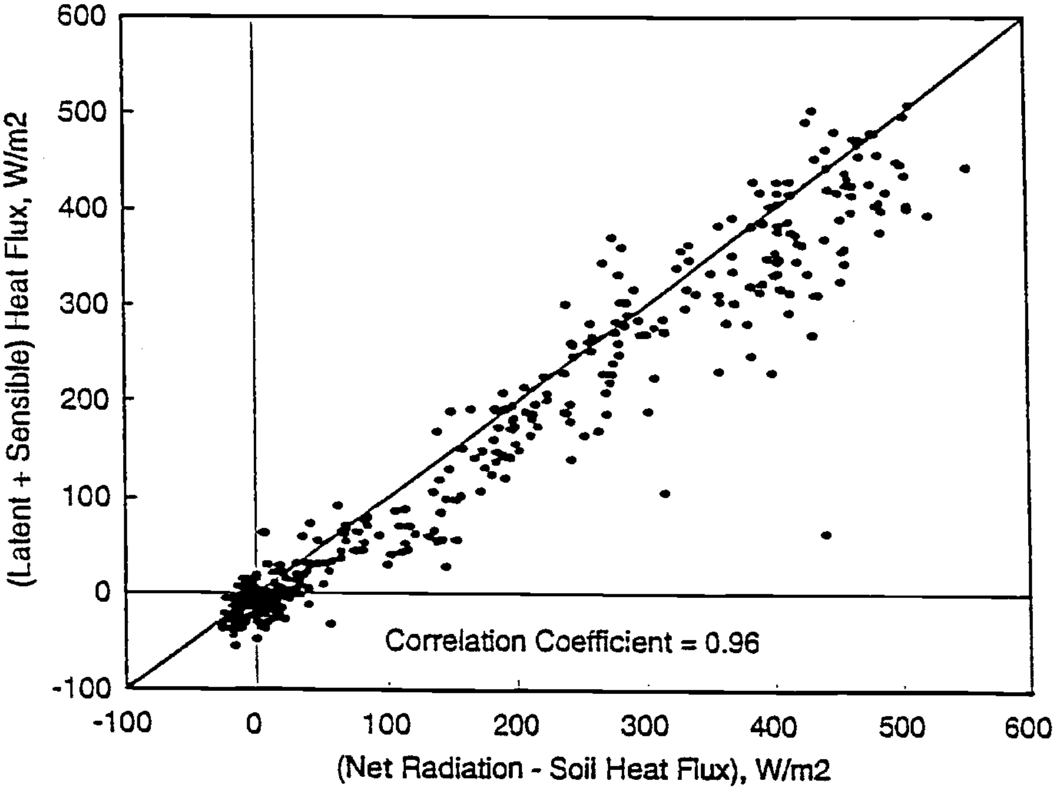

Figure 5. Comparison between the hourly average sum of the sensible and latent heat fluxes measured with the eddy covariance system and the measured net radiation minus the soil heat flux for equivalent hours.

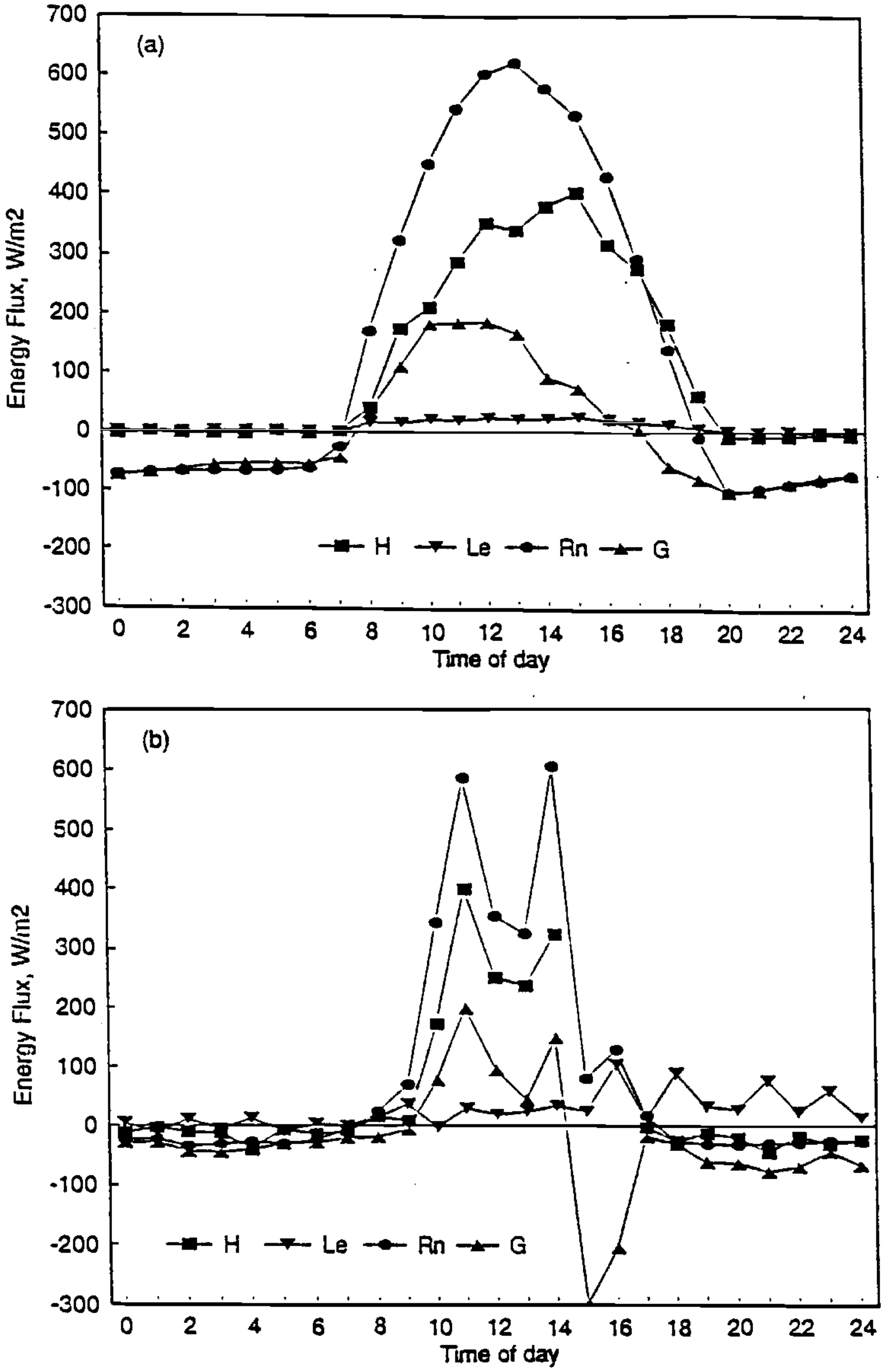

Figure 6. The diurnal pattern of surface energy fluxes measured by the eddy covariance system (a) for a typical dry day with clear skies (July 22, 1993), and (b) for a day with substantially more cloud and a late afternoon rain storm (August 7, 1993). In each diagram the sensible heat flux is labeled *H*, the latent heat flux *Le*, the net radiation flux *Rn*, and the soil heat flux *G*. For reference, the daily solar maximum occurs at about 12:30 pm local time.

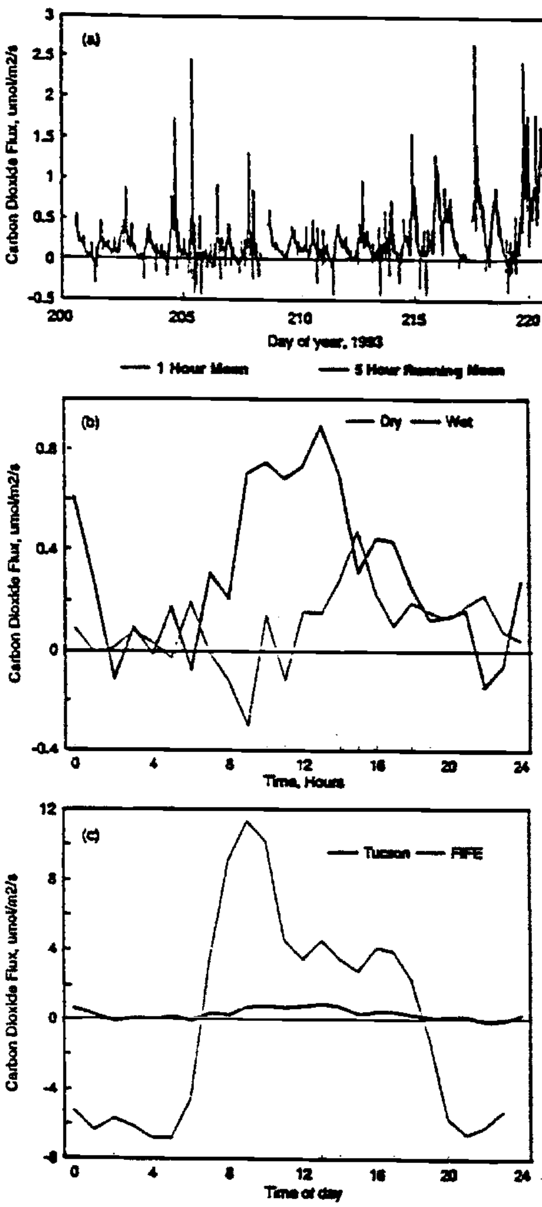

Figure 7. (a) One hour mean and 5-hour running mean of the storage-corrected carbon dioxide flux measured with the eddy covariance system for the period between July 19 and August 9, 1993, (b) the diurnal carbon dioxide flux at the experimental site on a typical dry day (July 22, 1993) and on a typical wet day (August 7, 1993), and (c) the diurnal carbon dioxide flux at the experimental site on this typical wet day in comparison with that measured during the First ISLSCP Field Experiment (*FIFE*, August 10, 1987; Kim and Verma, 1990). Notice that the measured fluxes for the Sonoran Desert are lower than those measured at the FIFE site and, at this time of year are generally downward, even at night.

