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ABSTRACT

To facilitate the study of flux heterogeneity within a region, the authors have designed and field-tested a portable eddy covariance system to measure exchange of CO_2, water vapor, and energy between the land surface and the atmosphere. The combination of instrumentation used in this system allows high precision flux measurements without requiring on-site infrastructure such as prepositioned towers or line power. In addition, the system contains sensors to measure a suit of soil, climatic, and energy-related parameters that are needed to quality control the fluxes and to characterize the flux footprint. The physical design and instrument packaging used in the system allows for simple transport (fits in a standard minivan) and for rapid deployment with a minimal number of field personnel (usually less than a day for one person). The power requirement for the entire system (instruments and data loggers) is less than 35 W, which is provided by a companion solar power system.

Side-by-side field comparisons between this system and two permanent AmeriFlux sites and between the roving AmeriFlux intercomparison system are described here. Results of these comparisons indicate that the portable system is capable of absolute flux resolutions of about ± 1.2 μmol m^{-2} s^{-1} for CO_2, ± 15 W m^{-2} for LE, ± 7 W m^{-2} for H, and ± 0.06 m s^{-1} for u* between any given 30-min averaging periods. It is also found that, compared to a permanent Ameriflux site, the relative accuracy of this flux estimates is between 1% and 7%. Based on these results, it is concluded that this portable system is capable of making ecosystem flux measurements with an accuracy and precision comparable to most permanent AmeriFlux systems.

1. Introduction

The influence of land use and management is a central question in climate change research. Spatial patterns of use and management generate strong heterogeneity in surface albedo, and fluxes of heat, water, and carbon dioxide, as well as in other surface properties that force climate. Previous work in forests (e.g., BOREAS, more information available online at http://www.daac.ornl.gov/BOREAS/boreas_home_page.html.) and in grazed or crop ecosystems (e.g., Bremer and Ham 2002) has shown the importance of land alteration. Climate, edaphic variables, and history may also create heterogeneity within a given vegetation type or crop management regime. Because the first priority of most flux networks has been to achieve representation of the major different vegetation types, there are few replicates within a single vegetative land cover type. As a result, regional estimates of carbon exchange commonly must extrapolate a single eddy flux site to all areas within the same vegetation type or management regime, without an empirical estimate of the uncertainty due to spatial heterogeneity. We seek to explore this heterogeneity on the scale of 50 to 100 hectars, or on a field-to-field basis. The magnitude of the differences between different fields with the same crop type or the same land cover type is currently unknown.

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To characterize the carbon cycle dynamics in a heterogeneous region, we are developing a program of atmosphere–biosphere carbon exchange measurements in the Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) of the Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) program. The ARM–CART encompasses an area of 140 000 km^2 in Oklahoma and southern Kansas (ARM SGP, more information available online at http://www.arm.gov/docs/sites/sgp/sgp.html). It is heavily instrumented with atmospheric-observation technologies at the central facility (located near the town of Lamont, Oklahoma; 36°37′N, 97°30′W) and at a distributed network of extended facilities. The mission of this project is to improve understanding and modeling of cloud and convection processes in general circulation models. Addressing these objectives requires measurement of carbon, water, and energy fluxes in many plots, with accompanying measurements of other variables needed to drive and test the ecosystem models and other approaches to scaling and prediction.

With the goal of facilitating measurements that capture the landscape scale heterogeneity in cropped and grazed systems, we have identified a set of performance criteria for an ideal portable flux system. This system should (i) be easily and rapidly moveable from site to site while requiring only one or two people for setup; (ii) operate continuously and unattended for weeks at a time with low power consumption and infrastructure requirements, such as permanent towers or line power; (iii) be comprehensive enough to make all the measurements necessary for quality control of fluxes and for modeling; (iv) provide accuracy and precision comparable to permanent eddy covariance installations; and (v) be built at fairly low cost.

Existing portable flux systems have shown the utility of this concept. One portable system is currently being used to cross calibrate carbon flux sites within the AmeriFlux program (Evans 2000). It makes high precision measurements, but it is typically set up using the infrastructure (such as the tower, power, and ancillary energy-budget sensors) of the permanent AmeriFlux installation. An earlier portable system was used to examine spatial and climatic heterogeneity in fluxes from arctic ecosystems (Eugster et al. 1997). While the instrumentation of this system was indeed portable, it required 150–200 W of power to operate. The authors estimated that (at the time) different instrumentation could have saved 45–60 W, but such a system would still require 90 W or more to operate. Supplying this resource required the use of a generator and its associated fuel supply. A third system, was described by Meyers (2001) and, although it was used in a long-term experiment, it did have the potential for portability. This system was based on a noncommercial gas analyzer designed and produced at the National Oceanic and Atmospheric Administration's Atmospheric Turbulence and Dispersion Division (NOAA ATDD) laboratory in Oak Ridge, Tennessee (Auble and Meyers 1992). Unfortunately, this analyzer is only available from the authors and exhibits limited offset stability.

Since the time that these systems were designed, new gas analyzer technology has become available that allows the design of more precise and energy-efficient eddy flux systems. It is now possible to design a compact portable system that minimizes power requirements with good long-term stability.

The key instrument that makes this system effective is an accurate and stable open-path infrared gas analyzer (IRGA; LI-7500, LICOR Inc., Lincoln, Nebraska) that measures the densities of CO_2 and H_2O. Compared to earlier analyzers (Auble and Meyers 1992), this instrument contains feedback and signal processing systems that provide improved gain and offset stability, and that significantly reduce the frequency of calibrations needed to make precise density measurements. As with other open-path instruments, the LI-7500 requires little power to operate ($<$10 W during operation) because the measurement does not require the pumps used to transport gas samples to closed-path analyzers.

In the absence of advection, the true surface flux of a trace gas (as measured by the eddy covariance technique) is the sum of three terms. The first is simply the raw covariance between the fluctuations of the density of the trace gas and the fluctuations in the vertical wind speed. The other two are proportional to the sensible heat flux and the latent heat flux, respectively, and are commonly referred to as the Webb–Pearman–Leuning (or WPL) corrections (Webb et al. 1980; Paw U et al. 2000). We prefer the nomenclature of WPL terms instead, since they are not corrections in the sense that they make up for some perceived defect in the measurement system. The relative magnitudes of these terms differ between open and closed-path IRGAs. In particular, the term proportional to the sensible heat flux often reduces to 0 for closed-path analyzers but can be quite large for open-path analyzers, sometimes exceeding the raw covariance in magnitude. It is thus obvious that all three of these terms must be measured and accurately calculated to produce high-quality eddy covariance surface fluxes.

