Surface flux measurement and modeling at a semi-arid Sonoran Desert site

Helene E. Unland *, Paul R. Houser, William J. Shuttleworth, Zong-L. Yang

Department of Hydrology and Water Resources, The University of Arizona, P.O. Box 210011, Tucson, AZ 85721-0011, USA

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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, AZ. 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

* Corresponding author.
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 and 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 sub-models 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, AZ, 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 D₁₀ 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.,
Fig. 1. Micrometeorological instruments at the field site west of Tucson, AZ, viewed from the direction of the prevailing winds and longest fetch towards the Tucson mountains, which are approximately 1 km distant 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.

1993, their 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 < 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, their 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 Fig. 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 tempera-
ture 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, Logan, UT, 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-min 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 (REBS, WA, 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, Lincoln, NE, USA; model LI-200SZ) and a combined thermometer and hygrometer (Campbell Scientific, Logan, UT, 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⁻¹ for the specific humidity (q) range 0–14.5 g kg⁻¹, and 3% for the RH range 90–100% or 0.5 g kg⁻¹ for the q range 14.5–16.1 g kg⁻¹. 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, Lincoln, NE, 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, Lincoln, NE, USA; model LI-610), a compressed reference gas (400 ppm CO₂ 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 m (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-min 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\textsubscript{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 the similarity theory of Monin and Obukhov (1954) 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, $\sigma_T$, and the mean air temperature, $\theta$, at height, $z$, together
with an estimate of the zero plane displacement height, $d$. The sensible heat flux is
estimated from:

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

where $k$ is the von Kármán 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 devia-
tions.

In this study, the measurements required to apply this technique were made using
fine-wire (76 $\mu$m 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-min 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:

$$
H + LE = R_n - G
$$

Here the net radiation, $R_n$, and the soil heat flux, $G$, are directly measured; while the
ratio of $LE$ 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, $\beta$, the ratio of the sensible to the latent heat flux, is assumed to be proportional to
these differences, thus:

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

where $p$ is the atmospheric pressure (kPa), $c_p$ is the specific heat of air (kJ kg$^{-1}$ °C$^{-1}$),
$\lambda$ is the latent heat of vaporization (kJ kg$^{-1}$), and $\varepsilon$ is the ratio of molecular weight of
water to that of air.

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

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

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

$$
H = R_n - G - LE
$$

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, Logan, UT, 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., MA, 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 May 12, 1993 to May 11, 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-min 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, $|\Delta \theta|$, 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. Fig. 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
Fig. 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.

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. Fig. 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. Fig. 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\(^{-1}\) for daily averages, but increases to 9 g kg\(^{-1}\) 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.
Fig. 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 May 12, 1993.

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. Fig. 4 shows comparisons between the measured sensible heat given by the thermocouple-based sigma-T method and those from the eddy covariance system in Fig. 4(a) and the Bowen ratio method in Fig. 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 Fig. 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. Fig. 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 \((LE + H)\) 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 Fig. 6(a) for a typical dry day (July 22, 1993) with clear skies, and in Fig. 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.

Fig. 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 \(\mu\text{mol m}^{-2}\text{s}^{-1}\) 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 \(\mu\text{mol m}^{-2}\text{s}^{-1}\) for the drier period (July 19–31, 1993) and about 1 \(\mu\text{mol m}^{-2}\text{s}^{-1}\) in wetter conditions (August 3 to 9, 1993). Fig. 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 Fig. 7(c) shows a comparison between this same wet day and the CO\(_2\) uptake pattern for
Fig. 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.

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

<table>
<thead>
<tr>
<th>Meteorological variables</th>
<th>Typical dry day (July 22, 1993)</th>
<th>Typical wet day (August 7, 1993)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. air temperature (°C)</td>
<td>24.9</td>
<td>19.5</td>
</tr>
<tr>
<td>Max. air temperature (°C)</td>
<td>34.9</td>
<td>33.0</td>
</tr>
<tr>
<td>Min. soil temperature (°C)</td>
<td>29.2</td>
<td>25.1</td>
</tr>
<tr>
<td>Max. soil temperature (°C)</td>
<td>45.1</td>
<td>40.3</td>
</tr>
<tr>
<td>Min. relative humidity (%)</td>
<td>16.4</td>
<td>35.9</td>
</tr>
<tr>
<td>Max. relative humidity (%)</td>
<td>44.5</td>
<td>84.1</td>
</tr>
<tr>
<td>Min. wind speed (m s^{-1})</td>
<td>0.20</td>
<td>0.75</td>
</tr>
<tr>
<td>Max. wind speed (m s^{-1})</td>
<td>4.5</td>
<td>9.9</td>
</tr>
<tr>
<td>Total daily precipitation (mm)</td>
<td>0.0</td>
<td>17.5</td>
</tr>
</tbody>
</table>

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.

