Design of the AmeriFlux Portable Eddy Covariance System and Uncertainty Analysis of Carbon Measurements

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ABSTRACT

The AmeriFlux network continues to improve the understanding of carbon, water, and energy fluxes across temporal and spatial scales. The network includes ~120 research sites that contribute to the understanding of processes within and among ecosystems. To improve the network's ability and confidence to synthesize data across multiple sites, the AmeriFlux quality assurance and quality control laboratory was established to reduce the within- and among-site uncertainties. This paper outlines the design of the portable eddy covariance system (PECS) and subsequent data processing procedures used for site comparisons. Because the PECS makes precision measurements of atmospheric CO₂, the authors also present the results of uncertainty analyses in determining the polynomials for an infrared gas analyzer, estimating the CO₂ in secondary standards, and estimating ambient CO₂ in field measurements. Under field conditions, drift in the measurement of CO₂ increased the uncertainty in flux measurements across 7 days by 5% and was not dependent on the magnitude or direction of the flux. The maximum relative flux measurement error for unstable conditions was 10.03 μmol CO₂ m⁻² s⁻¹.

1. Introduction

AmeriFlux is a network of ~120 long-term research sites across North America measuring the exchange of water vapor (q) (see Table 1 for a list of variables, etc.), sensible heat, and carbon fluxes between the atmosphere and biosphere using the eddy covariance (EC) technique. EC has enhanced our understanding of the net ecosystem exchange of these scalars at different temporal and spatial scales (cf. Baldocchi 2003; Loescher et al. 2006). Sources of systematic and random error in datasets from individual sites have been discussed (Moncrieff et al. 1996; Goulden et al. 1996b; Foken and Wichura 1996; Kruijt et al. 2004; Loescher et al. 2006) and reducing these uncertainties has increased our confidence in and interpretation of research activities. As more datasets from individual sites are being used for cross-site comparisons and for regional scaling activities, the focus is also on reducing among-site uncertainties and in examining flows not accounted for that may contribute to the net exchange of scalars (Loescher et al. 2006). To reduce and quantify these uncertainties, the AmeriFlux quality assurance and quality control (QAQC) laboratory was created to enhance data quality and ensure consistency in EC measurements within and among sites.

The primary activities of the AmeriFlux QAQC laboratory involve the use of a portable eddy covariance system (PECS, discussed below). This system includes all necessary hardware and software to make EC measurements, including other meteorological sensors (i.e., air temperature, radiation measurements, atmospheric pressure). During conditions when fluxes span a large range (i.e., during the active growing season), the PECS is transported to selected AmeriFlux sites, set up next to the existing EC systems, and ~5 days’ worth of data are collected and compared. Sources of uncertainty in EC measurements can result from hardware, software, and the instrument installation. The goal of site comparisons is to identify systematic errors due to hardware (e.g., instrument bias, malfunctioning hardware, or outdated calibrations) and software. We identify errors due solely to different software routines by asking each site to process a standard and independent raw data file developed by the Euroflux and AmeriFlux networks (“gold files” for closed- and open-path infrared gas analyzers, respectively, which can be found on-
Concerns regarding the installation strategy of permanent instruments may be discussed during site comparisons, but the ultimate decision on instrument configuration and site representativeness is left to the principal investigators.

A few research groups that participate in the AmeriFlux network have begun using automated calibration systems to improve the quality of their CO$_2$ measurements. Accurate and precise measurements of atmospheric CO$_2$ concentration (c, $\mu$mol CO$_2$ mol$^{-1}$) are needed in the EC approach to (i) measure the turbulent...
fluctuations of $c$; (ii) calculate the Webb, Pearman, and Leuning (WPL) term (Webb et al. 1980) that can account for mass transport due to changes in water vapor density and temperature not accounted for in the covariance between vertical wind velocity and $c$ (Leuning et al. 2004; Massman 2004); and (iii) calculate the vertical (Lee 1998) and horizontal advection (Paw et al. 2000), which are based largely on theoretical arguments that rely on our ability to estimate a true $c$. The AmeriFlux QAQC portable EC system also utilizes an automated calibration system to reduce the uncertainty in field measurements of $c$ during site comparisons.