To validate the correct operation of our portable flux system, we undertook a series of flux measurement comparisons between our system and other established flux systems under a variety of conditions. In the first experiment, we compared our system with a closed-path IRGA based flux system under typical prairie growth conditions. This allowed us to compare our system to a traditionally designed, closed-path IRGA based flux system, and to evaluate our system under conditions providing a wide range of flux values. In the second experiment, we compared our system with another closed-path IRGA based system under conditions where the CO_2 flux was expected to be very small, but the sensible heat flux was expected to be very large. This provided us an opportunity to test how well our system

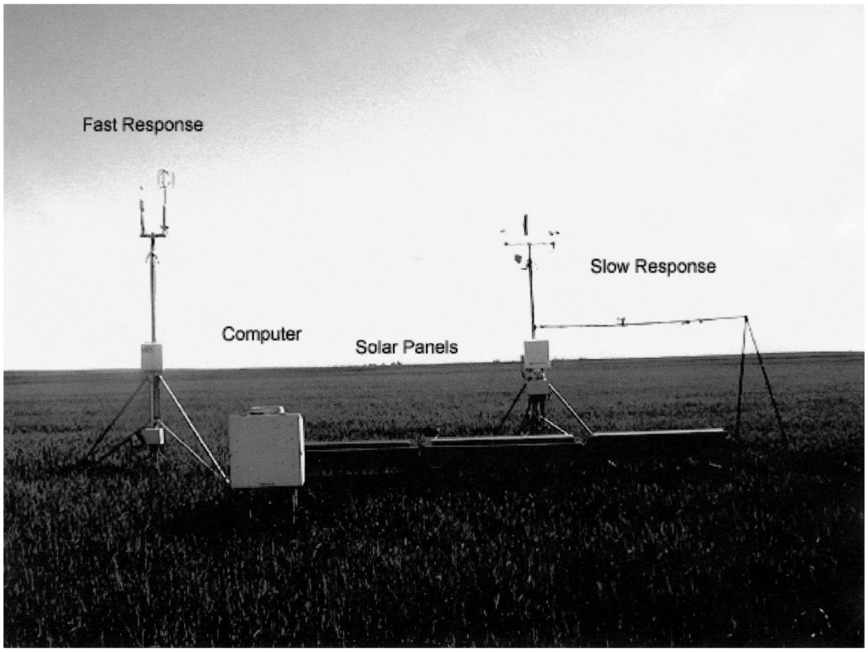

FIG. 1. Photo of the complete system deployed in a wheat field in north-central Oklahoma.

was able to measure and calculate the WPL term proportional to sensible heat flux under extreme conditions. Also this allowed us to verify the precision and resolution of our flux calculations. Finally, in the third experiment, we compared our system with the AmeriFlux roving intercomparison system under growth conditions similar to the first deployment. This exercise provided an estimate of the relative accuracy of our system with respect to the AmeriFlux standard.

To summarize, we describe here the design and field testing of a portable, rapidly deployable, precision eddy covariance CO_2 flux system. It takes advantage of the LI-7500 IRGA to reduce power demands, while increasing instrument portability, reliability, and precision. The results of our field intercomparisons with existing flux systems will demonstrate the measurement accuracy and precision of the system under a range of conditions, that include both large and small WPL terms.

2. Instrument description

The design that was eventually chosen can be broken down into two major subsystems, referred to as the ''fast-response'' subsystem and the ''slow-response'' subsystem. This nomenclature describes the measurement frequency and the time response of the instruments within each subsystem. In addition to these two subsystems, there is also a flexible power module that is adaptable to most field sites, and a suite of data collection and analysis software. The full system is shown deployed in Fig. 1.

3. Fast-response subsystem

The primary function of the fast-response subsystem is to measure the variables needed to compute the turbulent transfer of CO_2, H_2O, heat, and momentum. It is composed of two sensors, the sonic anemometer and the CO_2–H_2O IRGA. The anemometer chosen was the Gill-Solent WindMaster Pro, three-dimensional sonic anemometer/thermometer (Gill Instruments, Ltd, Lymington, United Kingdom). This anemometer incorporates an analog input system that may be configured as either four differential or eight single ended channels. These inputs can digitize signals between ± 5 V with 14-bit precision. Data from the anemometer (wind speed components, sonic temperature, and analog inputs) are output as a single serial stream on an RS-422 data port at the selected sampling rate (usually 10 Hz).

A LiCor LI-7500 open-path CO_2–H_2O infrared gas analyzer (LiCor, Inc) was chosen to make density measurements of CO_2 and water vapor. The calibrated CO_2 and H_2O densities are output as analog voltages (0–5 V range, 16-bit resolution) and are connected (at the signal junction box described below) to the WindMaster Pro analog inputs. By taking advantage of the anemometer analog inputs, we avoid possible time shifting problems that could be caused by using two unsynchronized instrument clocks to control two separate serial data streams. While not recording the full serial data stream from the LI-7500 looses some of the ancillary data available from the IRGA (e.g., pressure, temperature, diagnostics), it simplifies the data collection system by requiring only a single serial data channel.

TABLE 1. Instrumentation and measurements made by the slow-response subsystem.

Instrument	Measured variable
Climatronics CS800-12 wind set (Climatronics Corp., Bohemia, NY)	Mean horizontal wind speed and direction
Vaisala Humiter 50Y (2) (Vaisala, Inc., Woburn, MA)	Temperature and relative humidity profiles
Vaisala PTB101B barometer	Mean atmospheric pressure
HFT3 soil heat flux plates (4) (Radiation and Energy Balance Systems, Seattle, WA)	Soil heat flux
Type E thermocouples (6) (inhouse)	Soil temperature profiles
ECH_2O soil moisture probes (8) (Decagon Devices, Inc., Pullman, WA)	Soil moisture profiles
LiCor LI-190SA quantum sensor (LiCor, Inc., Lincoln, NE)	PAR
LiCor LI-200SA pyranometer	Total insolation
Kipp & Zonen CNR-1 radiometer (Kipp & Zonen Inc., Bohemia, NY)	Upwelling and downwelling radiation (0.3–2.8 and 5–50 μm)
Kipp & Zonen NR-lite net radiometer	Net radiation
TE525 tipping bucket rain gage (Texas Electronics, Dallas, TX)	Mean precipitation

The fast-response instruments are mounted at the top of a Campbell Scientific CM10 tripod tower (Campbell Scientific Inc., Logan, Utah). The sensors (IRGA and anemometer) are mounted on a common horizontal bar such that their lateral separation can be adjusted from about 15 cm to more than 30 cm. To minimize flux loss and flow distortion, the IRGA is mounted about 25 cm below the anemometer volume (Kristensen et al. 1997). As recommended in the LiCor LI-7500 manual, the IRGA is tipped about 30° from vertical to facilitate drainage of condensation and rain from the optical windows. As received from the manufacturer, the tripod tower allows the instruments to be mounted between about 3 and 4 m above the ground. If higher or lower deployments are required, the central pole of the tower can be replaced with a longer or shorter piece of standard ANSI 1¼-inch galvanized steel water pipe. When the tower was properly deployed with its guy wires and foot pegs installed, it proved to be quite stable and vibration free, even in sustained winds of between 10 and 12 m s^{-1} (the strongest experienced on our test deployments).