Fig. 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.
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 et al., 1993, their 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 measure-
ments 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-min averages for the year from May 12, 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
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

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Standard CCM2 parameters</th>
<th>Improved, site-specific parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum fractional vegetation cover</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td>Seasonality factor (i.e. difference between maximum fractional vegetation cover and fractional cover at a temperature of 269 K)</td>
<td>0.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Roughness length (m)</td>
<td>0.1</td>
<td>0.12</td>
</tr>
<tr>
<td>Zero-plane displacement height (m)</td>
<td>0.0</td>
<td>0.9</td>
</tr>
<tr>
<td>Minimum stomatal resistance (s m$^{-1}$)</td>
<td>200.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Maximum leaf area index</td>
<td>6.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Minimum leaf area index</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Stem and dead matter area index</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Inverse square root of leaf dimension (m$^{-1/2}$)</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Light sensitivity factor (m$^2$ W$^{-1}$)</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Vegetation albedo for $l &lt; 0.7 , \mu m$</td>
<td>0.17</td>
<td>0.17</td>
</tr>
<tr>
<td>Vegetation albedo for $l \geq 0.7 , \mu m$</td>
<td>0.34</td>
<td>0.34</td>
</tr>
<tr>
<td>Depth of upper soil layer (m)</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Depth of rooting zone soil layer (m)</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Depth of total soil layer (m)</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Fraction of water extracted by upper layer roots (saturated)</td>
<td>0.8</td>
<td>0.3</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Soil parameter</th>
<th>Standard CCM2 parameters (soil texture class 3)</th>
<th>Soil texture class 9</th>
<th>Modified Tucson parameters (modified from soil texture class 9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity (volume of voids to volume of soil)</td>
<td>0.39</td>
<td>0.57</td>
<td>0.57</td>
</tr>
<tr>
<td>Minimum soil suction (mm)</td>
<td>30.0</td>
<td>200.0</td>
<td>200.0</td>
</tr>
<tr>
<td>Saturated hydraulic conductivity (mm s$^{-1}$)</td>
<td>0.032</td>
<td>0.0022</td>
<td>0.0022</td>
</tr>
<tr>
<td>Moisture content relative to saturation at which transpiration ceases</td>
<td>0.151</td>
<td>0.455</td>
<td>0.266</td>
</tr>
<tr>
<td>Exponent 'B' defined in Clapp and Hornberger (1978)</td>
<td>4.5</td>
<td>8.4</td>
<td>5.0</td>
</tr>
<tr>
<td>Ratio of saturated thermal conductivity to that of loam</td>
<td>1.3</td>
<td>0.85</td>
<td>0.85</td>
</tr>
<tr>
<td>Soil color index</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>
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 Fig. 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; their 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, \( r_{\text{min}} \), and the two parameters \((s_w, B)\) 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 \( r_{\text{min}} \) 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, \( E_{\text{trmax}} \), is described by a 'plant wilting factor', \( W_{\text{LT}} \), through the equation:

\[
E_{\text{trmax}} = \gamma_0 \sum_i R_i (1 - W_{\text{LT}}^i)
\]

where \( \gamma_0 \) is the maximum total transpiration that can be sustained, with a summation over contributing soil layers each denoted by \( i \), where \( R_i \) is the fraction of roots in a given soil layer. \( W_{\text{LT}}^i \) is zero at saturation and unity at permanent wilting point, and is calculated by:

\[
W_{\text{LT}}^i = \frac{(s_i)^{-B} - 1}{(s_w)^{-B} - 1}
\]

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 Fig. 8(a) and using site-specific parameters in Fig. 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 Fig. 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. Fig. 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 Fig. 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 Fig. 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 Fig. 9(a)), but there is no significant bias with the site specific parameters (see Fig. 9(c)). In the case of sensible heat flux shown in Fig. 9(b) and (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. Fig. 9(e) and (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
Fig. 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.

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.