Quantifying the error associated with flux measurements made by the PECS establishes a standard by which site comparisons are made, provides a statistical framework for comparing data among multiple sites, and establishes a basis to understand the sources of error in flux data used for model parameterization (cf. Hollinger and Richardson 2005). Emphasis is also being placed on providing uncertainty estimates when reporting net ecosystem exchange values. Here, the design of the PECS and its associated uncertainty in $c$ measurements is described, and the short-term uncertainty in carbon flux measurements is estimated to provide guidance for current and future research activities.

**Comparison philosophy**

The goal of an AmeriFlux site comparison is to investigate the whole system ability to measure all quantities necessary to calculate fluxes of $q$, $c$, energy, and momentum transport, as well as the mean quantities necessary for EC calculations and analyses, which include wind velocities, air temperature ($T_a$), incident and net radiation, atmospheric pressure, and photosynthetic photon flux density. To best carry out these tasks, the calibration of each PECS instrument is maintained according to manufacturers' recommendations, but often these calibrations are performed more frequently in efforts to achieve the measurement accuracy and precision necessary to answer key ecological questions. We acknowledge that there is no ideal instrument arrangement for all site conditions and that each site investigator understands their measurement system and ecosystem best. So, whether each site's EC system adequately measures the ecosystem in question is left to the individual investigators to justify (e.g., averaging times, measurement heights, fetch, source areas, and fluxes not accounted for).

During a site comparison, the PECS instrumentation is installed as close as possible to the permanent instruments while minimizing any flow distortion or shadowing. In this way, each EC system is subject to the same source area and turbulent regime, and any apparent differences between the two EC systems are assumed to be associated solely with the measurement system (software and hardware). Comparisons are made at ~20 sites per year, collecting at least two hundred forty 30-min averaging periods per visit. We prefer to compare data during periods when fluxes span a large range, because measuring small fluxes near zero provides little understanding of how the whole EC system behaves in response to changes in ecosystem function. After a field campaign, each site must provide both the field data and the results from processing the gold files for comparison. Results from the comparison are communicated to the site investigator and attempts are made to resolve any apparent discrepancies in the data. Data analyses are made as quickly as possible, so if problems
are identified they can be promptly resolved thereby minimizing any long-term and avoidable systematic errors.

2. **PECS description**

The PECS includes the sensors needed to measure meteorological variables necessary for eddy covariance calculations (i.e., turbulent exchange) and analyses (http://public.ornl.gov/ameriflux/; Table 2). The instrument models used in the PECS were chosen based on their proven quality, reliability, and robustness. The use of any instrument in the PECS, however, is not a direct endorsement of that product by the AmeriFlux network. The PECS includes both an open-path (LI-7500, LI-COR, Inc., Lincoln, NE) and closed-path (LI-7000, LI-COR, Inc.) infrared gas analyzer (IRGA) for $c$ and $q$ measurements. The open-path sensor is best suited to measure turbulent fluctuations in the in situ environment, but relative uncertainties can be large when fluxes are close to zero, while the closed-path sensor is ideal for inclement weather and for higher precision in $c$ measurements (Leuning and Judd 1996).

### a. Master enclosure

The core component of the PECS is the master enclosure (Fig. 1), which includes the electronics for the open-path IRGA, datalogger, atmospheric pressure sensor, a module to linearize the raw platinum resistance thermometer (PRT) signal, relays, closed-path IRGA and pressure controller, temperature controls, power converters, and miscellaneous connectors, all housed in a lightweight and waterproof aluminum case. Custom-made racks were installed to mount the instruments and provide a chase to route cables and tubing. Instruments are mounted on sliding shelves made of nonconductive material, which provide access to the rear of the instruments. To facilitate rapid deployment, all external sensors (Table 2), except the LI-7500, connect to the datalogger through fast connecting bulkhead fittings (Weathertight series, Switchcraft, Inc., Chicago, Illinois). The LI-7500 uses a custom 6-m cable with 20 signal lines and connects the probe directly to the electronics board with a special connector.