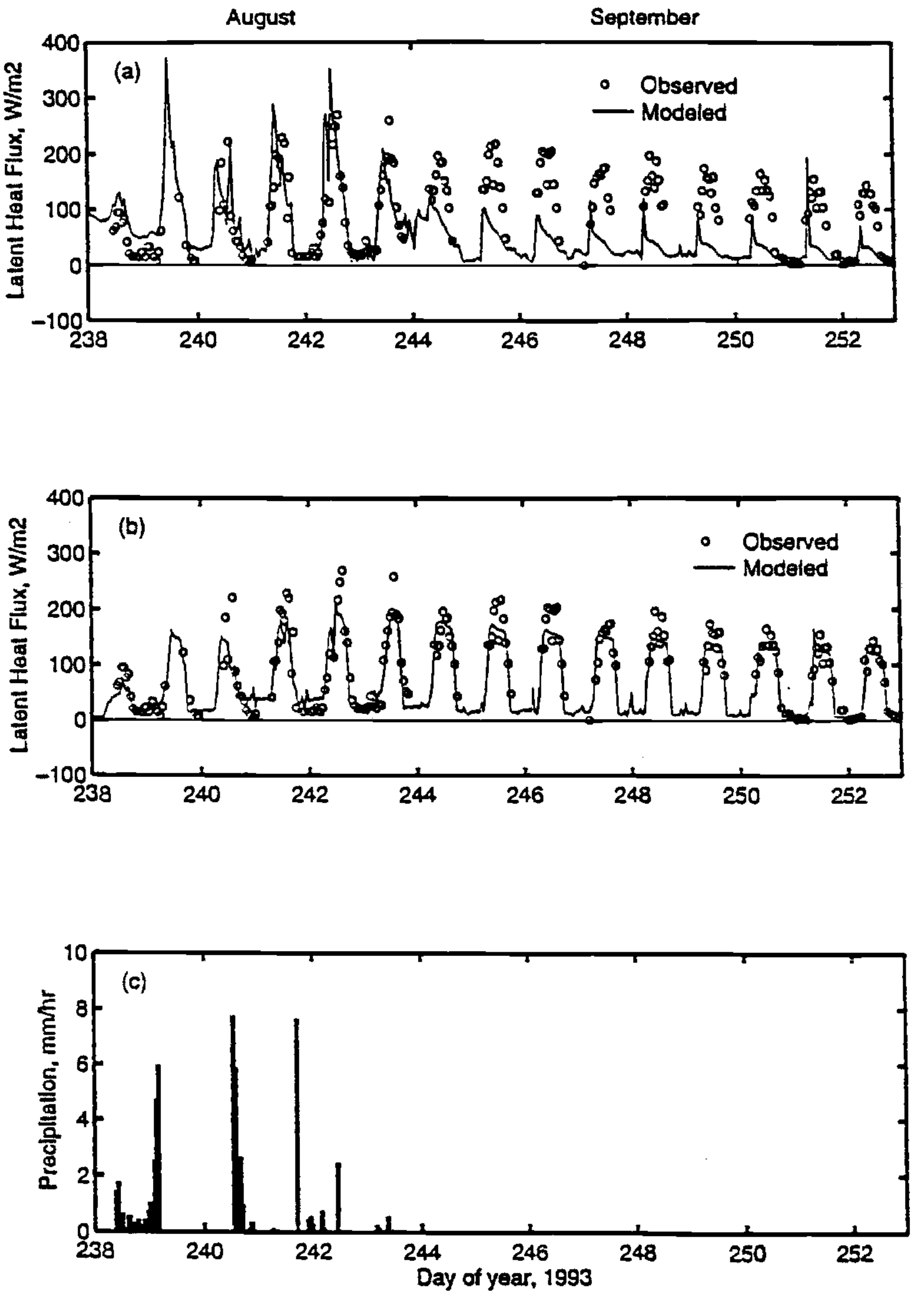

Figure 8. Hourly average latent heat flux observed using the Bowen ratio system for the period between August 26 and September 9, 1993 is compared (a) with that calculated by the *BATS* using the parameters used in the *CCM2*, and (b) using site-specific parameters. Panel (c) shows the observed hourly precipitation.

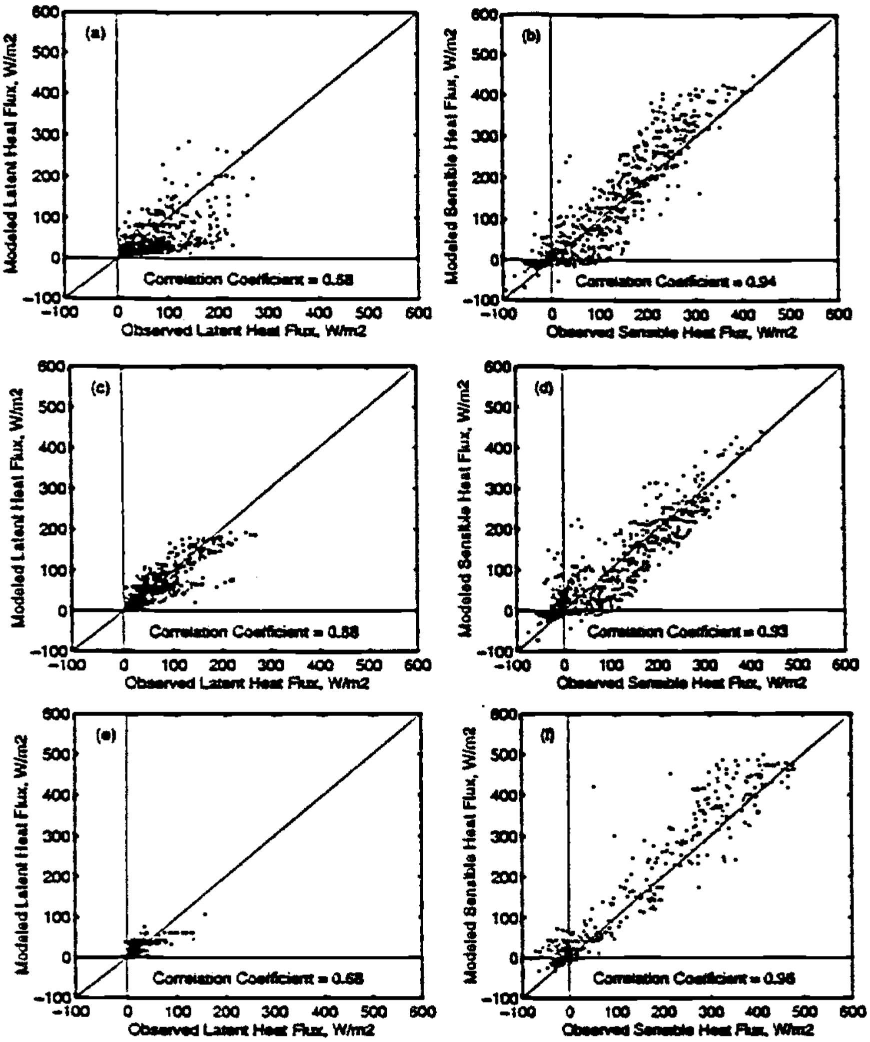

Figure 9. Correlations between modeled and hourly average observations of latent and sensible heat flux. Figures (a) and (c) show latent heat flux, and Figures (b) and (d) show sensible heat flux measured with the Bowen ratio system. Figure (e) shows latent heat flux, and Figure (f) shows sensible heat flux measured with the eddy covariance system. The modeled fluxes in Figures (a) and (b) are calculated using the parameter set used in the *CCM2*, while those in the remaining figures are made using the site-specific parameters defined in this study. The eddy covariance data were collected between July 19 and August 9, 1993, while the Bowen ratio data were collected between August 10, 1993 and March 26, 1994.

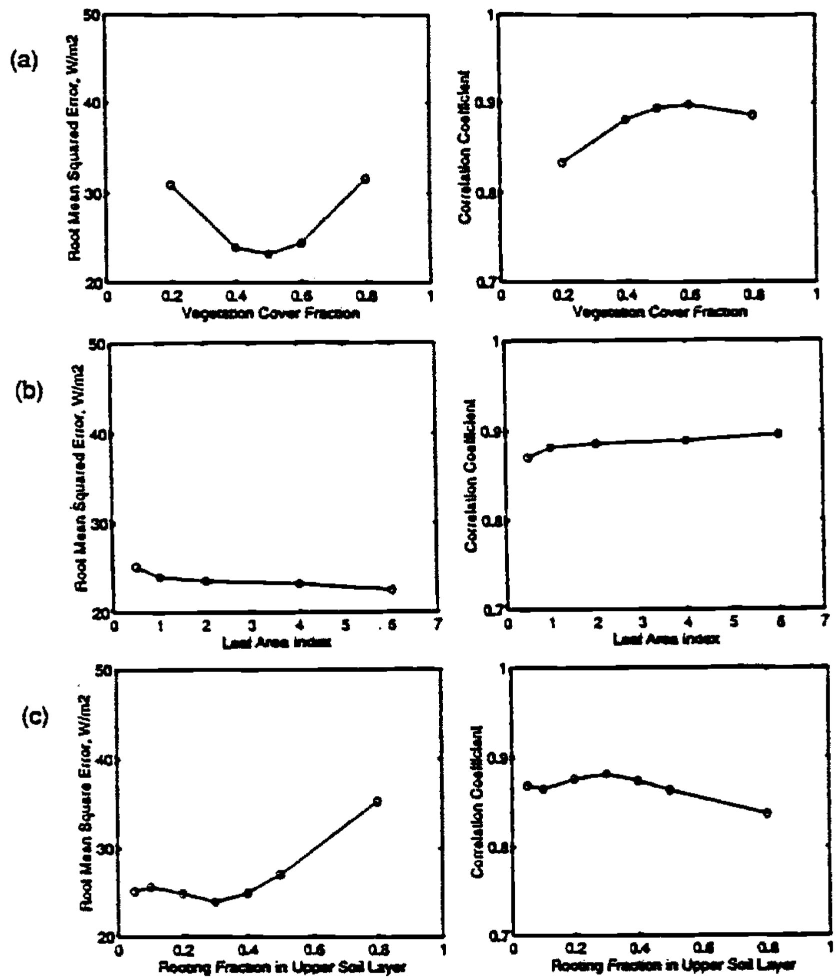

Figure 10. Variation in the root mean square error (in W m^{-2}) and the correlation coefficient between measured and modeled latent heat fluxes calculated over the complete (Bowen ratio) data set for a range of values of (a) fractional vegetation cover, (b) leaf area index, (c) the proportion of roots in the upper soil layer, (d) zero-plane displacement, (e) roughness length, and (f) *BATS* soil texture class for other than plant wilting parameters (wilting parameters are fixed to correspond to soil texture class 4). In each case, the full circle shown in each of these figures is the preferred value of the parameter.