Fig. 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.
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. Fig. 10(a)–(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 displace-
Fig. 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).

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 May 12, 1993.
Table 4
Components of the annual water balance and net radiation for the year from May 12, 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

<table>
<thead>
<tr>
<th>Component</th>
<th>BATS model using standard CCM2 parameters</th>
<th>BATS model using modified Tucson parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net radiation (mm)</td>
<td>1181</td>
<td>1180</td>
</tr>
<tr>
<td>Precipitation (mm)</td>
<td>275</td>
<td>275</td>
</tr>
<tr>
<td>Evaporation (mm)</td>
<td>230</td>
<td>262</td>
</tr>
<tr>
<td>Surface runoff (mm)</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Baseflow (mm)</td>
<td>31</td>
<td>0</td>
</tr>
</tbody>
</table>

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

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

<table>
<thead>
<tr>
<th>Month</th>
<th>Precipitation (mm month$^{-1}$)</th>
<th>Evapotranspiration (mm month$^{-1}$)</th>
<th>Surface runoff (mm month$^{-1}$)</th>
<th>Baseflow (mm month$^{-1}$)</th>
<th>Monthly mean RSW (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>0.3</td>
<td>11.6 (6.5)</td>
<td>0.0 (0.0)</td>
<td>0.0 (2.6)</td>
<td>137.7 (162.9)</td>
</tr>
<tr>
<td>February</td>
<td>35.7</td>
<td>18.8 (19.4)</td>
<td>1.2 (2.2)</td>
<td>0.0 (2.8)</td>
<td>149.9 (172.7)</td>
</tr>
<tr>
<td>March</td>
<td>30.6</td>
<td>28.6 (26.3)</td>
<td>1.1 (0.9)</td>
<td>0.0 (3.1)</td>
<td>150.8 (171.1)</td>
</tr>
<tr>
<td>April</td>
<td>3.2</td>
<td>21.8 (11.4)</td>
<td>0.0 (0.0)</td>
<td>0.0 (2.5)</td>
<td>138.0 (163.0)</td>
</tr>
<tr>
<td>May</td>
<td>14.9</td>
<td>14.9 (16.5)</td>
<td>0.1 (0.2)</td>
<td>0.0 (2.4)</td>
<td>101.8 (125.2)</td>
</tr>
<tr>
<td>June</td>
<td>0.1</td>
<td>1.2 (8.9)</td>
<td>0.0 (0.0)</td>
<td>0.0 (2.0)</td>
<td>129.8 (158.1)</td>
</tr>
<tr>
<td>July</td>
<td>14.7</td>
<td>14.3 (16.9)</td>
<td>0.1 (0.2)</td>
<td>0.0 (1.9)</td>
<td>133.4 (159.3)</td>
</tr>
<tr>
<td>August</td>
<td>100.9</td>
<td>36.4 (46.7)</td>
<td>8.2 (6.9)</td>
<td>0.0 (2.3)</td>
<td>148.3 (170.0)</td>
</tr>
<tr>
<td>September</td>
<td>15.0</td>
<td>51.7 (27.8)</td>
<td>1.1 (0.5)</td>
<td>0.0 (3.1)</td>
<td>164.5 (178.6)</td>
</tr>
<tr>
<td>October</td>
<td>16.0</td>
<td>25.0 (17.6)</td>
<td>0.3 (0.3)</td>
<td>0.0 (2.9)</td>
<td>146.3 (169.0)</td>
</tr>
<tr>
<td>November</td>
<td>35.9</td>
<td>20.9 (20.7)</td>
<td>1.3 (2.4)</td>
<td>0.0 (3.0)</td>
<td>149.5 (171.9)</td>
</tr>
<tr>
<td>December</td>
<td>8.1</td>
<td>16.4 (11.5)</td>
<td>0.2 (0.1)</td>
<td>0.0 (3.0)</td>
<td>147.9 (168.3)</td>
</tr>
</tbody>
</table>
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 C_{3} and C_{4} 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 dicarboxic acid (malate) inside the vacuoles, followed by rapid decarboxylation of the acid to carbohydrates in the chloroplasts though photosynthesis. Though a substantial proportion of the vegetation cover present in the Sonoran Desert (and at the field site) are C_{3} and C_{4} 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 dicarboxic 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 C_{3} 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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References


Weltz, M., 1995. Personal communication. ARS-USDA, Tucson, AZ, USA.