The master enclosure is mounted on the tower as close as possible to the sonic anemometer and closed-path inlet without distorting the turbulent structures of...
interest. The primary motive is to minimize the length of tubing between the sample inlet and the closed-path sensor (therefore minimizing the high-frequency attenuation by the tubing). The tubing inlet is located as close to the sonic transducers as possible without removing air from the sonic volume. The sample tubing (1/8" ID Bev-a-line IV, Thermoplastics Processing, Inc., Stirling, New Jersey) is 6 m long and is heated and insulated to a constant temperature (38°C) from the inlet to the entrance of the master enclosure to avoid condensation and to dampen the temperature fluctuations (cf. Webb et al. 1980). Before the sample air enters the closed-path IRGA, it passes through a heat exchanger mounted on the back of the master enclosure to avoid condensation and to dampen the temperature fluctuations. The heat exchanger is 1 m of 1/8" ID stainless steel tubing surrounded by a jacket of deionized water.

The closed-path IRGA samples the flow of air at ~25 kPa below atmospheric pressure, which results in a flow rate of ~8.5 L min⁻¹. The sample air first passes through a solenoid valve (used for the autocalibration system described below) then a 1.0-μm Gelman filter (Pall Corporation, Ann Arbor, Michigan) before it enters the optic cell of the IRGA. The optic cell pressure is controlled with a pressure controller mounted after the outlet of the IRGA. A buffer volume of ~1.4 L is placed between the pressure controller and a 120-VAC rotary vane pump so that oscillations caused by the pump will not affect the measurement of turbulent fluctuations in the sample cell. Reference zero air (either high purity N₂ or CO₂-free air) is supplied from a tank at ground level and passes through a large desiccant chamber (flow passing through soda lime, then magnesium perchlorate) before it enters the reference cell of the closed-path IRGA. Flow rate through the reference cell is controlled at ~15 mL min⁻¹ by a rotameter (Aalborg, Inc., Orangeburg, New York).

The specification for zero drift in the closed-path IRGA is 0.1 μmol CO₂ mol⁻¹ °C⁻¹ (cf. LI-7000 instruction manual). To minimize zero drift, temperature of the optic cell is held stable by two 12-VDC 25-W heat strips attached to the top and bottom of the sensor and two 12-VDC fans [38–45 cubic feet per minute (cfm)] that pull ambient air across the analyzer for cooling. The optic cell temperatures are controlled by the data-logger that switches the heat strips and fans. Cell temperature is maintained near the expected maximum daytime $T_a$ (set point) because the PECS is capable of heating the closed-path IRGA above ambient temperatures, but it cannot cool the closed-path IRGA below...
ambient temperatures because cooling is accomplished by passing ambient air across the analyzer. When ambient temperatures are below the set point the closed-path IRGA temperature is maintained within ±0.15°C of the set point. An external shield is also mounted on the outside of the master enclosure ~3 cm away from the housing to help reflect incident radiation and stabilize cell temperatures during daytime conditions.