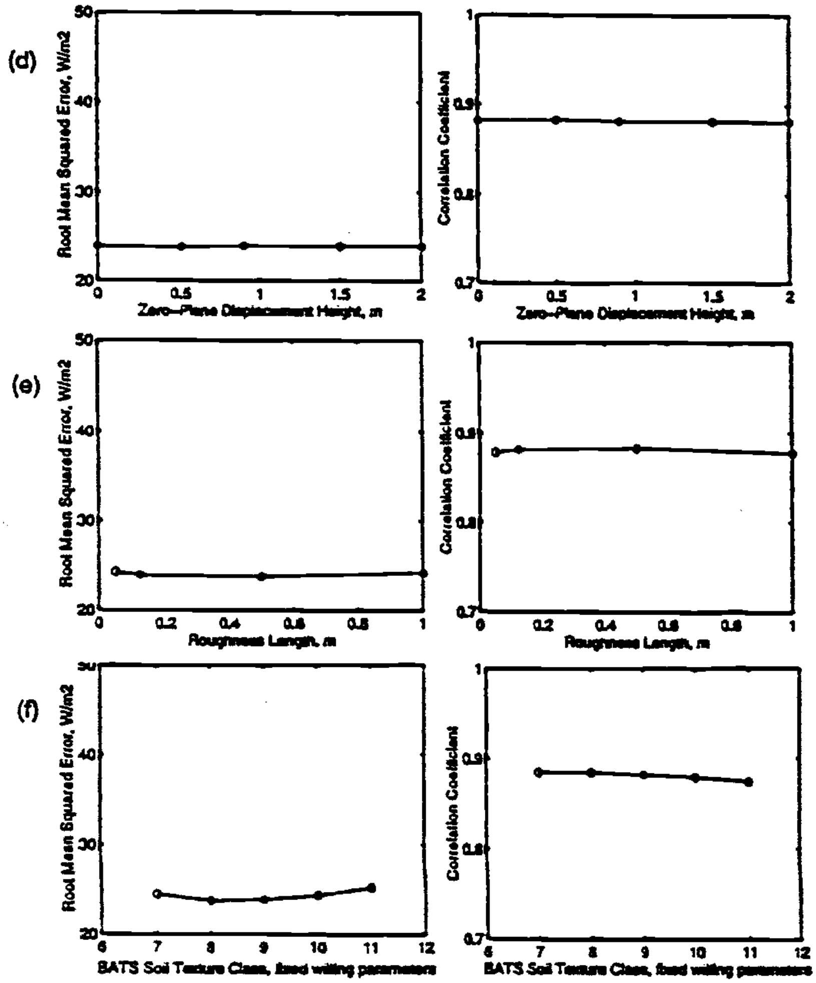

Figure 10 (continued).

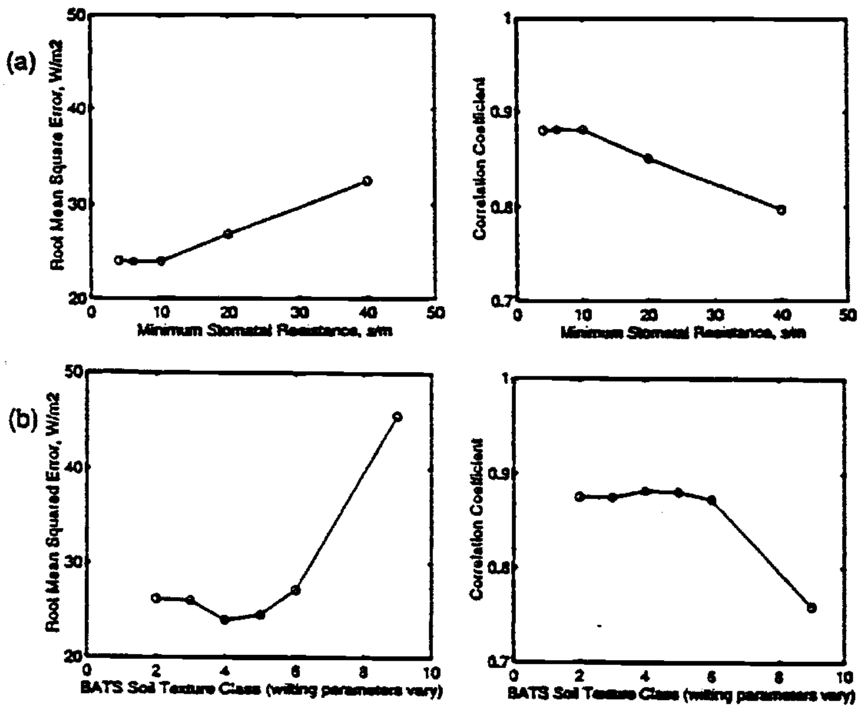

Figure 11. Variation in the root mean square error and the correlation coefficient between measured and modeled latent heat fluxes calculated over the complete observational data set for a range of values of (a) minimum stomatal resistance, and (b) the *BATS* soil texture class for plant wilting parameters (soil parameters not associated with wilting are fixed to correspond to soil texture class 9).

APPENDIX B: TUCSON MOUNTAIN FIELD SITE MANUAL

ADC Micrometeorological Site Methods and Procedures

Revision:
May 6, 1996

Presented By:
Helene Unland and Paul Houser

A Note on This Document: This is a document in evolution, so please forward any comments, additions, or improvements to the authors for inclusion.

Department of
Hydrology and Water Resources

The University of Arizona

INTRODUCTION:

This document describes micrometeorological instrumentation and methods that developed from field experiences at the Arthropod Discovery Center between January 1993 and March 1996. This manual is intended to be used by site personnel as a reference for proper maintenance of instrumentation, data handling, etc. It is acknowledged that this manual is not perfect, and will need to be revised as improved procedures are developed, as new hardware is utilized, and as new sites are established.

A site checklist was made to accompany this document, that will help maintain accuracy and consistency in record keeping, and site maintenance performed by various people. All activities performed at the site should also be recorded in the site note book in permanent ink, and should be recorded with the date and recorder's name. It has been found that dedicated use of this checklist and notebook are extremely valuable in interpreting the data at later times.

DATA HANDLING PROCEDURES

NOTE: The automatic weather station, Bowen ratio and sigma-T data handling may be done in series as described here, or done in parallel, as there are many common elements for each respective procedure list.

AUTOMATIC WEATHER STATION DATA (Weekly)

Required Field Equipment: Laptop Computer and 3.5" Data Transfer Disk or Campbell Storage Module.

Introduction: The automatic weather station is located on the northernmost tower, and comprises various instruments (wind speed, wind direction, temperature, humidity, net radiation, soil heat flux, etc.). These measurements are read and recorded using a Campbell CR10 datalogger linked to a Campbell SM716 storage module that contains a backup datalogger program (that reloads after a power loss), and a backup of the weather station data.

As it is set up now the sensors running into the datalogger on the Automatic Weather Station Tower are the following:

R.M. Young Wind Sentry: SN with multipliers and offsets from the manual.
Vaisala Relative Humidity and Temperature Probe: SN
Li-Cor Pyranometer: 17145 with a calibration of 99.8 which leads to a multiplier of 0.1002 by the formula $m=1/(C*0.1)$.
Soil Heat Flux Plates: #1 931009 in the open, calibration 42.7, #2 931011 under a bush, calibration 37.1.
TCAV, Averaging Thermocouple: SN
Net Radiometer: 92275 calibration 12.9
Tipping Bucket Rain Gauge: with a multiplier of 0.1 to get mm.

Objective: The objective here is to transfer the automatic weather station data from the datalogger to a subdirectory on the Hydrology Department's SUN computer network. This can be accomplished in two ways at the present time: 1) Using a MS-DOS laptop computer in the field, download data directly from the datalogger, and then transfer that data to the SUN. 2) Using the SM716 storage module (currently attached to the automatic weather station), transfer the data from the datalogger, then using a MS-DOS computer at the university, transfer the data off the storage module. Lastly, transfer the data from the MS-DOS computer to the SUN.

Method 1: Using the MS-DOS laptop computer to transfer data

1) Open the automatic weather station box (using the common key), and locate the automatic weather station CR10 datalogger, which is closer to the top of the box than the sigma-T 21X datalogger. Locate the serial extension cord that links the CR10 datalogger to the storage module (a long metallic box). A 9-pin serial connector is located at the middle of this serial cord, which is used to communicate with the computer. The serial cord is kept in the first black box under the solar array. A key to this box is kept in the Bowen Ratio Box.

2) Prepare the laptop computer by opening the screen, and turning it on (it may need to be shielded from the direct sun). Locate the OISI (Optically Isolated Serial Interface - a small metal box with a serial connection at both ends). Plug the printer/computer side of the OISI into the laptop's serial port (located on the left side of the computer all the way to the back). Then plug the other end of the OISI "to datalogger" to the location specified in part 1. NOTE: this procedure will not work without using the OISI.

3) Switch directories on the laptop by typing "cd logger" at the "C" prompt. Next, type "gt aws" to start a program called graphterm. A menu should appear on the right side of the screen; choose "U" to collect uncollected data. The computer will switch screens and display some downloading information. When this is done select "Q" to quit.

4) The graphterm program has created a data file on the C:\logger directory called "aws.dat" that contains all of the automatic weather station data that was just collected. Copy this file to a file with the following format: aMMDDYY.dat, where DD is the day, MM is the month, and YY is the year (i.e. "a091093.dat") . Do this by issuing the command "copy aws.dat aMMDDYY.dat".

5) Put a 3.5" data transfer disk into the laptop floppy disk drive, and copy this new file to it using the command "copy aMMDDYY.dat a:". Remove the 3.5" disk, and turn off the laptop.

6) To transfer these data to the appropriate subdirectory on the Hydrology department's SUN system, log on to a SUN computer workstation and insert the data disk into the SUN's 3.5" disk drive. Issue the command "mcopy -t a:aMMDDYY.dat /home/monteith/data/micromet/aws/dataYY" where YY is the current year (*e.g.* data93 for data from 1993) to copy the aws data to the SUN. If you forgot the name of the file, type "mdir" to get a directory listing of your transfer disk. When data transfer is completed, type "eject" to recover the 3.5" data disk. (one could also use a modem kermit transfer, telnet, ftp, etc. to accomplish this from a remote site).

Method 2: Using the SM716 storage module to transfer data

1) Open the automatic weather station box (using the common key), and locate the automatic weather station CR10 datalogger, which is closer to the top of the box than the sigma-T 21X datalogger. Locate the serial extension cord that links the CR10 datalogger to the SM716 storage module (a long metallic box).

2) The automatic weather station is constantly updating the storage module with its data,

so simply unplug the storage module from the CR10, and bring it back to the university.
3) Prepare the MS-DOS computer by turning it on (we suggest you use the field laptop, as it has all of the necessary hardware and software). Locate the PPRI (9 Pin Peripheral to RS232 Interface - a small metal box with a serial connection at both ends). Plug the RS232 side of the PPRI into the PC's serial or RS232 port. Then plug the other end of the PPRI "Peripheral" to the SM716 storage module. NOTE: this procedure will not work without using the PPRI. Plug the PPRI power supply into an electrical outlet. This procedure will not work without supplying AC power to the PPRI.
4) Switch directories on the PC by typing "cd pc208" at the "C" prompt. Next, type "smcom" to start the storage module communications program. Smcom will prompt you for the com-port to use (choose COM1 if you are using the laptop). The program then will attempt to communicate with the storage module. If this fails, an error message will appear and you should then restart smcom and try a different com-port and make sure the power supply of the PPRI is plugged in. The program will give you the option to download all the data on the storage module. Choose this option to ensure all new data will be transferred. Smcom then prompts you for a name to give the downloaded file, you should name it "aMMDD" where MM and DD are the current month and day, respectively. Smcom then prompts you for the file delineation type - choose "comma-delineated". Downloading will proceed and the program will return you to the C:\pc208 prompt automatically.
5) The smcom program has created a data file on the C:\pc208 directory called "aMMDD001.dat" that contains all of the automatic weather station data which were just collected. Copy this file to a file with the following format: aMMDDYY.dat, where DD is the day, MM is the month, and YY is the year (i.e. "a091093.dat") . Do this by issuing the command "copy aMMDD001.dat aMMDDYY.dat". For detailed instructions on how to use smcom, consult the PC208 reference manual.
6) Put a 3.5" data transfer disk into the PC's floppy disk drive, and copy this new file to it using the command "copy aMMDDYY.dat a:". Remove the 3.5" disk, and turn off the PC.
7) To transfer this data to its appropriate subdirectory on the Hydrology department's SUN system, log on to a SUN computer workstation and insert the data disk into the SUN's 3.5" disk drive. Issue the command "mcopy -t a:aMMDDYY.dat /home/monteith/data/micromet/aws/dataYY" where YY is the current year, to copy the aws data to the SUN. Type "eject" to recover the 3.5" data disk. (one could also use a modem kermit transfer, telnet, ftp, etc. to accomplish this from a remote site).