To record the raw, high speed data from the fast-response subsystem, we used a small notebook computer. The particular models used (Toshiba Portege 3110CT or Toshiba Portege 7200CT) were chosen specifically for their low power consumption. The notebook computer is housed in a small, insulated plywood shelter. The shelter is passively cooled with a standard roof ventilator installed on top and five small soffet vents installed in the bottom. The shelter has four, ANSI 1-inch floor flanges attached to its bottom. These allow legs to be mounted to the shelter to elevate it above the vegetation for improved ventilation. Field tests showed that the interior temperature never rose more than about 5°C above ambient.

To facilitate quick set up of the system, a signal junction box was fabricated from a weatherproof, polycarbonate box. Cables from both the anemometer and the LiCor IRGA were terminated in black plastic circular connectors (Amphenol Series One, Columbia, South Carolina). Mating connectors were mounted to the junction box and all interconnections were made inside. Since the serial data stream from the anemometer conforms to the RS422 standard, an RS422 to RS232 converter (Telebyte Inc., Greenlawn, New York) was also installed in the junction box. A similar box with mating connectors was mounted on the outside of the computer shelter. On the inside of the shelter, standard nine-pin serial connectors were mounted in a small plastic workbox attached to the wall. These allowed standard serial cables to be used for all signal connections. The total cost for the fast response subsystem was about $25,000.

4. Slow-response subsystem

The slow-response subsystem contains instrumentation used to measure ancillary parameters needed to calculate accurate fluxes, validate their quality, and to quantify other ecosystem variables necessary for modeling. In this subsystem, the instruments are read once every 1–5 s by a Campbell Scientific datalogger. These readings are then averaged in 30-min blocks to match the usual averaging period of the fast-response subsystem. Quantities measured by this subsystem include, mean wind speed, wind direction, air temperature and relative humidity at two heights, barometric pressure, soil temperature profiles, soil heat flux, soil moisture profiles, total incoming solar radiation, photosynthetically active radiation (PAR), incoming and reflected radiation in long and short wavelength bands, and net solar radiation. The system is built around a Campbell Scientific Inc. CR23X datalogger and AMT-25 multiplexer. Instruments attached to the data logger are listed in Table 1. While this is the list of instruments attached to the current system, it can easily be modified for other applications.

As in the fast-response subsystem, the slow-response sensors are mounted on a Campbell Scientific Inc. CM-10 tripod tower. The tower was modified by adding a removable, horizontal outrigger bar for mounting the radiation instruments. This bar is at a height of about 2.3 m and extends approximately 2 m out from the central tower.

The outrigger and all other similar parts were constructed from ANSI standard plumbing fittings and pipe. This has the advantage that any lost or damaged parts can be easily obtained from a local hardware or plumbing supply store. We have found that this can be a distinct advantage for systems that are frequently moved. For deployments outside the United States, these parts can be replaced with near-equivalent metric parts.

The datalogger is housed inside an environmental enclosure (Campbell Scientific Inc., ENC 12/14) that attaches to the tower. To facilitate instrument set up, a signal junction box similar to the fast-response junction box is permanently attached to the bottom of the data logger enclosure, with short lengths of PVC pipe. These also form wiring chases for the cables that run from the connectors on the bottom of the junction box to the terminal strips of the datalogger. All of the slow-response instruments are terminated in the same kind of connectors that were used with the fast-response subsystem or in thermocouple connectors. This approach realizes significant savings in setup time. The datalogger stores averaged values of each quantity measured and the user may download this data to a laptop computer at any time without interrupting the measurements. The total cost of the slow response system was about $16,000.

5. Power system

The entire system (fast-response and slow-response) runs from a power source supplying between 11 and 18 VDC. In the tests described here, the system drew between 2.2 and 2.5 A (at 13.6 V) or between 30 and 35 W. In later, longer-term deployments, the total system power requirements were measured at 1.8 A (at 12.9 V) or less than 25 W.

Power may be supplied from various sources, but for remote deployments at unimproved sites, we have assembled a solar panel system capable of running the system indefinitely. This power system consists of three 120-W solar panels and associated controllers charging a pair of 105 A h batteries. The batteries are common deep-cycle marine–RV types and, in the event of failure, may be replaced from local vendors. The power distribution system incorporates 0.01Ω resistors in series with each solar panel and with each load distribution box. These are connected to input channels on the slow-response datalogger to monitor the condition of the power system. Power is distributed to the various system components using 18-gauge cable with reverse-gender plugs (Amphenol Series One) to avoid accidental sensor damage. The total cost of the solar power system was about $2000.

6. Software

The fast-response data collection program is of our own design and was coded by D. P. Billesbach. This program, which runs under the MSDOS operating system, has proven reliable at five different AmeriFlux towers since 1998. Only a few modifications were needed to adapt the program to this project. The central function of the program is to read the serial data stream from the anemometer and store it in binary form on a hard disk. The program can operate at any of the baud rates available from the anemometer, but is capable on only reading a single serial data stream. In addition, the program does online unit conversions and keeps running statistics (means, variances, and covariances) from which online fluxes and correction factors are calculated. We note that a new data collection program, which runs under most versions of the Windows operating system, is currently being developed and field tested. The new program will be capable of reading multiple serial data streams and will be able to interface to many different anemometers and IRGAs.

While the online flux values are considered fairly accurate, proper reprocessing of the raw data is necessary to obtain fluxes of the highest possible precision. The program used for this task (written by D. P. Billesbach) calculates and applies the optimum delay factor for each channel (Chahuneau et al. 1989) and removes mean values using a linear detrending technique (Rannik and Vesala 1999). Should the user desire, the program can be reconfigured to remove mean values by block averaging, or high-pass filtering. The program also calculates covariances, fluxes, and other relevant statistics. Finally, the program calculates all terms and correction factors (Webb et al. 1980; Moore 1986; Schotanus et al. 1983) needed to assemble nonadvective surface fluxes. To provide an estimated system error, the program calculates the worst possible covariance for each averaging period by correlating data points separated by at least one half of the averaging period. This number should represent only accidental correlations and is thus assumed to provide an estimate of the total system flux error. We assume that this total system flux error is also a good estimate of the point-to-point flux resolution of the system.