Specific field conditions differ among sites, for example, the range of ambient temperatures, tower configurations, power restrictions, site access, etc., forcing the design of a portable system to be very adaptable. We use several designs of custom-mounting brackets to facilitate rapid, adjustable mounting. If the site has limited power availability, the pump and ±15-VDC power supply are replaced with units that operate on 12 VDC. The open-path IRGA’s optic path and the anemometers’ sonic volume are mounted at the same height vertically.

b. Data acquisition

The datalogger is used to (i) acquire all data at a high frequency, (ii) store 20-Hz time series, (iii) calculate preliminary fluxes online, (iv) control optic cell temperature, and (v) control the automated calibration system (discussed below). Although not all the instruments of the PECS have response times greater than 20 Hz, we collect and store them all at this frequency in order to have one complete dataset, which eliminates postprocessing errors due to linking datasets. Data from the open-path IRGA are triggered with the sonic anemometer using the synchronous device for measurement in the datalogger. Because the sonic anemometer and open-path IRGA have different internal processing speeds, data from these instruments lag behind the timestamp by several records (2 and 5 records for the CSAT-3 and LI-7500, respectively, referred to here as a timestamp delay). This timestamp delay is accounted for by programming a ~250-ms delay in capturing the LI-7500 signal by our data acquisition system, as per the manufacturer’s instructions.

Because the two EC systems are only compared for a few days, we collect the data on Personal Computer Memory Card International Association (PCMCIA) cards (maximum storage 4 Gb corresponds to 16 days’ worth of data) and examine it daily. Even during these short field campaigns small data gaps may occur in the high-frequency time series. A program (TOB32.exe, Campbell Scientific, Inc.) is used to identify discontinuities in the time series by directly checking the timestamp for each line of 20-Hz data and to create separate files for each continuous time series before we begin processing the data for EC estimates. Discontinuities are rare and occur only during a few (<10) 30-min averaging periods per year.

c. Processing software, screening procedures, and diagnostics

EdiRe (v1.4.3.1021) is used to process all PECS data; it is robust, adaptable, programmable, and routines can be archived, which maintains long-term consistency in measurements, and can be freely downloaded at http://www.geos.ed.ac.uk/abs/research/micromet/EdiRe/.

Before using processed PECS data for a comparison, data are removed when (i) signals were out of range, (ii) 30-min collection periods were incomplete, (iii) precipitation occurred, (iv) flow occurred through the tower or other instrumentation that could cause significant flow distortions, (v) rotation angles were outside the manufacturer’s limits, (vi) poor data quality was indicated by either the sonic anemometer or by the IRGAs (i.e., data flags) (vii) periods of nonstationarity occurred, and (viii) simple diagnostic values were met according to Foken et al. (2004, discussed below). Spikes in each acquired signal are identified and also removed when a data point (in the raw, high-frequency dataset) is >6 standard deviations above the mean and exists for no more than four consecutive records within each 30-min averaging period. Additional data are removed based on the screening procedures used by the individual site. For example, our data are not explicitly filtered using a $u_*$ criterion [see appendix A, Eq. (A3); Black et al. 1996; Goulden et al. 1996a; Gu et al. 2005; Loescher et al. 2006], but when site investigators use a $u_*$ filter to determine their data quality, our data are accordingly removed from the comparison.

Stationarity is one of the diagnostic values and is estimated by determining each turbulent flux with a 5-min averaging period, averaging six 5-min averaging periods, subtracting this ensemble 30-min flux from the original 30-min estimate, then determining what percent of the original flux this difference represents (Foken et al. 2004). These authors recommend that if this difference is >30%, nonstationarity occurs violating an assumption of the EC technique. This is a reasonable criterion when determining the flux from a specific ecosystem. But because objectives of the comparison are to assess the system response to changing turbulent environments, and because both the PECS and the site EC system are subject to the same change in environmental conditions, the nonstationarity criteria is relaxed to >50% (Fig. 2a).