BOWEN RATIO DATA (Weekly)

Required Field Equipment: Laptop Computer or Campbell Storage Module.

Introduction: The Bowen ratio system is located on the southwest tower, and comprises various instruments (Bowen ratio, net radiation, soil heat flux, etc.). These measurements are read and recorded using a Campbell 21X datalogger.

Objective: The objective here is to transfer the Bowen ratio station data from the datalogger to a subdirectory on the Hydrology Department's SUN computer network. This can be accomplished in two ways at the present time: 1) Using a MS-DOS laptop computer in the field, download data directly from the datalogger, and then transfer that data to the SUN. 2) Using the SM716 storage module (currently attached to the automatic weather station), transfer the data to the datalogger, then using a MS-DOS computer at the university, transfer the data off the storage module. Lastly, transfer the data from the MS-DOS computer to the SUN.

Method 1: Using the MS-DOS laptop computer to transfer data
1) Open the Bowen ratio station box (using the common key), and locate the Bowen Ratio station 21X datalogger, which is the only datalogger in this box. Locate the 9-pin serial connector which is located on the front (top) of the 21X datalogger; this is used to communicate with the computer.
2) Prepare the laptop computer by opening the screen, and turning it on (it may need to be shielded from the direct sun). Locate the OISI (Optically Isolated Serial Interface - a small metal box with a serial connection at both ends). The OISI is kept in the first black box under the solar array. A key to this box is kept in the Bowen Ratio Box. Plug the printer/computer side of the OISI into the laptop's serial port (located on the left side of the computer all the way to the back). Then plug the other end of the OISI "to datalogger" to the location specified in part 1. NOTE: this procedure will not work without using the OISI.
3) Switch directories on the laptop by typing "cd logger" at the "C" prompt. Next, type "gt bowen" to start a program called graphterm. A menu should appear on the right side of the screen; choose "U" to collect uncollected data. The computer will switch screens and display some downloading information. When this is done select "Q" to quit.
4) The graphterm program has created a data file on the C:\logger directory called "bowen.dat" that contains all of the bowen ratio data that was just collected. Copy this file to a file with the following format: bMMDDYY.dat, where DD is the day, MM is the month, and YY is the year (i.e. "b091093.dat") . Do this by issuing the command "copy bowen.dat bMMDDYY.dat".
5) Put a 3.5" data transfer disk into the laptop floppy disk drive, and copy this new file to it using the command "copy bMMDDYY.dat a:". Remove the 3.5" disk, and turn off the laptop.
6) To transfer this data to its appropriate subdirectory on the Hydrology department's SUN system, log on to a SUN computer workstation and insert the data disk into the SUN's 3.5" disk drive. Issue the command "mcopy -t a:bMMDDYY.dat /home/monteith/data/micromet/bowen/dataYY" where YY is the current year (*e.g.* data93

for the year 1993) to copy the Bowen ratio data to the SUN. Type "eject" to recover the 3.5" data disk. (one could also use a modem kermit transfer, telnet, ftp, etc. to accomplish this from a remote site).

Method 2: Using the SM716 storage module to transfer data
1) Open the Bowen ratio station box (using the common key), and locate the Bowen ratio station 21X datalogger, which is the only datalogger in this box. Locate the 9-pin serial connector on the front (top) of the 21X datalogger; this is used to communicate with the SM716 storage module. Connect one of the free plugs on the serial connector to the SM176 storage module.
2) Unlike the automatic weather station, the Bowen ratio system is not constantly updating the storage module with its data, so the following procedures must be followed to transfer data to the SM716 storage module: (NOTE: the following commands are typed on the 21X datalogger keypad)

> *9 (shows 09:00)
> enter 31 A (display reads: 01:nnnnnn starting location of data transfer)
> enter 1 A (if data transfer is from the beginning)
>   next it shows: 02:nnnnnn the final position of data
> enter A
>   next it shows: 03:00, ready for data transfer
> enter 1 (or any number to start data transfer)
>   wait until 09: remains on the screen

Next, disconnect the storage module, and bring it back to the university.
3) Prepare the MS-DOS computer by turning it on (we suggest you use the field laptop, as it has all of the necessary hardware and software). Locate the PPRI (9 Pin Peripheral to RS232 Interface - a small metal box with a serial connection at both ends). Plug the RS232 side of the PPRI into the PC's serial or RS232 port. Then plug the other end of the PPRI "Peripheral" to the SM716 storage module. NOTE: this procedure will not work without using the PPRI. Plug the power supply of the PPRI into an AC power outlet. This procedure will not work without supplying AC power to the PPRI.
4) Switch directories on the PC by typing "cd pc208" at the "C" prompt. Next, type "smcom" to start the storage module communications program. Smcom will prompt you for the com-port to use (choose COM1 if you are using the laptop). The program then will attempt to communicate with the storage module. If this fails, an error message will appear and you should then restart smcom and try a different com-port and make sure the power supply of the PPRI is plugged in. The program will give you the option to download all the data on the storage module. Choose this option to ensure all new data will be transferred. Smcom then prompts you for a name to give the downloaded file, you should name it "bMMDD" where MM and DD are the current month and day,

respectively. Smcom then prompts you for the file delineation type - choose "comma-delineated". Downloading will proceed and the program will return you to the C;\pc208 prompt automatically.
5) The smcom program has created a data file on the C:\pc208 directory called "bMMDD001.dat" that contains all of the Bowen ratio data which were just collected. Copy this file to a file with the following format: bMMDDYY.dat, where DD is the day, MM is the month, and YY is the year (i.e. "b091093.dat") . Do this by issuing the command "copy bMMDD001.dat bMMDDYY.dat". For detailed instructions on how to use smcom, consult the PC208 reference manual.
6) Put a 3.5" data transfer disk into the PC's floppy disk drive, and copy this new file to it using the command "copy bMMDDYY.dat a:". Remove the 3.5" disk, and turn off the PC.
7) To transfer this data to its appropriate subdirectory on the Hydrology department's SUN system, log on to a SUN computer workstation and insert the data disk into the SUN's 3.5" disk drive. Issue the command "mcopy -t a:bMMDDYY.dat /home/monteith/data/micromet/bowen/dataYY" where YY is the current year, to copy the Bowen data to the SUN. Type "eject" to recover the 3.5" data disk. (one could also use a modem kermit transfer, telnet, ftp, etc. to accomplish this from a remote site).

SIGMA-T DATA (Weekly)

Required Field Equipment: Laptop Computer and 3.5" data transfer disk or Campbell Storage Module.

Introduction: The sigma-T system is located on the northern tower with the automatic weather station, and only has three components (thermocouples that measures temperature very quickly). These measurements are read and recorded using a Campbell 21X datalogger.

Objective: The objective here is to transfer the sigma-T station data from the datalogger to a subdirectory on the Hydrology Department's SUN computer network. This can be accomplished in two ways at the present time: 1) Using a MS-DOS laptop computer in the field, download data directly from the datalogger, and then transfer that data to the SUN. 2) Using the SM716 storage module (currently attached to the automatic weather station), transfer the data to the datalogger, then using a MS-DOS computer at the university, transfer the data off the storage module. Lastly, transfer the data from the MS-DOS computer to the SUN.

Method 1: Using the MS-DOS laptop computer to transfer data
1) Open the weather station box (using the common key), and locate the sigma-T 21X

datalogger. Locate the 9-pin serial connector located on the front (top) of the 21X datalogger; this is used to communicate with the computer.
2) Prepare the laptop computer by opening the screen, and turning it on (it may need to be shielded from the direct sun). Locate the OISI (Optically Isolated Serial Interface - a small metal box with a serial connection at both ends). The OISI is kept in the first black box under the solar array. A key to this box is kept in the Bowen Ratio Box. Plug the printer/computer side of the OISI into the laptop's serial port (located on the left side of the computer all the way to the back). Then plug the other end of the OISI "to datalogger" to the location specified in part 1. NOTE: this procedure will not work without using the OISI.
3) Switch directories on the laptop by typing "cd logger" at the "C" prompt. Next, type "gt sigmat" to start a program called graphterm. A menu should appear on the right side of the screen; choose "U" to collect uncollected data. The computer will switch screens and display some downloading information. When this is done select "Q" to quit.
4) The graphterm program has created a data file on the C:\logger directory called "sigmat.dat" that contains all of the sigma-T data that was just collected. Copy this file to a file with the following format: swMMDDYY.dat, where DD is the day, MM is the month, and YY is the year (i.e. "sw091093.dat") . Do this by issuing the command "copy sigmat.dat swMMDDYY.dat".
5) Put a 3.5" data transfer disk into the laptop floppy disk drive, and copy this new file to it using the command "copy swMMDDYY.dat a:".
6) Repeat steps 1 to 5 above for the datalogger located in the small box on the EC tower. Proceed with downloading sigma-T data as before, only naming the new file "seMMDDYY.dat", i.e. use the commands "copy sigmat.dat seMMDDYY.dat" and "copy seMMDDYY.dat a:". Then remove the 3.5" disk, and turn off the PC.
7) To transfer these data to the appropriate subdirectory on the Hydrology department's SUN system, log on to a SUN computer workstation and insert the data disk into the SUN's 3.5" disk drive. Issue the commands "mcopy -t a:swMMDDYY.dat /home/monteith/data/micromet/sigmat" and "mcopy -t a:seMMDDYY.dat /home/monteith/data/micromet/sigmat" to copy the sigma-T data to the SUN. Type "eject" to recover the 3.5" data disk. (one could also use a modem kermit transfer, telnet, ftp, etc. to accomplish this from a remote site).