7. Field measurements

To validate and test the precision and accuracy of the system, we conducted three short field experiments in 2000 and 2001. The first two were intercomparisons at a pair of established AmeriFlux field sites. The first of these was in north-central Oklahoma near the town of Shidler and took place in a tall-grass prairie. The second was also in north-central Oklahoma, near the town of Ponca City and took place in a cultivated wheat field. The third experiment was an intercomparison between our portable system and the AmeriFlux reference system at the U.S. Department of Energy's Atmospheric Boundary Layer Experiment (DOE–ABLE) pasture site near Smileyberg, Kansas.

When the first experiment was conducted, the slow-response subsystem had not been completed and only the fast-response subsystem was deployed. The goal of this test was to establish the correct operation of our fast-response subsystem and to compare the precision of the fluxes obtained with those being collected from the closed-path IRGA flux system, already in operation at the site, under typical prairie growing conditions. The goal of the second test was to determine the precision with which we could make our fully corrected flux estimates and, because of the field conditions, to estimate the accuracy and minimum detectable levels of our measured fluxes. The third experiment had the objective of measuring the accuracy of our system, relative to the AmeriFlux standard. In addition, this experiment offered an opportunity to compare our flux reprocessing software with that used by the AmeriFlux standard system. For all three deployments, we used a 30-min averaging time for fluxes and 10-Hz sampling rate for the fast response instruments. These parameters will capture all of the significant high and low frequency flux components for our particular instrument heights, mean wind speeds, and for the local topography.

8. Data quality control and instrument calibrations

In the first two experiments, only the raw, fast response data were available from the ''permanent'' AmeriFlux stations. We processed these data using the same program that we used with our portable system data. For the third experiment, we were supplied with reprocessed fluxes from the AmeriFlux reference system. Before comparisons were made, each dataset was independently quality controlled. The criteria applied to the CO_2 flux data were as follows. First, all averaging periods where the mean horizontal wind speed was less than 2 m s^{-1} were rejected. This assured that the measured flux was not local in nature and was representative of the surrounding landscape. To eliminate anomalous spikes, we also rejected periods where the standard deviation of the CO_2 density was greater than 0.57 mmol m^{-3} (25 mg m^{-3}). All covariance and WPL terms were corrected for frequency losses and then summed to yield corrected surface fluxes.

Throughout the development and testing period, the calibration stability of the IRGA was found to be very good. Before the first deployment, both the CO_2 and the H_2O channels of the LI-7500 were calibrated [on day of year (DOY) 196]. Prior to this, the IRGA had last been calibrated on DOY 78. The IRGA offset was measured to be −5 ppmv. After this offset was adjusted, span gas with a mixing ratio of 384.9 ppmv was then introduced into the calibration hood and measured as 385.5 ppmv. This represented a gain drift of less than 0.2%. A similar procedure was applied to the H_2O channel using dry N_2 and a Licor LI-610 dewpoint generator. The offset was −3.2 mmol mol^{-1} and a dewpoint of 20.00°C was measured as 19.65°C. As a check of the CO_2 calibration, N_2 and a span gas (338.5 ppmv) were run in the field on DOY 201. The measured offset was −5.5 ppmv, and the span gas was measured at 335.5 ppmv. Calibrations made for the second and third deployments showed similar results.

9. First deployment

The first deployment near Shidler, Oklahoma was at a native tallgrass prairie and lasted from 16 July 2000 (DOY 198) until 22 July 2000 (DOY 204). At the time of this deployment, the slow-response subsystem was not finished, so only the fast-response subsystem was taken to the field. The portable tower was set up approximately 8 m west of the existing AmeriFlux tower. The IRGA was mounted on the west end, and the anemometer on the east end of the cross bar at the top of the tower and they were separated by about 30 cm on this east–west line. The sonic anemometer was located 4.05 m above ground level and the LI-7500 IRGA was located 3.75 m above ground. The vegetation height was about 40 cm. The permanent eddy covariance flux system was comprised of a Gill-Solent model R3 research grade sonic anemometer and a LiCor LI-6262 closed-path IRGA. The sonic anemometer was mounted 4.4 m above ground, and the IRGA inlet cup was attached to the anemometer body, just below the active volume. The sample flow rate was maintained at 8 standard liters per minute (SLM). The IRGA was housed in a small, modified refrigerator and kept at a constant temperature. This system recorded its data on a desktop computer housed in a small, air-conditioned shed and used a version of the same data collection program as was used by the portable system. Raw data from both the permanent and the portable systems were analyzed with our reprocessing program.

Because the portable slow-response subsystem was not available for this deployment, we used meteorological data (means of temperature, pressure, and relative humidity) collected by the permanent system for flux reprocessing. A diurnal plot of CO_2 fluxes measured by both the permanent and portable systems is shown in Fig. 2a. To more clearly illustrate how the two flux systems compare, Fig. 2b shows CO_2 flux values measured by the portable, open-path LI-7500 based system as a function of flux values measured by the permanent, closed-path LI-6262 based system. Comparison data for latent heat fluxes are shown in Fig. 3.

Besides using different IRGAs, the two flux systems also used different anemometers. To compare this aspect of the systems, we examined the sensible heat flux H, since the anemometer measures all data for this quantity. Figure 4 is a comparison of sensible heat fluxes from our portable system and the permanent system. In ad-

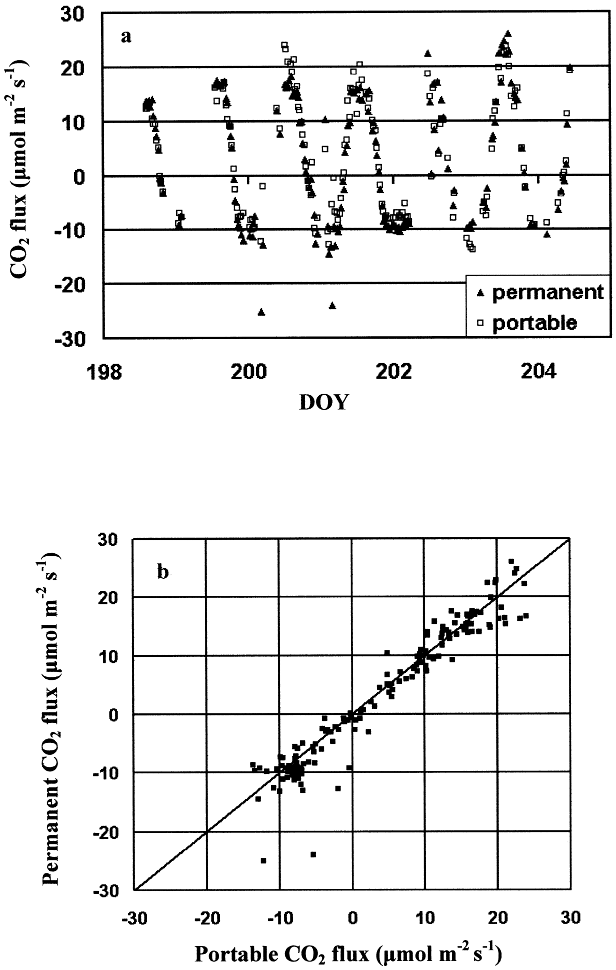

FIG. 2. Plots of the CO_2 fluxes measured during the first deployment (DOY 198–204). (a) The diurnal plot open boxes are fluxes from the portable system and the solid triangles are fluxes from the permanent system. (b) The horizontal axis represents the portable system and the vertical axis represents the permanent system.