Corrections are made to some of the raw data signals before postprocessing can begin. A 2D coordinate ro-
tation is performed to align the horizontal wind speeds with the local streamline and force the lateral velocity components to zero for each 30-min period. A 2D coordinate rotation is used rather than the planar fit method (cf. Wilczak et al. 2001) because the short duration of the comparison (i.e., ~5 days) does not allow for the correct determination of planar fit coefficients. Time delays between the measured sonic and IRGA signals can occur due to the physical separation between the sonic volume and the tubing inlet for the closed-path IRGA and between the sonic volume and the optic path for the open-path sensor. Additional time delays occur in the closed-path environments due to the time it takes a parcel of air to travel the tube length. These time delays are accounted for, in concert, by maximizing the correlation coefficient (in units of time) between the rotated vertical wind speed and the $c$ and $q$ of the open- and closed-path signals for each 30-min period. A fixed lag time is used when the correlation coefficients are not physically meaningful, that is, $\pm 1$ s from a theoretical lag time based on the physical dimensions of the tubing and the flow rate. Covariances are estimated using a block average for the operator (cf. Loescher et al. 2006; appendix A) as recommended by the AmeriFlux Steering Committee. Loss of high-frequency information in closed-path measurements are accounted for using a transfer function approach (Massman 2000; Massman and Lee 2002; Massman and Clement 2004). We also estimate cospectral similarity as an alternative way to assess the high-frequency loss if sites use this methodology (Loescher et al. 2003). But this method assumes scalar similarity, which may not be valid for all sites and conditions (cf. Moore 1986). The mass transfer due to changes in air temperature and humidity from one averaging period to the next is accounted for in the open-path measurements (Webb et al. 1980; Massman 2004). Because all IRGA measurements are a number density measurement (cf. Massman 2004), millivolt signals from the open path are first collected as mol m$^{-3}$, then the subsequent density corrections are applied to the flux estimate. The turbulent carbon flux from both the open- and closed-path IRGAs normally are in good agreement once their respective corrections are made (Fig. 2b).

Cospectral density often exhibits a sharp cascade in the inertial subrange (1–10 Hz), often with a slope $< -5/3$ (Fig. 3), and exhibited behavior close to ideal as described in Kaimal and Finnigan (1994). At frequencies $>6$ Hz the closed-path cospectra are often attenuated (Fig. 3a), but when compared to the cospectra from the open-path sensor (Fig. 3b), little contribution to the total flux is often measured at these higher frequencies.

d. IRGA calibrations during field comparisons

The $q$ and $c$ calibrations in the open-path IRGA are done manually and only at the beginning of each site comparison unless the data indicate a need for additional calibrations. Here, $q$ is always calibrated before $c$ with a dewpoint generator (LI-610, LI-COR, Inc.). Closed-path calibrations are also preformed at the be-
\[ c = T_c \psi_c f \left( \frac{A}{\psi_c P}, S_c \right), \]  

(1)

where \( A \) is the absorptance of \( c \) in the sample cell (dimensionless; cf. LI-7000 manual), \( T_c \) is cell temperature (K), \( \psi_c \) is correction for water vapor (dimensionless), \( P \) is cell pressure (kPa), \( S_c \) is the span gain parameter (i.e., adjustment value) for \( c \) (mV), and \( f \) is a polynomial applied to the normalized absorptance value. Here and elsewhere, a third-order polynomial is determined over a range of \( \sim 300-501 \mu \text{mol CO}_2 \text{ mol}^{-1} \), after performing a zero calibration. This differs from the factory calibration, which uses a fifth-order polynomial over the range of \( 0-3000 \mu \text{mol CO}_2 \text{ mol}^{-1} \). A third-order polynomial over a smaller range of ambient \( c \) maximizes our overall accuracy over this range. After \( c \) is calculated internally, its value is converted to an analog signal and is output by the IRGA using a digital-to-analog converter (DAC), such that

\[ c = V \left( \frac{X_c - X_0}{V_{\max}} \right) + X_z = aV + b, \]  

(2)

where \( V \) is the measured DAC signal (mV), \( V_{\max} \) is the full-scale millivolt output, and \( X_c \) and \( X_z \) are the \( c \) values associated with \( V_{\max} \) and the minimum output (e.g., 0 mV for unipolar output). Once the DAC is configured, the conversion can be expressed as a first-order expression [right-hand term in Eq. (2)], where \( a \) and \( b \) represent the slope and zero offset, respectively.