Method 2: Using the SM716 storage module to transfer data
1) Open the sigma-T station box (using the common key), and locate the sigma-T station 21X datalogger, which is below the automatic weather station CR10 datalogger. Locate the 9-pin serial connector on the front (top) of the 21X datalogger; this is used to communicate with the SM716 storage module.
2) Unlike the automatic weather station, the sigma-T system is not constantly updating the storage module with its data, so the following procedures must be followed to transfer data to the SM716 storage module: (NOTE: the following commands are typed on the

21X datalogger keypad)

*9 (shows 09:00)
enter 31 A (display reads: 01:nnnnnn starting location of data transfer)
enter 1 A (if data transfer is from the beginning)
next it shows: 02:nnnnnn the final position of data
enter A
next it shows: 03:00, ready for data transfer
enter 1 (or any number to start data transfer)
wait until 09: remains on the screen

Next, disconnect the storage module, and bring it back to the university.
3) Prepare the MS-DOS computer by turning it on (we suggest you use the field laptop, as it has all of the necessary hardware and software). Locate the PPRI (9 Pin Peripheral to RS232 Interface - a small metal box with a serial connection at both ends). Plug the RS232 side of the PPRI into the PC's serial or RS232 port. Then plug the other end of the PPRI "Peripheral" to the SM716 storage module. NOTE: this procedure will not work without using the PPRI. Plug the power supply of the PPRI into an AC power outlet. This procedure will not work without supplying AC power to the PPRI.
4) Switch directories on the PC by typing "cd pc208" at the "C" prompt. Next, type "smcom" to start the storage module communications program. Smcom will prompt you for the com-port to use (choose COM1 if you are using the laptop). The program then will attempt to communicate with the storage module. If this fails, an error message will appear and you should then restart smcom and try a different com-port and make sure the power supply of the PPRI is plugged in. The program will give you the option to download all the data on the storage module. Choose this option to ensure all new data will be transferred. Smcom then prompts you for a name to give the downloaded file, you should name it "swMMDD" where sw is for data from the sigma-T system on the AWS tower, and MM and DD are the current month and day, respectively. Smcom then prompts you for the file delineation type - choose "comma-delineated". Downloading will proceed and the program will return you to the C:\pc208 prompt automatically.
5) The smcom program has created a data file on the C:\pc208 directory called "swMMDD01.dat" which contains all of the sigma-T data just collected. Copy these files to a file with the following format: swMMDDYY.dat, where DD is the day, MM is the month, and YY is the year (i.e. "sw091093.dat") . Do this by issuing the command "copy swMMDD001.dat swMMDDYY.dat". For detailed instructions on how to use smcom, consult the PC208 reference manual.
6) Put a 3.5" data transfer disk into the PC's floppy disk drive, and copy these new files to it using the commands "copy swMMDDYY.dat a:".
7) Repeat steps 1 to 6 above for the datalogger located in the small box on the EC tower. Proceed with downloading sigma-T data as before, only naming the new file

"seMMDDYY.dat", i.e. use the commands "copy sigmat.dat seMMDDYY.dat" and "copy seMMDDYY.dat a:". Then remove the 3.5" disk, and turn off the PC.

8) To transfer these data to the appropriate subdirectory on the Hydrology department's SUN system, log on to a SUN computer workstation and insert the data disk into the SUN's 3.5" disk drive. Issue the commands "mcopy -t a:swMMDDYY.dat /home/monteith/data/sigmat" and mcopy -t a:seMMDDYY.dat /home/monteith/data/sigmat" to copy the sigma-T data to the SUN. Type "eject" to recover the 3.5" data disk. (one could also use a modem kermit transfer, telnet, ftp, etc. to accomplish this from a remote site).

SUMMARY OF PROCEDURES FOR DOWNLOADING AWS, BOWEN AND SIGMA-T DATA FROM TRANSFER DISK TO SUN-STATION (Weekly)

To copy the weather station, Bowen ratio and sigma-T files off the data transfer disk to the proper subdirectories on SUN-station "monteith", proceed as follows:

1) Log into your account, put the 3.5" data transfer disk into disk-drive a: on the SUN station, then change directories to the "micromet" subdirectory:

cd /home/monteith/data/micromet

2) Check contents of data disk in a: drive and write down the names of the files you want to transfer:

mdir

3a) To copy AWS files into subdirectory /home/monteith/data/micromet/aws/dataYY where YY is the current year, issue the following command - you need to repeat this for every file starting with "a" if there is more than one to copy:

mcopy -t a:aMMDDYY.dat aws/dataYY

where MMDDYY are month, day and year in the file name; i.e. for aws file of 1/16/94:

mcopy -t a:a011694.dat aws/data94

3b) Remember to issue one of these commands for EVERY aws file you want to copy off the disk, and that this will only work if you are issuing commands from the subdirectory "/home/monteith/data/micromet".

4a) To copy BOWEN files, proceed as in 3) above, only using files starting with "b" , and put them in subdirectory "/home/monteith/data/micromet/bowen/dataYY" where YY is the current year:

mcopy -t a:bMMDDYY.dat bowen/dataYY

4b) Remember to issue one of these commands for EVERY bowen file you want to copy off the disk, and that this will only work if you are issuing commands from the subdirectory "/home/monteith/data/micromet".

5a) To copy SIGMA-T files, proceed as in 3) above, only using files starting with "se" and "sw", and put them in subdirectory "/home/monteith/data/micromet/sigmat":

mcopy -t a:seMMDDYY.dat sigmat		for files starting with "se"

mcopy -t a:swMMDDYY.dat sigmat for files starting with "sw"

5b) Again, you need to issue one of theses commands for each and EVERY sigmat file you want to transfer off the disk, and still you need to be in directory "/home/monteith/data/micromet" for this to work properly.

6) A slightly different procedure of data transfer is described in this manual on page 3 for aws, page 5 for Bowen ratio, and page 7 for sigmat data, each time under the heading "Method 1: Using the MS-DOS laptop computer to transfer data". But be careful, as in those sections of the manual the assumption is made that you are issuing commands from your home directory, making it necessary to include the entire path to the subdirectory you want
(eg. /home/monteith/data/micromet/bowen/data94) in the mcopy command. I recommend first changing to the micromet subdirectory to save typing this long path every time you issue a mcopy command.

7) When you have finished copying make sure the files are actually in their proper directories by typing

    ls aws/data94
    ls bowen/data94
and
    ls sigmat

while you are still in the directory "/home/monteith/data/micromet" (Note: examples are for data from the year 1994).

8) When data transfer is completed, type

eject

to recover the 3.5" data transfer disk, then log off the system.

EDDY CORRELATION DATA (Weekly)

Required Field Equipment: Two 3M Trakker Tapes, one 3.5" disk

Introduction: The eddy correlation system, which comprises a Gateway laptop computer linked to a Sonic Anemometer and a Gas Analyzer, collects a great deal of data which requires special data handling capabilities. The system stores approximately 20 megabytes, or about 15 high density disks full of data per day. The laptop computer only has enough hard disk storage space to store 7 days of data, so the data must be downloaded at 7 day or less intervals!

Objective: The objective of this procedure is to transfer large quantities of data (about 170 megabytes) from the SASI field site to the University, and once it is there, store it in a safe location. This will be done by using 2 tape backup systems. The first is a Trakker 250 megabyte tape drive system manufactured by Colorado Tape Drive Systems that utilizes the parallel printer port for data transfer. The second tape system is an 8mm video, 2 gigabyte tape drive that is networked with the Hydrology SUN system.

Data Transfer from the Site to the University using the Trakker Tape Drive.

1) General information: There are two ColoradoTrakker tape drives in use by this section. One is located in the Eddy Correlation (EC) box at the SASI site, and the other is attached to the Gateway-PC in room 232F. The program used to operate this drive system is in subdirectories on these two systems: c:\trakker\tape.exe.

2) Tape archiving: The tapes to be used in these drives are located in the uppermost drawer of the file cabinet in the outer office of room 232 (they are the smaller, 3M tapes). When you are going out to the field, take the two tapes that are in the front, and a data transfer disk from the back of the stack. You will only use one, but if there is a tape error, it is nice to have a second tape to use. Then, you will perform the backup in the field using the lower numbered tape. Write the date (in pencil) of the backup under the title of the tape you put data on. When you return to the University and complete all of the archiving procedures, place any unused tapes back in front, and used tapes in the back of the tape stack in the file drawer in room 232. This way, we will have additional data safety by only erasing the oldest data.

3) At the SASI site, assuming all goes well, you will find the laptop computer that operates the eddy correlation system on the top shelf of the Eddy Correlation box installed on the sonic anemometer tower. It should be running the eddy correlation program "EDDYSOL". This program will need to be turned off by typing "CTRL-C ALT-X".

4) Now insert the Trakker 3M tape into the tape drive located to the right of the laptop on the top shelf.

5) Switch directories on the laptop as follows: "cd\trakker". Then start the Trakker program by typing "tape".

6) The tape will need to be erased so that new data can be stored on it. Type "ALT-U" for Utilities then select "ALT-Q" for quick erase. Answer the next several questions so that the tape is erased. This procedure should only take a minute or so.
7) At the main menu of the Trakker program select "backup". The program will ask you what kind of backup you want to perform; select "selective backup". Next it will ask you to for a specific subdirectory; respond with "c:\anem", which is where all of the eddy correlation data is stored. The next screen will display a directory, and will request that you mark the files you wish to backup. Select the wildcard-tag using "ALT-W", then type "s*.*" to select all of the eddy correlation data files. Proceed through the program to perform the backup, and be sure to choose the backup option "OPTIMIZE TIME". Name the back-up "sMMDDYY", where DD stands for the day, MM stands for the month and YY stands for the year (i.e. s091093").
8) When the backup has completed, exit the Trakker program, remove the tape and switch off the toggle switch labeled "tape" on the door of the EC-box. Bring the tape back to the University.
9) Now copy the flux and correlation files in the C:\anem directory to your data transfer disk: insert disk in laptop disk drive, then type "copy *.flx a:", and "copy *.cor a:". Make sure the files are actually on the disk by listing the directory: "dir a:".
10) To make room for the next week of data, all of the previous week's data files must be deleted from the laptop hard drive. Type "cd\anem" to change to the proper directory, then type "del s*.*" to delete all the data files. Check that they have been deleted by typing "dir" to get a directory.
11) The next procedure will copy the files to the SUN scratch disk. At the University, load the tape in the Trakker drive of the Gateway computer in room 232F. Open a dos-prompt window. At the "C:\" prompt, type "link2". The computer will then ask you for a user ID, and a password (for the SUN system). Next, the Trakker program will be automatically loaded. Choose "restore" from the main menu, and restore the tape to drive "R". This will be copying the files from the tape to a scratch disk directory on the SUN system called: "/usr/local/scratch/houser/anem/". Being a scratch disk, files are erased every 10 days, so make sure you do the following steps soon after this one.

Data Transfer from the SUN Scratch Disk to the 8mm Video Backup Tapes.

1) Locate a 8mm tape in the room 232 outer office top file drawer. The tapes labeled 3A, 3B, etc. are the tapes to use now. Check each tape to see if the red write-protect tab is in "Erase off" position - if so, slide it sideways to allow writing on the tape. Insert tape A into 8mm tape drive labeled "/dev/nrst1" which is located in the top of the large computer box in James B. Office, room 324J, and tape B into the drive labeled /dev/nrst0 next to the SUN station "cochise" in James B. outer office.
2) Log into the system server, "river" by issuing the command: "rlogin river" from any hydrology SUN workstation.
3) Issue the following commands:

cd /usr/local/scratch/houser/anem
mt -f /dev/nrst1 eom (Fast-forward to end of medium - this will take a while)
mt -f /dev/nrst1 stat (This will provide a tape status, make sure the number of files corresponds with the number written on the tape cover)
tar cvf /dev/nrst1 . (This will back up all of the files in the current directory to tape A)
mt -f /dev/nrst1 stat (There should now be one more file on the tape than before)
mt -f /dev/nrst1 rew (rewind the tape)

Repeat the above commands, after logging into "cochise" ("rlogin cochise") for an identical copy onto tape B, substituting "nrst0" for "nrst1" in the commands above. You may run these two procedures simultaneously from two different windows to save time.