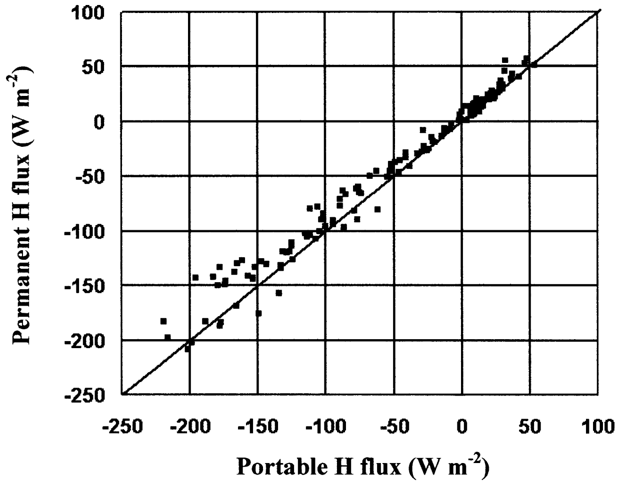

FIG. 4. Comparison of *H* fluxes between the portable system (horizontal axis) and the permanent system (vertical axis).

dition to the sensible heat flux, we also considered the friction velocity ($u*$), which is a function of the covariance between the vertical and horizontal wind speeds. A comparison between the two systems is shown in Fig. 5. Of the 261 individual flux averaging periods collected, 162 passed through the quality control filter.

10. Second deployment

The second deployment was in a freshly plowed, fallow wheat field near Ponca City, Oklahoma. The existing AmeriFlux site at this location was instrumented identically to the tall grass prairie site of the first experiment. This deployment lasted from 3 October 2000 (DOY 277) until 7 October 2000 (DOY 281). The portable fast-response tower was again set up approximately 10 m to the west of the permanent AmeriFlux tower. The portable sonic anemometer was mounted 4.2

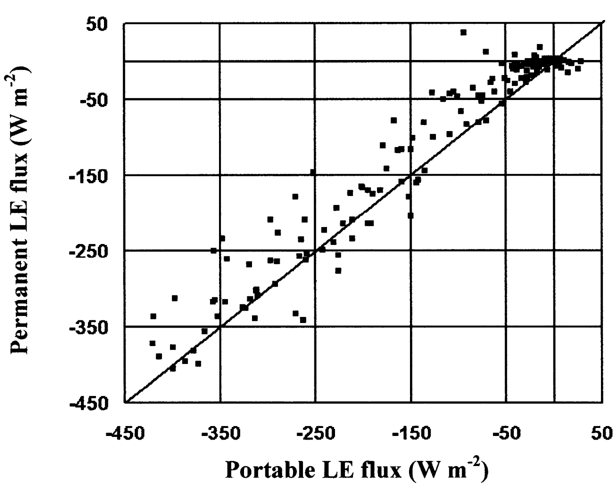

FIG. 3. Comparison of LE fluxes between the portable system (horizontal axis) and the permanent system (vertical axis).

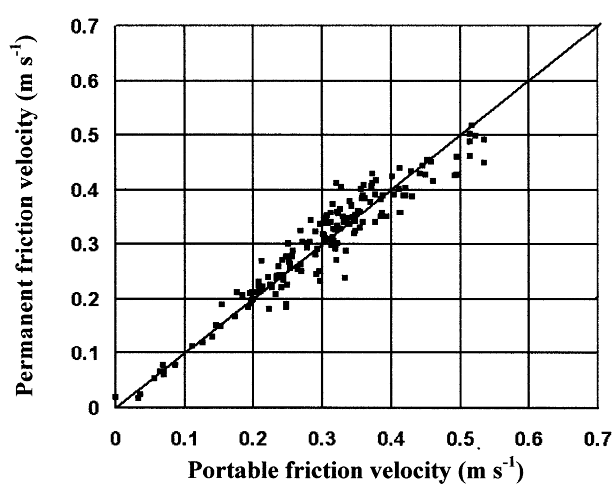

FIG. 5. Comparison of friction velocities between the portable system (horizontal axis) and the permanent system (vertical axis).

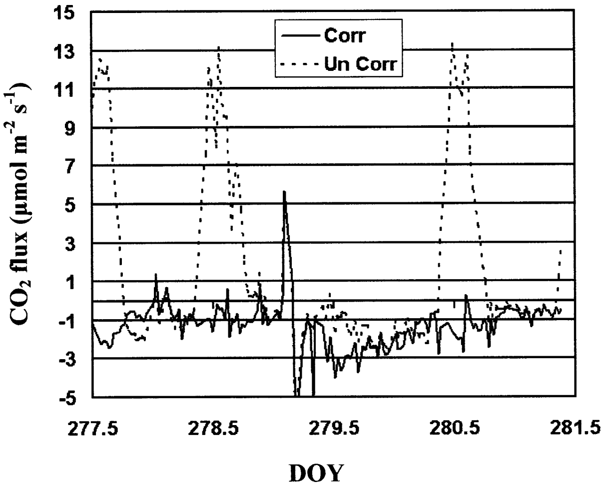

FIG. 6. Diurnal plot of the corrected (or total surface flux) (solid line) and uncorrected (or raw covariance) (dotted line) CO_2 fluxes obtained from the portable system during the second deployment (DOY 277–281).