To help correct for instrument drift of the LI-7000, we can directly estimate a new \( a \) and \( b \) using an automated calibration system with two secondary \( c \) standards (\( \sim 80 \mu \text{mol CO}_2 \text{ mol}^{-1} \) apart). Without reconfiguring the DAC output, a new \( c \) estimate can be calculated using Eq. (3a), where \( a_{\text{new}} \) can be estimated by the slope between the two gases, Eq. (3b), and then \( b_{\text{new}} \) can be calculated using Eq. (3c):

\[ c = a_{\text{new}} V + b_{\text{new}}, \]  

(3a)

\[ a_{\text{new}} = (C_H - C_L)(V_H - V_L), \]  

(3b)

\[ b_{\text{new}} = C_L - a_{\text{new}} V_L, \]  

(3c)

where \( C_H \) and \( C_L \) are the two respective high and low \( c \) standards, and \( V_H \) and \( V_L \) are their respective millivolt measurements from the IRGA. After every automated calibration cycle, \( a_{\text{new}} \) and \( b_{\text{new}} \) are recalculated and applied to estimate \( c \).

The automated calibration system used in the PECS is housed in one enclosure that is mounted on the tower near the master enclosure. The PECS contains three solenoid valves (7000 series three-way valves, Parker

![Figure 3. Variance normalized cospectra of the (a) closed- and (b) open-path IRGAs. These data are expanded cospectra within each stability class from a total of three hundred twenty-one 30-min averages. Data were collected from Howland Forest, ME (45°12’N, 68°44’W), 23–30 Jul 2005. Cospectra were calculated 2048 bytes per spectra size and outputted in 100 bins. Sensor separation between the closed-path IRGA and sample inlet was 6 m.](image-url)
Skinner, Inc., New Britain, Connecticut) and two 1.2-L gas tanks, which contain \( \sim 21 \) days’ worth of calibration gases at an output of 0.5 L min\(^{-1} \) (controlled by the tank regulators and a pressure controller; Table 2). The air sampled by the closed-path IRGA passes through the solenoid valves, which have an internal diameter that matches that of all sampling tubing to maintain the turbulent structure of the sample as much as possible. Constant and identical cell pressures are maintained during normal operation (sampling atmospheric air) and during the calibration cycle. The standard gases are cycled through the IRGA every 7 h, changing the 30-min periods from one day to the next that have to be removed from the flux estimates as a result of the automated calibration cycle. Two secondary gas standards are measured by the closed-path IRGA during each cycle (i.e., \( C_L \) and \( C_H \)). During the automated calibration cycle, each standard gas is sampled for 3 min and the data from the last minute are used in Eq. (3c).

3. Materials and methods

a. Theoretical considerations

Here, the term uncertainty is defined as an estimate that characterizes the distribution of the values that could reasonably be attributed to the measured value (ISO 1995). The measured value may include uncertainty from multiple sources, such as the case with trace gas measurements that may incorporate uncertainty due to primary gas standards, secondary standards, instrument precision, instrument drift, and residual error in calibration coefficients. An uncertainty analysis of a system directly measuring a quantity is relatively straightforward once all sources of uncertainty have been identified and can be calculated as follows (ISO 1995; Lira 2002):

\[
u = \sum \sqrt{\alpha_i^2 s_{d_i}^2} \quad \text{and} \quad \alpha_i = \sqrt{\frac{1}{n_i}}, \quad (4)
\]
where \( u \) is the uncertainty for the measurement of interest, \( \alpha_i \) is the sensitivity coefficient expressing the contribution of each component \( i \) to the overall uncertainty \( (u) \), \( s_d \) is the standard deviation of the individual source of uncertainty, and \( n \) is the number of samples. For this analysis, \( \alpha_i \) is simplified because the raw absorptance signal is the only input variable used in the polynomial to calculate \( c \). Here, the uncertainty takes a similar statistical form as the standard error. To provide a comprehensive uncertainty estimate, \( u \) can be expanded to a specific confidence level,