4) The following tape commands may be useful:

REWIND TAPE: "mt -f /dev/nrst1 rew"

FAST-FORWARD TAPE: "mt -f /dev/nrst1 fsf [n]" where [n] is the number of files to fast-forward through - default is 1

FF TO END OF MEDIA: "mt -f /dev/nrst1 eom

TAPE STATUS: "mt -f /dev/nrst1 stat

WRITE FILES: "tar cvf /dev/nrst1 ." the "." may be replaced by a directory name, but it is preferable to simply back up the files in the current dir.

EXTRACT FILES: "tar xvf /dev/nrst1 ." again the "." can be replaced to restore specific portions of the backup

LISTING OF BACKED-UP FILES: "tar tf /dev/nrst1" this provides a directory of the files contained in the backups on the tape

5) Remember these important rules:

a) the tape can contain multiple backups, but you must be sure that you are at the end of the last file on the tape before creating another backup. If you are at the beginning of a tape with backups on it, and then put another backup at the beginning, all the old backups on the tape will be lost. So, be careful!

b) Always rewind and label tapes so that we always know where our data is, and make sure you verify that what you want is on the tape before you erase it from the hard disk.

c) When you are backing up to 8mm tape, and for some reason you have to leave the tape in the drive (say the door is locked), PLEASE make sure to rewind the tape to the beginning. This is a precaution to avoid loosing data which could happen if the tape write head is still stuck at the end of the last file written, and someone tries to eject the tape.

6) Once the tape backup is done, and you are sure all the files made it safely to the 8mm tape, erase the entire contents of the scratch directory by issuing the command "rm /usr/local/scratch/houser/anem/*.*".

7) Next, take the "A" tape out of /dev/nrst1 and the "B" tape out of /dev/nrst0, and switch

the red tab at the top of this tape to "write off", or read only.
8) When this is done, add your "tar #", date of backup, initials, and indicate which range of dates the files just backed up cover, *e.g.* "TAR 1: s2671014 - 2740640 10/4/93 PH" to the card in each tape box, and put them back in the file cabinet drawer.
10) At some point the first, second, etc. tapes will fill completely up. When this happens, please write "tape full" at the end of the card in the tape box, and use the next set of tapes in line.
11) Note: Tape 2B is currently being used to make monthly total backups of the subdirectory "/home/monteith/data/micromet" where eddy correlation, automatic weather station, bowen, and sigma-T data are stored.

EDDY CORRELATION START-UP PROCEDURES:

Introduction: The eddy correlation system is a complex, multi-component system that uses a fast laptop computer as a controller, datalogger, and numerical analyzer. A Pascal program called "EDDYSOL" is the software that controls the whole system.

Objective: Describe the procedures for starting and running the eddy correlation system and "Eddysol". We will start form the assumption that the entire system is off.

Procedures for Turning on the System:
1) There are 5 switches that must be turned on to power up the eddy correlation system, they are:

a) The main power switch on EC-box door must be on.
b) The switch labeled "sonic" on EC-box door must be toggled off and back on every time EDDYSOL is restarted to reset the sonic anemometer.
c) The switch labeled "pumps" on EC-box door controlling the pumps that duct air to the gas analyzer must be on.
d) The Li-cor 6262 gas analyzer and laptop computer also have switches that must be independently switched on.

2) At the "C" prompt on the laptop computer switch to the "anem" directory, by typing "cd\anem", then type "eddysol" to start the program.
3) Type "ALT-L" and select "SOLENT" to start logging. Three screens will follow, asking various specifics for the operation. The only changes needed are to the second page, where the flux averaging time should be set to 10 minutes, and raw data should be saved at 20 minute intervals. Choose the default settings on pages 1 and 3 by hitting the enter key.
4) After the third page is complete, the system should begin to log the fluxes; but if the screen remains blank, try turning the "sonic" switch off, then back on.
5) To stop Eddysol, simply type "CTRL-Q ALT-X", then power down the system. When

performing a calibration or tape backup, the main power will need to stay on.

LICOR 6262 CO_2/H_2O GAS ANALYSER CALIBRATION PROCEDURES

1) Check water level in the fill/drain tube in the condenser block of the Dewpoint Generator. If necessary, slowly add distilled water with small squirt bottle until the water level reads about half-way between "Min" and "Max". See the Dew Point Generator Manual under "Filling the Condenser Block", page 2-3 for detailed instructions.
2) Make sure the battery in the back of the dewpoint generator is charged - if in doubt, plug it into the battery charger in the lab overnight before going out to the field.
3) In the field, open the EC-box with key kept inside Bowen ratio box, then turn off the eddysol program on the laptop inside the EC-box (hit Ctrl-Q and then Alt-X) and shut the switch labeled "pumps" on EC-box door.
4) When chemicals inside scrubber tubes are indicating, i.e. changing colors from white to blue (soda lime) and from light blue to pink (drierite or silica gel), refill the affected scrubber tube half and half with soda lime and magnesium perchlorate (to scrub CO_2 and H_2O, respectively). Silica gel or drierite may be substituted as H_2O scrubber if magnesium perchlorate is not available. Note that magnesium perchlorate does not indicate when a change in chemicals is needed, therefore, change this scrubber material periodically, before it starts caking up (every two weeks). It is preferable to change all scrubber chemicals before they start changing color, i.e. before they loose their optimal scrubbing ability. Now you need to remove the reference and/or sample scrubber tube from the back panel by taking off the nuts and bolts on the clamps holding each tube in place, then unplugging the connectors attached to the "To Scrubber In" and "To Scrubber Out" ports on the back panel. The scrubbing chemicals and a funnel as well as spare parts such as Gelman air filters are in the first black box under the solar panels. A key to this box is also kept inside the Bowen ratio box. Put the used chemicals in plastic ziplock bags and bring back to the lab. All scrubbing chemicals should be disposed of according to University of Arizona hazardous materials policies and procedures. Silica gel may be recharged by oven-drying.
5) Change the Gelman filters on the left (Sample) and right (Reference) side of the panel whenever the flowrates indicated on the flow meters drop significantly below normal pump rates (4.5 l/min for big pump, about 0.7 l/min for small pump) before calibrating. Make sure they are put in-line pointing the right way.
6)a. CO_2 and H_2O Zero Calibration: Make sure the sample scrubber tube is hooked up with the soda lime side closest to the "Sample-Scrubber In" port (left side of panel) so that carbon dioxide is scrubbed first (flow is from left to right through the scrubber tubes). Now turn on both pumps with switch labeled "pumps" on the door, and adjust the sample flowrate if necessary to give a reading of about 4.5 l/min, using the air-flow controller valve next to the pumps at the bottom of the box. Check all connections for leaks by blowing on them through a length of tubing and checking the CO_2 display on the Licor (just press "1" on keypad for the proper display mode). If the CO_2 concentration suddenly increases there is a leak. Do not forget to check the connections behind the panel and tubing connected to the back of the gas analyser. Tighten all connections that are leaking. Pay special attention to the places where you disconnected lines for refilling scrubber

tubes etc. Turn on the switch labeled "Zero Calib." to start calibration.
6)b. Switch to display function 9 (press "9" on Licor keypad) to show CO_2 and H_2O data. Wait for scrubbing to settle down i.e. display doesn't change a whole lot any more - this might take 5 to 10 minutes. If the display doesn't stabilize and keeps on drifting in one direction, set zero on the CO_2 and H_2O potentiometers after 30 min of scrubbing: unlock the potentiometer at the left front of the Licor, adjust until the readout shows as close as possible to zero, then lock the knob again.
6)c. If at any time during calibration one of the knobs cannot be turned far enough to set Zero or Span, proceed as follows: For CO_2, select Function 59, "C2 R" - the CO_2 Reference (in micromol/mol) on Gas Analyser keypad. Enter a new value bigger than the previous one if knob can't be turned past 10, smaller than previous value if you can't turn knob below zero. This will shift the CO_2 concentrations displayed by the amount entered. If you still can't turn the knob far enough, try a bigger value. Similarly, for H_2O choose Function 68, "H2 R" to adjust the H_2O Reference (in mmol/mol). Changing the reference values will also affect the settings of calibration constants in the file "eddy.cal" which is necessary to run eddysol. Before you make changes to "eddy.cal", please remember to save a copy of the old version to disk, naming it "eMMDDYY.cal". For example, if the change occurred on 11/29/93, copy the "eddy.cal" file to disk as follows: "copy eddy.cal a:e112993.cal". Now you can edit the file "eddy.cal" to reflect the new reference constants. If you changed the CO_2 reference on the gas analyser, adjust the constant "c" on the line for CO_2 in "eddy.cal" by the same amount. Eg. if C2 R was changed from 0 to 5 μmol/mol, and "eddy.cal" shows c= 200 μmol/mol, you need to change it to c= 200 + 5= 205 μmol/mol. The constant c is actually telling eddysol what concentration corresponds to a 0 Volt signal coming from the gas analyser. Now if you had changed the H_2O reference on the gas analyser, say from 0 to 2 mmol/mol, you need to change the value of constant c on the H_2O line in "eddy.cal" by that same amount. So if previously c= 0 mmol/mol, change it to read c= 2 mmol/mol. After making changes to "eddy.cal", save the file with the new values before restarting eddysol.
6)d. Note that you can get back a normal display on the Licor when it shows "AUX" (reading off scale) by adjusting the flow rate. For further H_2O calibration instructions see the Dewpoint Generator manual, pages 4-2 and 4-3. Detailed CO_2 calibration instructions are in the Gas analyser manual, pages 4-2 to 4-3.
7) CO_2 Span Calibration: Turn off pumps. Turn the "Zero Calib." switch off and the switch labeled " Span Calib" on. Connect the tubing from the CO_2 span gas cylinder to the "Calib. Gas In" port. Open the valve on top of the cylinder all the way and then open the other valve with the plastic tube attached to it also all the way. Choose display "1" on gas analyser, turn on pumps, then adjust the third adjustment knob on the cylinder to give a span gas flow rate where the display on the gas analyser doesn't show "AUX" and the sample flow meter shows about 4.5 l/min. Check for leaks. After 5 to 10 minutes when the reading stabilizes, set the span potentiometer for CO_2 to give a reading of 400 ppm (same as micromoles/mol). Turn off the switch labeled "pumps" and also turn off span gas supply

on CO_2 cylinder by closing the two valves. Disconnect span gas tubing from "Calib. Gas In" port on right side of panel.