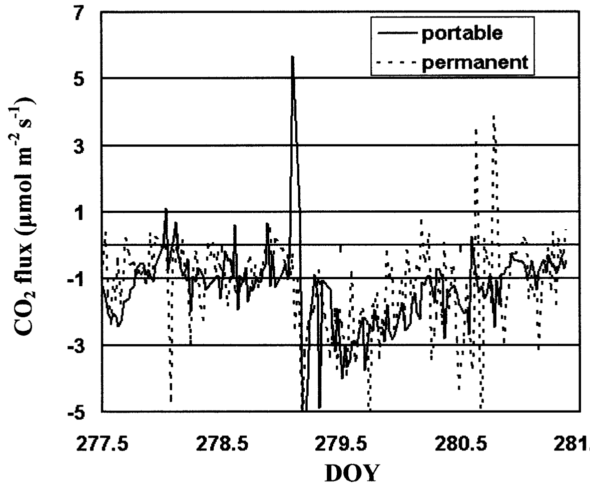

FIG. 7. Diurnal plot of the corrected surface CO_2 fluxes from the portable system (solid line) and the permanent system (dotted line) obtained during the second deployment (DOY 277–281).

m above ground and the IRGA was installed at 3.9 m. Like the first deployment, they were separated by 30 cm on an east–west line. The slow-response tower was located about half way between the portable fast-response tower and the AmeriFlux tower. The cup anemometer and wind vane were 3.45 m above ground and temperature/relative humidity sensors were located at 3.15 and 2.30 m above ground. The radiometers were mounted on the outrigger at a height of 2.35 m above ground. During the time of this deployment, the site was bare soil and had been under drought conditions for a number of weeks. The field had been freshly turned over about a week prior to our deployment. Because of the lack of vegetation, we anticipated little or no CO_2 uptake, and because of the dry conditions, we expected very small soil respiration fluxes. The net effect is that we anticipated very small total CO_2 fluxes. Because of the field conditions (freshly turned over, extremely dry and hard soil chunks), we decided that the soil heat flux and soil temperature sensors could not be properly installed and were left out of the system. Also, since there was no vegetation, the PAR sensor was not deployed. We expected relatively large sensible heat fluxes and small latent heat fluxes (i.e., large Bowen ratios). These are the most difficult conditions to accurately apply the WPL terms for flux measurements with an open-path sensor. Since the range of CO_2 flux values obtained during this deployment is very limited, a direct comparison plot does not yield any information that is not already contained in Fig. 2b. Figure 6 shows the diurnal series of raw and fully corrected CO_2 fluxes obtained from the portable system, and in Fig. 7, we show the corrected CO_2 fluxes from both systems. Of the 170 individual flux averaging periods collected, 161 were passed through the quality control filters.

11. Third deployment

The third deployment was in a grazed pasture near Smileyberg, Kansas, at the DOE–ABLE site. The intercomparison began on 14 May 2001 (DOY 134) and lasted until a strong storm forced the site to shut down on 17 May 2001 (DOY 137). Four eddy covariance flux systems were deployed at this site, but we will only report on the intercomparison between our system and the AmeriFlux reference system. Our fast-response tower was set up 12.6 m to the east of the AmeriFlux system. Our fast-response instruments were installed at a height of 3.79 m, and the other flux systems were installed at 4 m. Because of the limited space inside the fenced area, our slow-response tower was located about 3 m to the north of the fast-response tower. Since the predominant wind direction was from the south, this arrangement introduced minimal flow distortion to the fast-response instruments. The land surface was an actively grazed pasture with a vegetation height of about 20 cm. The AmeriFlux system was composed of an Applied Technologies, Inc. model SATI/3SX sonic anemometer and a LiCor LI-6262 closed-path IRGA. Further details of this system can be found in Evans (2000). Comparisons of CO_2, LE, H, and u* are shown in Fig. 8. Of the 113 flux averaging periods collected, 63 passed the quality control criteria.

Because we had our full complement of sensors deployed, we were able to estimate the degree of energy closure. This is shown in Fig. 9 where we plot H + LE as a function of available energy ($R_n - G$). A free regression fit to the data yields a slope of 0.887 ± 0.016 and an intercept of 22.5 ± 5.6 W m^{-2} ($R^2 = 0.97$). If we constrain the regression to pass through the origin, we obtain a slope of 0.929 ± 0.013 ($R^2 = 0.960$). It should be noted that energy balance as an indicator of the correctness of eddy covariance fluxes is a contro-