\[
U = ku,
\]

where \( U \) is an expanded uncertainty of the measurement, and \( k \) is the \( t_{\alpha/2, v} \) critical value obtained from the \( t \) table for the appropriate number of degrees of freedom (cf. Ott 1993) and is referred to as the coverage factor (ISO 1995); \( k \) is difficult to quantify empirically and with large degrees of freedom \( k \approx 2 \) (ISO 1995; Bevington 1969). Care must also be used when purchased standards are used, as the reported uncertainty may be either \( u \) or \( U \). If the uncertainty of a purchased standard is reported as \( U \), this must first be converted to \( u \) before it can be included in Eq. (5).

The uncertainty analysis described here is for each component that contributes toward the field measurement of \( c \), the calibration of the laboratory IRGA used to measure the primary and secondary \( c \) standards, the least squares method to convert millivolts to \( c \), and the use of an automated calibration system under field conditions.

### b. Estimating uncertainty of \( c \) measurements

1) **Laboratory calibration system**

   The AmeriFlux QAQC laboratory uses a dedicated temperature and pressure-controlled LI-6262 IRGA (SN LI-784, LI-COR, Inc.) to calibrate secondary \( c \) standards. Drift in the instrument is discussed in section 3d. The IRGA temperature is maintained at 30° ± 0.02°C (~9°C above room temperature) by placing it inside an acrylic chamber vented with a fan for cooling and heated with two 25-W heat strips placed on the upper and lower surfaces of the IRGA casing and collocated with the optic cell. A datalogger monitors IRGA cell temperature (model 23X, Campbell Scientific, Inc.) and is used to control the switching of the heat strips and fan. Flow rate is 0.025 L min⁻¹ through the sample cell regulated by a mass flow controller (model AFC 2600, Aalborg, Inc.). The outlet pressures from the primary standard tanks are adjusted so that the cell pressure does not vary more than ±0.06 kPa (data not shown). The IRGA is operated in absolute mode with high purity N\(_2\) gas scrubbed with a large desiccant chamber and flowed continuously through the reference cell at ~15 mL min⁻¹ controlled with a rotameter (model EW-03217-02, Cole Parmer, Inc., Vernon Hills, Illinois). Contamination of the desiccant is avoided because it is replaced or redried between each application. When the temperature of the IRGA has stabilized, five World Meteorological Organization–Climate Monitoring and Diagnostics Laboratory (WMO–CMDL) standards (within the normal range of ambient \( c \), 330–500 \( \mu \)mol mol⁻¹) and high-purity N\(_2\) are each sampled at 1 Hz for 180 s and data from the first 120 s are discarded. This 120 s allows for the system to flush ~6 times with gas and allows the flow controller to stabilize. Outlet pressures (~20 psi) from each tank of gas are maintained using high-precision, low-volume regulators (5114C590, Scott Specialty Gases, Plumsteadville, Pennsylvania). Gas transport from the tank to the solenoid is through ~6 m of 0.48-cm ID tubing (Synflex 1300 tubing, Synflex Hose and Tubing, Inc., Aurora, Ohio). Cycling of the standard gases is from low to high concentration, then from high to low concentration to minimize any sampling bias from the previous sampled concentration. Gases are switched using three-way solenoid valves, relays (model G4PB4R, Opto 22, Inc., Temecula, California), a small volume manifold (<0.8 mL), and the datalogger. A third-order polynomial is then used to describe the relationship between instrument millivolts and \( c \) using the least squares method. Note, the millivolt data are normalized by cell pressure and the \( c \) values are normalized by cell temperature as per recommended by LI-COR, Inc. (see LI-6262 CO\(_2\)/H\(_2\)O analyzer instruction manual, LI-COR publication number 9003–59).