8) H_2O Span Calibration: Turn on the power switch on the Dewpoint Generator (DPG). Turn the dial on the right flow meter on front of DPG all the way to open position so that all flow is going through the right air outlet. Now turn on the pump switch on the DPG and verify that all flow is coming out of the right port by checking flow meters - the left one should read zero. Read the ambient temperature display (select temperature display with toggle switch). Look up the appropriate dewpoint setting from the psychrometric chart in the DPG manual, page 3-14. Read off ambient temperature at the x-axis, go up to the 80% Humidity curve, then over to the left to the 100% curve and back down to the x-axis where you can read off the dewpoint temperature. Set the dewpoint generator to that temperature (use "temperature set" dials on front of the instrument, and switch the toggle switch to also display temperature set. Now switch the toggle switch on the DPG to show actual "Temperature" and turn on cooler switch. Temperature reading should decrease to the dewpoint temperature set. Outside of the monsoon season, when relative humidity is low, using the 20% humidity curve will give better results as this will prevent condensation formation in the DPG tubing. If condensation is formed anyway, choose a lower dewpoint and run cooler on DPG until all condensation is cleared out of the lines. When the set dewpoint temperature is reached, turn the dial on flowmeter above right DPG air-outlet so that all flow is now coming out of the left air outlet, and plug the tubing coming from left air outlet of the DPG into the "Calib Gas In" port on the panel. Turn the EC-pumps back on using switch on EC-box door and adjust flow rate to 4.5 l/min (read off on sample-flowmeter in EC box, left side of top shelf), using the dial on DPG just below the two temperature set dials. Select display "8" on gas-analyser keypad to show water vapor concentration and dewpoint temperature. (Or push FUNCTION key and then "38"). Check for leaks. When display doesn't change much any more (should take about 10 to 20 minutes) set the H_2O span potentiometer so that the dewpoint temperature reading on the gas analyser matches the temperature set on the dewpoint generator.

9) Turn off pump and "Span Calib" switches on EC-box door, disconnect the dewpoint generator from the "Calib Gas In" port and turn off cooler, pump and power on DPG. Turn on the EC-pumps again. Now toggle the "Sonic" switch off and on to reset the anemometer. Restart eddysol on the laptop, put calibration tools and supplies back in first box under solar array and lock this and the EC box. Note: All equipment except the dewpoint generator and accessories can stay at the field site.

LI-COR 6262 CO_2/H_2O GAS ANALYZER MAINTENANCE PROCEDURES

1) External Soda Lime/Desiccant: Change when or, preferably, before scrubbing chemicals are indicating (changing color from white to blue for soda lime, and from light-blue to

pink for silica gel and drierite) or at two-week intervals, whichever comes first.
2) Gelman External Air Filters: Change when flow rate drops due to particle retention or when the apparent LI-6262 response to changes in humidity becomes slow due to filter retention of hygroscopic material. A monthly change should be sufficient.
3) External Fan Filter: check monthly, clean (shake out dust and rinse out) or replace as needed. The filter can easily be removed with your fingers.
4) Internal Soda Lime/Desiccant: Change annually, see manual section 7.3 on page 7-3 for procedure.

LI-COR LI-610 PORTABLE DEW POINT GENERATOR MAINTENANCE PROCEDURES

1) Condenser Block: Drain and refill with distilled water weekly.
2) External Fan Filter: Check monthly - shake out and rinse if needed, replace when torn. Black filter cover on instrument side panel pulls straight off to expose filter (see manual page 5-4).
3) Internal Water Filter Screen: Check monthly to see if mesh filter screen on internal side of "TO COOLER" fitting is clogged, limiting the flow of cooling water through the system. You need to remove the cover of the Dewpoint Generator to do this check (see manual pages 5-3 to 5-4).
4) Radiator: Check water level monthly, fill with distilled water if needed. Drain and refill radiator annually.
5) Algicide: Add 15 to 20 drops to the radiator reservoir every two months.
6) Internal Air filter: Replace Balston filter annually. Blow clean air through the new filter to remove loose debris before installing. For details of changing the filter see page 5-2 in the manual.

BOWEN RATIO MAINTENANCE

Introduction: The Bowen ratio system ducts air from two levels, and measures its dew point using a cooled mirror. The ducting points are at two levels on a 30 foot tower at which there are replaceable filters. Additionally, the cooled mirror must be cleaned, the flow rates adjusted, and the datalogger batteries recharged.

BEFORE YOU DO ANYTHING, TURN OFF THE DATA FLOW!

The bowen ratio program has a provision that allows you to toggle the data flow so that bad data produced during maintenance will not be recorded. Before you do anything to the Bowen ratio system (except download data) follow this procedure. And do not forget to turn it back on after you are done:

To stop data flow:

1. On the 21X datalogger keypad, press "* 6 A D". You should see "00:00:00:00", these are the program's internal flags. Press "4" to toggle flag 4, which turns off the bowen ratio program data flow.

To Start Data Flow:

1. On the 21X datalogger keypad, press "* 6 A D". You should see "00:01:00:00", these are the program's internal flags. Press "4" to toggle flag 4, which turns on the Bowen ratio program data flow.

CLEANING THE DEW POINT MIRROR (Weekly)

Required Equipment: Cotton Swab, and a 40% methanol solution (in the Bowen ratio box).

MIRROR CLEANING PROCEDURE: Access the mirror by rotating and pulling the block cylinder from the square metal box on the control panel (behind the flow meters). Turn the probe sideways so you can see the edge of the metal plate at a 45 degree angle. Mounted on the metal plate is a black box with a trapezoid shaped cover, and on the center of the cover is the mirror. It's about "o" big. Dip one end of the cotton swab into the methanol solution, and run it across the mirror once or twice, then dry it off with the other end of the cotton swab. Re-insert the probe into the metal box (it may need to be turned somewhat to make it fit).

TO ADJUST THE BIAS:

Locate the switch on the upper right corner of the DEW-10 mirror control board,(lower right corner of the panel). Move the switch all the way up (to "bal"). The red LED light just below the switch should be on. Use a screwdriver to turn the potentiometer below the light to the right counterclockwise just until the light goes off, then turn it clockwise until it is just on again (you will need to turn beyond the point you were before). If the light was not on initially, turn the screw clockwise first until it does come on, then continue as above. Now move the switch back to original, middle position. Repeat this procedure 8-24 hours later for best results.

ADJUST THE FLOW METERS (Weekly)
Procedure: The flow through the system needs to be maintained at 0.4 l/min, corresponding to a reading of 4 on the flow meters inside the Bowen ratio box. Adjust the flow on the two active meters by rotating the dial, then wait at least 120 seconds for the height switch, and adjust the other flow rates.

CHECK THERMOCOUPLES (Weekly)
The thermocouples will work with only one good junction, but should be replaced at that point so no data is lost. As long as the junctions are not broken, the thermocouples are good (i.e. bent thermocouples are acceptable). The thermocouples can be repaired by anyone who can weld a 0.003 inch wire. The thermocouple connections can be checked by eye, or by putting the logger in *6 mode and blowing on the junctions. Don't forget to shut off the data flow before doing any such diagnostic procedure or changing the thermocouples. If there is at least one good connection, the reading should change; if the thermocouple is bad, it should register 6999. It is also possible to monitor the thermocouple readings using the program "graphterm" in the c:\logger directory.

CHANGING THE FILTERS (Every other week)
Procedure: The filters are approximately 1 inch in diameter, and are currently located in the Bowen ratio box. Climb up the tower with the appropriate climbing harness (which is kept in first black box below solar array), and reach out to unclip the filter holder and hose. Unscrew the filter housing, and replace the filter. Make sure the plastic backing has been removed from the filter itself - if not, there will be no flow through the tubing connecting the affected air-intake port to the buffer vessel in the Bowen ratio box, and erroneous vapor pressure readings will result. Re-attach the filter tubing, and proceed with replacing the filter on the second Bowen ratio arm.

RECHARGING THE DATALOGGER BATTERIES (Monthly)
Purpose: The Bowen ratio 21X datalogger has internal rechargeable batteries which should be recharged periodically to guard against system failure when there is a power loss.

Procedure: A grey cord with a plug on its end is located near the right side of the datalogger. Once a month or so, plug the power into the side of the datalogger for a few hours to recharge its battery. A red light will come on indicating that the system is charging. Do not leave this plugged in for more than a few hours, as it could damage the internal batteries.

For help with the Bowen Ratio system, call one of the following Campbell Scientific technicians:

Ed Swiatek (801-750-9534)
Joel Green (801-753-2342)

ADDITIONAL STUFF ABOUT THE BR SYSTEM

1. Mirror stuff
(a) The mirror position in the hygrometer is not critical, however Ed recommends placing it more or less in line with the air flow.
(b) The mirror can be removed from the circuit board at the circuit board connection (about 17 pins). This may make it easier to access for cleaning, but be careful to get the pins lined up right when putting it back together.
© The extra orange O-rings on the mirror tubing are replacements for the ones around the mirror. The mirror should fit pretty tightly (extremely tightly with a new ring). If it starts to be loose, or the o-ring shows any signs of cracking, replace it.

2. When changing the air filters on the BR arms, make sure that only the filter is put in, NOT the shiny plastic or paper that separates filters. If the paper is also in place, the system will not be able to draw air through the tubes.

3. It is recommended to use some method to detract birds from damaging the fine wire thermocouples. Our team has been somewhat successful by using plastic wire ties tied onto the metal rod at the end of which the thermocouple junctions are installed. This will keep the birds from sitting on the end of the thermocouples and destroying the junctions. Another method is to use reflective metal tape in a similar manner, tied to the thermocouples.

4. The effect of water in the radiometer shields is that the data become useless. However, plots of the radiation data should reveal the time at which water first entered the dome. If the graphs do not show a definitive abnormal signature indicating where the bad data started, it is safest to discard all data collected since the last download before the damage was discovered, up to the time new domes were installed. Net radiometer domes should be replaced every 4-6 months to prevent yellowing or cracking of the plastic wind shields which invalidates the data.

5. The program for the BR system is written so that a user can disable output while working on the system to avoid collecting erroneous data. To do this, set Flag 4 high from "graphterm" monitoring mode or directly through the keyboard on the

21X (*6 AD, followed by 4 to set flag 4 high - see 21X datalogger manual). This will cause the datalogger to output the current time and values (even if it's not yet to a 20-minute interval) and disables further output processing until the flag is reset. This information is reflected in the data file under array #112. After doing work on the system (cleaning mirror, changing filters, etc.), reset Flag 4 low. Array #303 will record the time at which the system started up again.

DEEP-CYCLE SOLAR BATTERY MAINTENANCE

Introduction: The SASI micrometeorological site is equipped with a large solar array, with the purpose of powering the system components (the most power being demanded by the eddy correlation system). The system is designed in several parts, so that the system components can be easily separated. The main components are the solar cells, solar commanders, batteries, and interconnecting wires. The batteries are the only serviceable, and degradable components of the system.

The system consists of the following equipment:
12 Kyocera 51-Watt photocells
3 Photocomm Solar Commander charge regulators
2 M-8 charge regulators

The Solar Commanders can take up to four solar panels as inputs; only one of them has four connected to it at this time.
The M-8s can take up to two solar panels.

The M-8s are hooked to the two singly mounted panels. The four double mounted panels in the front are hooked to one solar commander. The six in the back are hooked to the other two commanders.

See the diagram to follow the wiring.
It is done as follows. Connect photo cells in parallel + to + ,and - to -. Connect the last cell to the regulator. Connect the regulator to the batteries and the batteries to the DC to DC converters.