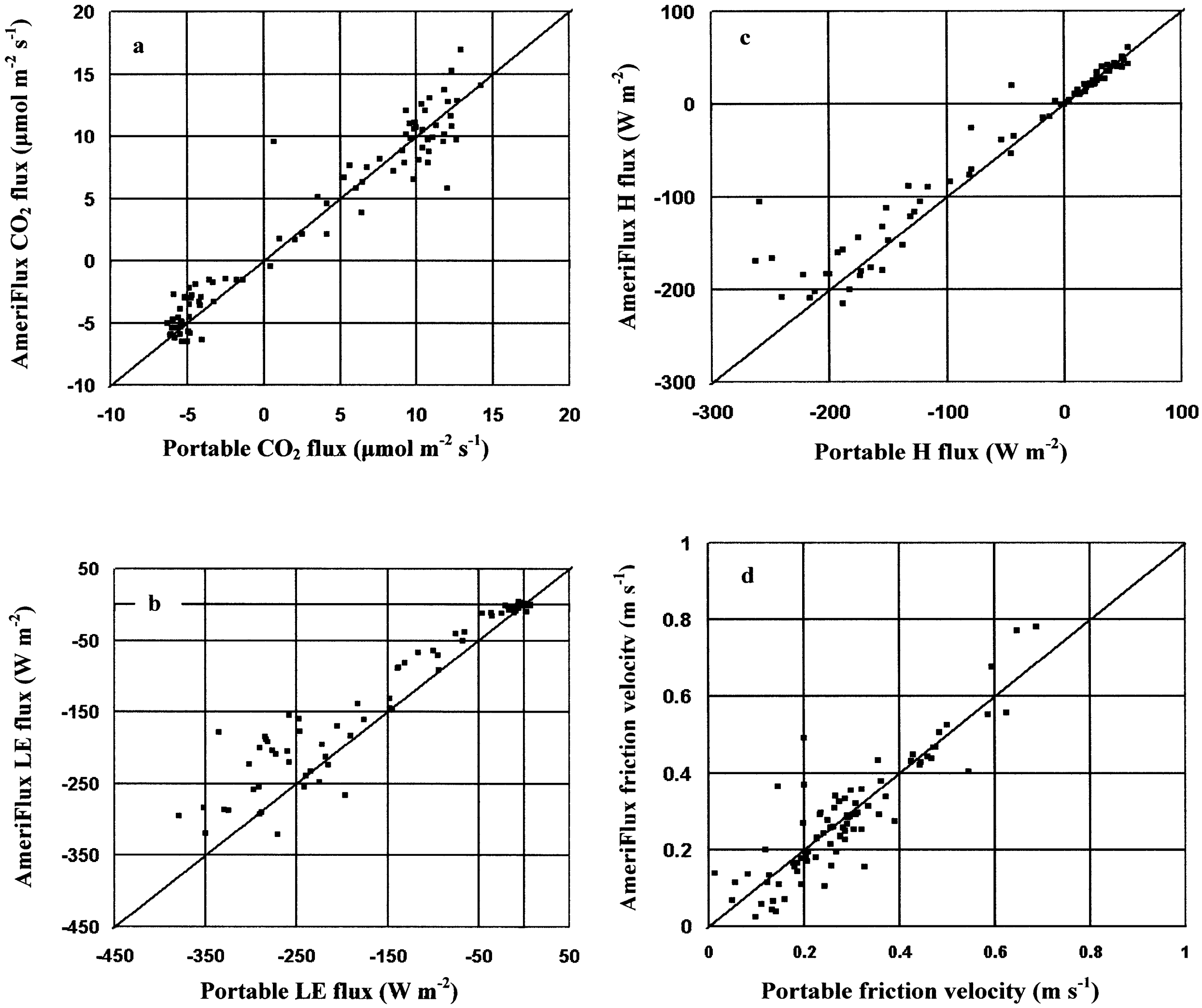

FIG. 8. Comparison of (a) CO_2, (b) LE, and (c) *H* fluxes and (d) friction velocities between the portable system (horizontal axis) and the AmeriFlux reference system (vertical axis).

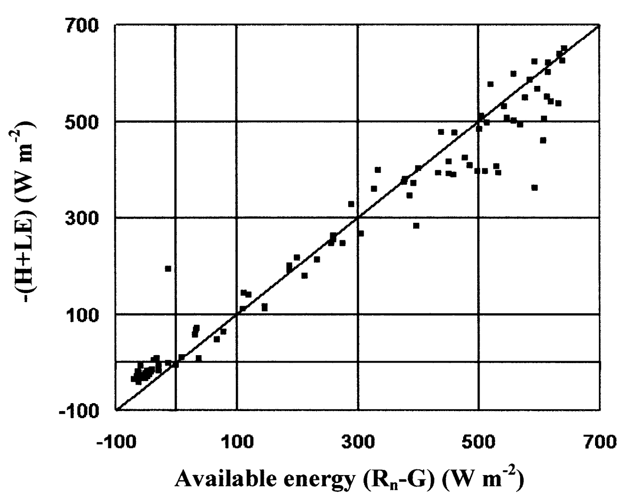

FIG. 9. Energy balance measured by the portable system during the third deployment.

versial issue. A comprehensive study of energy balance at more than 20 AmeriFlux sites (Wilson et al. 2002) indicates that the energy budget can often be open by 20% or more with the worst periods happening at night. We therefore include these results, not as conclusive evidence of the correctness of our fluxes, but simply as supporting evidence of the consistency of our slow-response results with our fast-response results within the limits of current energy balance theory.

12. Discussion of field results

The data in Fig. 2a show good qualitative agreement between the two flux systems. We note in the figure, that there are several gaps where flux values have been removed from the portable system record. Most notable is the early morning of DOY 199. During this period, strong thunderstorms moved across the region and produced rain events at the flux tower site. Data points that exhibited unrealistically large values of the variance in the CO_2 density were eliminated from further analysis. This effect was believed to be the result of rainwater collecting on the LI-7500 window and attenuating the infrared beam. This was not unexpected behavior for an open-path IRGA. When the LI-7500 was first installed, it was mounted vertically. After this rain event, we tilted it about 30° away from vertical to promote runoff. While this should have improved performance, we were not able to quantify the effect because there were no more significant rain events (note that the large gap in the morning of DOY 202 was caused by power problems). In this respect, the closed-path IRGA exhibited an advantage over the open-path design. While neither system performed adequately in heavy rains, the closed-path system was observed to operate in periods of light to moderate rain. Other rain events were noted in the early morning of DOY 202, and during the night and early morning of DOY 202 and 203. The data span a range of +24 (uptake) to −14 (respiration) μmol m^{-2} s^{-1}, and a regression fit to the data in Fig. 2b yields a slope of 1.03 ± 0.02 and an intercept of −0.97 ± 0.25 μmol m^{-2} s^{-1} (R^2 = 0.93) with an estimated system error (flux resolution) of ±1.2 μmol m^{-2} s^{-1}. While the slope is only 3% from ideal, the apparent bias of almost −1 μmol m^{-2} s^{-1} could be significant. Examination of Fig. 2b, however, shows that there are at least two points where the permanent system significantly overestimates fluxes relative to the portable system. It is possible that with more rigorous quality control, these points would be flagged as suspect, which would have the effect of reducing the relative offsets. Careful examination of Fig. 2b also reveals that no apparent nonlinear differences exist between the two systems. We note that the quality control criteria for this data ($u > 2$ m s^{-1}, and $\sigma_{pCO_2} <$ 0.57 mmol m^{-3}) are fairly simple and may include data where the strict conditions for good flux measurements were not met. We chose this approach to include as many data points as possible.

The one-to-one comparison of LE shown in Fig. 3 indicates some differences between the two systems. We note that the slope is 0.95 ± 0.02 and the intercept is 12.6 ± 3.6 W m^{-2} (R^2 = 0.94) with an estimated system error (flux resolution) of ±15 W m^{-2}. While the intercept is not excessive, it is significantly larger than the intercept of the sensible heat (H) comparison (see below). This behavior suggests that either the closed-path, LI-6262 based permanent system may be underestimating LE by several percent or the open-path, LI-7500 based portable system may be overestimating LE. Of particular interest are small values of LE, where we observe a distinct nonlinearity in the data. This nonlinear behavior suggests that for small LEs, the closed-path system may underestimate fluxes worse than at high LEs. This is consistent with expectations about closed-path IRGAs and their response to water vapor. Water vapor has one of the strongest dipole moments of all of the permanent atmospheric gases (Weast 1974). This implies that it will adsorb (or stick) to almost any surface, including the inner surface of a sampling tube or the walls of a closed-path analyzer cell. This could obviously cause serious high frequency loss in the water vapor spectral density, resulting in underestimation of the fluxes. In fact, Billesbach has observed exactly this effect in spectral plots of unpublished data comparing open-path with closed-path IRGAs. In addition, the nonlinear behavior combined with the large number of data points clustered at small values where the nonlinearity is strongest, may have biased the linear regression. A fit to points with LE values (from the portable system) of −50 W m^{-2} or less yielded a slope of 1.01 ± 0.04 with an intercept of 27.6 ± 0.3 W m^{-2} (R^2 = 0.88).