SOLAR COMMANDER CHECK (Weekly)

A series of "Solar Commanders" are located inside the western-most black box. There are two different designs which must be checked differently. In general, one must check the following:
1) When there is sufficient light, the 3 larger solar commanders will display the amperage being produced by each set of solar cells. This amperage should reach a maximum of 10

amps per solar cell set in direct sunshine.
2) There are 3 LED indicator lights on the solar commanders that will alternate between charging, charged, and finishing. Check that the solar commanders are cycling through these different states.
3) Two smaller, orange colored, M-8 solar controllers for the single panel mounts, have a similar LED configuration, and should be checked for proper cycling.

WATER LEVELS (Monthly)
Water levels must be maintained in the batteries as follows:
1) Carefully remove one of the battery caps with a screwdriver (remember, the batteries contain sulfuric acid, which should not come in contact with skin or other objects).
2) Using a funnel, accurate pouring, or by using the "Professional Battery Hygrometer" (described in the next section), fill each battery cell with distilled water, up to the bottom of the plastic flange that extends below each battery cell opening. This will bring the water level to about 1.5 cm below the top of the battery.
3) Continue this procedure until all the battery cells have the proper water levels.

SPECIFIC GRAVITY READINGS (Monthly)
Using the "Professional Battery Hygrometer", which is kept in the middle black box, and looks a lot like a turkey baster, follow the following steps:
1) Carefully remove one of the battery caps with a screwdriver (remember, the batteries contain sulfuric acid, which should not come in contact with skin or other objects).
2) Hold the battery hygrometer in a vertical position, and insert the rubber tip into one of the battery cells. Squeeze the bulb and draw up enough liquid to float hygrometer freely, watching to see that the top of the float stem does not touch the rubber stopper at the top of the barrel.
3) The mark on the hygrometer float which is in line with the surface of the liquid indicates the condition of the battery, thus:

SPECIFIC GRAVITY READINGS:

RED	1.100 1.225	Battery cell is in discharged condition
WHITE	1.225 1.260	Battery cell needs attention (electrolyte needs to be changed, battery recharged, water added, or battery replaced)
GREEN	1.260 1.300	Battery cell O.K.

4) Continue this test to assess the overall state of the entire battery set.

NOTE: A proper test can not be made unless each battery cell has sufficient electrolyte to permit hygrometer float to rise freely. An accurate reading can not be obtained if water has just recently been added to cells.

21X DATALOGGER FIELD COMMANDS (BOWEN RATIO SYSTEM)

Note: for a detailed description of datalogger commands, see the 21X datalogger manual.

TIME SETTING/CHECKING ON 21X

*5 shows year (default 90)
enter 93 A (next it will show day of year, default 191)
enter 123 A (123 is an example dat, now it will show hours and minutes)
enter 1345 A (for 01:45 pm)
(note: there is no direct entry for seconds correction, but you may delay by pressing A after time)
*5 shows minutes and seconds for current time

CHECKING PROGRAM STATUS ON 21X

*0 shows program status
:LOG No Program
:LOG1 Program in area 1
:LOG12 Program in area 1 and area 2

LOADING PROGRAM FROM SM716 TO 21X

*D (shows 13:00)
enter 71 A (shows 71:00)
enter 21 A (wait till sign 71 remain on screen)
(Note: 21=nz where
n = 1 to load from 21X to SM716
n = 2 to load from SM716 to 21X
n = 3 to clear program area in SM716
z = 1-8 program area in SM716

CHECKING PROGRAM LISTING ON 21X

*1 A (shows the first line)
enter A for advance and B for backward listing

START/STOP BOWEN RATIO SYSTEM

*6 A D (display 8 flags 00:00:00:00, entering 1-8 will toggle that flag position)
enter 6 (start the pump within 10 seconds)
enter 7 (shut off the pump within 10 seconds)
NOTE: After the pump is started, adjust the flowmeters on the hygrometer panel to read 4 (0.4 liters/minute)

CHECKING BOWEN RATIO INPUT LOCATIONS

*6 (shows the first location, panel temperature) enter A to move forward and B for backward. The complete list of all input locations:

01: Panel Temperature
02: Upper TC Temperature
03: Lower TC Temperature
04: Delta Temperature (lower TC - Upper TC)
08: Dew Point
09: Vapor Pressure
10: Battery Volts
11: second into minutes (to stabilize cooled mirror)
15: Net Radiation (W/m^2)
16: Flux #1
17: Flux #2
20: Ts (Soil Temperature)
22: No. Samples
23: Previoue Average
24: Average Ts
25: Delta Ts

MANUAL DATADUMP FROM 21X TO SM716

*9 (shows 09:00)
enter 31 A (display reads: 01:nnnnnn starting location of data transfer)
enter 1 A (if data transfer is from the beginning)
next it shows: 02:nnnnnn the final position of data
enter A
next it shows: 03:00, ready for data transfer
enter 1 (or any number to start data transfer)
wait until 09: remains on the screen

BOWEN RATIO WIRING TEMPLATE

21X Input		Connection	Color
ANALOG			
1	H	R NET +	RED
	L	R NET -	BLACK
GND			
2	H	COOLED MIRROR PRT	GREEN
	L	COOLED MIRROR PRT	WHITE
GND		COLLED MIRROR PRT	BLACK
3	H	SOIL TEMP TC CHROMEL	PURPLE
	L	SOIL TEMP TC CONSTANTAN	RED
GND			
4	H	UPPER 0.0003 TC - CHROMEL	PURPLE
	L	LOWER 0.003 TC - CHROMEL	PURPLE
GND		AIR TEMP TCs - CONSTANTAN	RED
5	H	SOIL HEAT FLUX PLATE #1 HIGH	BLACK
	L	SOIL HEAT FLUX PLATE #2 HIGH	BLACK
GND		HEAT FLUX PLATE GROUNDS	WHITE
6	H		
	L		
GND			
7	H		
	L		
GND			
8	H		
	L		
GND			
EXCITATION			
	1	COOLED MIRROR EXCITATION	RED
	2		
	3		
	4		
CONTROL PORTS		023 RELAY DRIVER CABLE	
	1	PULSE FOR LOWER AIR INTAKE	GREEN
	2	PULSE FOR UPPER AIR INTAKE	WHITE
	3	PULSE TO TURN ON POWER TO	BLACK

	MIRROR AND PUMP (FLAG 6)	
4	PULSE TO TURN OFF POWER TO MIRROR AND PUMP (FLAG 7)	RED
GND	GROUND WIRE	CLEAR

TOWER INSTALLATION:

1. Select site and pound in base with sledge if required. Make base as secure as possible and level with the ground.

2. Lay out tower sections in a convenient direction, keeping in mind that you will need to pull the tower up using the guy wires.

3. Connect tower sections with bolts. Use the punch to align the holes.

4. Cut guy wires to 35' (should be done ahead of installation time.)

5. Attach the guy collar at the twenty foot level. Be sure that the fat washers have the round side toward the wire. Attach the preform to the bracket putting a thimble around the preform.

6. Preforms. Begin with the short end and wrap the preform onto the guy wire then wrap the other half of the preform onto the wire and preform wrap. Line up the colored marks when wrapping the two halfs of the preforms together. Do not wrap preforms all the way on until the final adjustments have been made.

7. Attach a preform to the other end of the guy wire.

8. Arrange the group as follows: one person on each guy wire, one at the base and two at the top of the tower. Raise the tower toward one guy wire. The person at the base keeps the base from slipping, the side guy wire persons keep it from tipping to the side; the front guy wire person pulls the tower up while the two at the top of the tower walk it up.

9. When the tower is vertical the people on the guy wires hold it vertical while the others lift it onto the base and bolt it to the base.

10. Use stakes to temporarily anchor the guys.

11. Measure 24' from the base of the tower in the direction of each guy and set an anchor.

12. Attach a turnbuckle to each anchor. Screw the turnbuckle in or out depending on the direction the tower needs to be tipped to be straightened. When checking the tower's plumbness place a level on the tower and measure the plumbness in the direction of each guy wire.

13. One at a time detach the guys and re-attach them to the turnbuckle.

14. When all the wires are attached plumb the tower as much as possible. If the tower is not plumb, (and it will probably not be) determine the direction of least plumbness. Loosen the other two turnbuckles the same number of turns. Detach the offending guy and screw the turnbuckle in or out and re-attach the guy. Screw the two loosened turnbuckles back in. Try to level again repeating this procedure until the tower is plumb.

AUTOMATIC WEATHER STATION WIRING TEMPLATE

21X Input	Connection	Color
1H	10T CRT	
E3		
AG		
P1	Tipping Bucket	Black
G		Whire
G		Clear
S1	Wind Vane	Black
1L		Red
AG		White
G		Clear
P2	Anemometer	Black
G		White
G		Clear
2H	TCAV	Purple
2L		Red
4H	Soil Heat Flux Plate #1	Black (Single Ended #7)
AG		White
G		Clear
3H	Pyranometer	Red
#L		Black
AG		Jump to 3L
G		Clear

SUMMARY OF DOS/UNIX COMMANDS

DOS:

copy <drive:\path\(copy from)filename> <drive:\path\(copy to)filename>
del <drive:\path\filename>
cd <path> -Change directory
cd.. -Switch one directory towards root directory
cd\ -Switch to root directory
format a: -erases everything on drive a:
rename <drive:\path\filename> <drive:\path\filename>

NOTES:
path=directory names seperated by "/"
wildcard "*.*" - can be used to refer to all files in a directory

UNIX:

cp </path/(copy from)filename> </path/(copy to)filename>
rm </path/filename> -Delete a file
cd <path> -Change directory
cd .. -Switch one directory towards root directory
cd -Switch to home directory
rename </path/filename> </path/filename>

NOTES:
path=directory names seperated by "/"
wildcard "*.*" - can be used to refer to all files in a directory

LAPTOP DISK MAINTENANCE:

Occasionally, the hard disk on the laptop computers should be checked for bad or missing sectors, be defragmented, and restacked. The media of the hard disk can degrade with time and become ineffective. So, using a program such as Norton Disk Doctor (type "norton"), the surface should be scanned for bad sectors. Next, program information can get "lost" when a directory pointer is written incorrectly. To find these "lost sectors" type "chkdsk /f". The hard disks we use are "stacked" using a program called Stacker. This program compresses the files we write to the disk so they use less space, and effectively enlarge the size of the hard drive. Stacker has a utility called "stac" that should be run periodically to maintain the condition of the compressed drive. A summary of the commands needed to properly maintain the hard disks is as follows:

chkdsk /f
norton
stac

LAPTOP COMPUTER BATTERIES:

The laptop computers use Ni-Cad rechargeable batteries that must be carefully maintained. Ni-Cad batteries have a "memory" so that their performance decreases with short uses followed by long recharges. So the best way to lengthen the lifespans of these batteries is to use them until they are discharged, then charge them to full capacity, etc. This can be facilitated by utilizing a fully charged spare battery that can replace the discharged battery. Currently, we have 4 batteries and 2 laptop computers, so this should be a simple task.