The regression fit to the sensible heat flux H shown in Fig. 4 yields a slope of 0.93 ± 0.01 and an intercept of 3.5 ± 0.9 W m^{-2} (R^2 = 0.98) with an estimated system error (flux resolution) of ±7 W m^{-2}. As with the CO_2 fluxes and the LE fluxes, this result indicates good agreement between the two systems. There does seem to be a region of possibly anomalous behavior at high values of H. In this region, it is possible that the permanent system might be underestimating, or the portable system overestimating the sensible heat flux. This effect, however, is manifest only in a small number of points and cannot be verified by this study.

The friction velocity comparison shown in Fig. 5 has a slope of 0.93 ± 0.02 and an intercept of 0.02 ± 0.01 m s^{-1} (R^2 = 0.91) with an estimated system error (resolution) of ±0.06 m s^{-1}. Again, this indicates good agreement between two different instrument systems. The similarities between the slopes of these two quantities, which are derived only from sonic anemometer data, suggest that both anemometers behave similarly.

Using the same reasoning as Eugster et al. (1997), the above slope data suggest that our system can resolve trend differences of 3% in CO_2 fluxes, 5% in LE fluxes, 7% in H fluxes, and 7% in friction velocity when compared to similar permanent flux systems.

During the second deployment, we concentrated on the problem of calculating precise WPL terms for CO_2 fluxes (Webb et al. 1980). As seen in Fig. 6, the raw CO_2 covariance (from the portable open-path system) showed a very strong diurnal variation. Because of the field conditions, we know that there was no photosynthetic contribution to the fluxes (there was no vegetation in the fetch) and, because of the extremely low soil moisture, that the heterotrophic soil respiration component was also small. Our expectation was that there should be very little diurnal pattern to the net CO_2 fluxes and we would see only a relative small and constant respirative flux. When all of the WPL terms are added, the resulting surface flux indeed conforms to these expectations. The corrected data show that the flux was almost constant until DOY 279. In the early morning of DOY 279, the site received several millimeters of precipitation, which was quickly absorbed by the soil surface. We expected to see the respirative CO_2 flux increase (grow more negative) slightly, and then taper off as the soil again dried out. This trend, while quite small is clearly apparent in the corrected data. The fully corrected surface CO_2 fluxes from the portable and permanent systems (Fig. 7) both show the above-described behavior, and quantitatively agree quite well. Careful examination of DOY 277 in Fig. 6 reveals that the corrected flux does show some diurnal pattern (slight respirative flux). When we compare this to the permanent closed-path system (no WPL *H* term and only a small WPL LE term), we see a similar trend and therefore believe that this is indeed a physiological effect. The only significant difference between the two systems seems to be less scatter in the portable fluxes (see Fig. 7) compared to the permanent system.

Examination of Fig. 8 shows that our portable system measures fluxes that are in good agreement with the AmeriFlux reference system. The regression parameters for CO_2 fluxes are slope $= 0.94 \pm 0.03$, intercept $= 0.50 \pm 0.22$ μmol m^{-2} s^{-1} ($R^2 = 0.93$); for LE, slope $= 0.84 \pm 0.02$, intercept $= 1.48 \pm 4.2$ W m^{-2} ($R^2 = 0.93$); for *H*, slope $= 0.86 \pm 0.02$, intercept $= 1.48 \pm 2.7$ W m^{-2} ($R^2 = 0.94$); and for u*, slope $= 0.98 \pm 0.06$, intercept $= 0.002 \pm 0.02$ m s^{-1} ($R^2 = 0.78$). As before, our analysis indicates a good comparison between these two flux systems. We note that the same nonlinear behavior of LE fluxes seen at low values in deployment 1 is also observed here. This is consistent with our hypothesis that there are attenuation processes associated with closed-path instruments, which are not properly accounted for, and cause excess attenuation of H_2O density fluctuations. We also note that the good energy balance (closure between 7% and 12%) shown in Fig. 9 indicates good internal consistency among our own instruments. Because the AmeriFlux roving system does not include soil heat flux sensors, we cannot directly compare our results to that system.

Even though these validation deployments were of limited duration, the data collected for the key eddy covariance fluxes (CO_2, LE, *H*, and u*) covered a large span of values. The comparison slopes for these quantities showed only small deviations from ideal comparisons, indicating little (if any) systematic differences between the flux systems. The extremely small gain drifts observed during our calibrations verify that little field maintenance is required for the IRGA. While some offset drifts were observed, they were small and are eliminated in the eddy covariance process.

The actual setup of the instruments went very smoothly. During the first deployment, Billesbach and Fischer set up the fast-response subsystem in about 2 h. During the second deployment, Billesbach set up both the fast and slow-response towers alone in less than 4 h. It should be noted, however, that these sites allowed easy and close vehicle access. For less accessible sites, longer setup times would be expected. In later deployments, we found that we could set up everything except the soil moisture and temperature sensors in similar times. Installation of the soil sensors added considerable time to the process and was found to be highly dependent on field conditions. For transportation, all components of both subsystems and the solar power module fit easily in a minivan and broke down into light sections, each less than 2 m in length. The heaviest components were the batteries and the tripod towers, which weigh between 25 and 30 kg each. The computer shelter unbolts into six flat panels if desired, or can be transported assembled. After the second deployment, the entire system was dismantled, loaded, and ready to travel in less than two hours. By design, only a minimal number of tools were required to set up and dismantle the system (two end wrenches, two Allen wrenches, a flat-blade screwdriver, wire cutters, a pipe wrench, and a hammer).

13. Conclusions

As demonstrated by these validation deployments, the portable eddy covariance flux system described here meets the stated design goals. As shown by the short setup and dismantling times and the minimal number of field personnel, the first two goals, portability and ease of setup, are well met. The measured power consumption of 35 W (or less) is much less than the 150–200 W required by previous systems based on closed-path analyzers (Eugster et al. 1997). The majority of the power savings come from elimination of the vacuum pump necessary in a closed-path flux system. The excellent calibration stability and good comparison with the established AmeriFlux system show that we have produced a high-precision, low-maintenance flux system. The close agreement with the AmeriFlux tall-grass prairie closed-path system under typical growth conditions shows that our system is capable of making flux measurements as precise as current closed-path based systems. Similarly, the good agreement with the AmeriFlux closed-path system during the second deployment shows that the WPL terms can be calculated with a high level of precision using this instrumentation. Despite this success, more work should be done to better understand the differences between fluxes made with open-path and closed-path IRGAs, especially for LE. Comparison to the AmeriFlux reference system shows that we can make flux measurements with the same relative accuracy as permanent or long-duration facilities. The system performed well in all field conditions except during periods of moderate to heavy rain. This clearly points out that no single flux system design is best for all environments. We would expect to have greater instrument availability in rainy environments (such as in the Amazon basin) with a closed-path based system. Finally, by using off-the-shelf parts and eliminating some instrument redundancies, the system was built for a relatively low total cost of less than $45,000.

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