   Calibrating the IRGAs used in the PECS is almost identical to the method used for the LI-6262 to calibrate the secondary \( c \) standards (described above). The only difference is that the absorption of \( c \) by the LI-7000 and LI-7500 is measured directly, rather than acquiring the raw millivolt signal, like that from the LI-6262. The respective absorption signals are normalized by cell temperature and pressure differently to estimate new \( c \) polynomials (cf. LI-7000 and LI-7500 manuals). New \( q \) polynomials are also estimated in the same way as the \( c \) polynomials using an airstream with a known dewpoint (made by a LI-610 portable dewpoint generator) and are measured independently by a chilled mirror as the standard (D2 sensor and Optica VGA monitor, General Eastern, Bussum, Netherlands, with an accuracy of ±0.2°C and precision of ±0.05°C). The polynomial is generated using data over the dewpoint temperature range of 0°–20°C.
2) The uncertainty of IRGA calibrations

There are three sources of uncertainty in calibrating the IRGAs, namely, the use of primary standards, inherent variability in the measurement system, and least squares polynomial fit (Fig. 4). The uncertainty attributed to our measurement system includes two components, variability in the physical environment in the optic cell and electronic signal “noise” (from both the IRGA and datalogger). The uncertainty of our measurement system was assessed by determining the precision of the IRGA while sampling CO₂-free air. CO₂-free air was sampled at 1 Hz for 60 s after the CO₂ signal stabilized and then the standard deviation (sd) was calculated for this period. By making this measurement, the uncertainty from each component is inherently pooled and is defined as the precision in our measurement system (ISO 1995). The gas standards were assumed to be well mixed when passed through the measurement system and did not create c fluctuations in the optic cell (i.e., steady-state conditions prevail).

3) The uncertainty in estimating secondary c standards

Secondary c standards are mixed and calibrated in the AmeriFlux QAQC laboratory. In addition to the uncertainty described in section 3b, the uncertainty in the secondary c standards also includes the respective measurement errors while sampling the gases to be calibrated. The calibration cycle described above is used with one modification; the secondary c gas is sampled for 180 s at 1 Hz between the two ramp schedules and the first 120 s were discarded.

4) The uncertainty in field measurements of ambient c

Field measurements of c have more uncertainty than those measured in the laboratory because the IRGA is subject to two additional sources of instrument drift: changes in the physical environment of the optic bench and electronic drift. Changes in the physical environment of the optic bench can be caused by temperature and pressure changes as well as accumulation of debris in the sample and/or reference cell. Electronic drift can result from the continual measurement of the reference gas to determine a baseline measurement (zero drift) and changes in the response of the IRGA to c (span drift). A few researchers account for this drift in field measurements by periodically (e.g., every 4–12 h) sampling secondary c standards with the closed-path IRGA. The uncertainty in field measurements includes these sources of instrument drift over time unless an automated calibration system is used to correct for them. If an automated calibration system is implemented, then the uncertainty for field measurements only includes the uncertainty associated with the secondary c standards and DAC conversions (see detailed discussion in appendix B; Fig. 4). When using an automated calibration system, a span drift can cause a change in the resolution of c calculated according to Eq. (3). The resolution of c in Eq. (6) can be determined when the c range represented by the DAC mV output is known:

\[ \text{DAC resolution} = \frac{c_0 - c_{\text{max}}}{2^{14}} \]

where \( c_0 \) and \( c_{\text{max}} \) are the expected CO₂ values at 0 and 5 VDC, respectively. The denominator in Eq. (6) is fixed because the LI-7000 DAC channel is a 14-bit device. A span drift (i.e., change in the sensitivity of the instrument) results in a change of the c range that is represented by the DAC output, which can be accounted for by re-estimating \( a_{\text{new}} \) (Eq. (3)) after an automated calibration cycle. It is important to note, however, that the physical resolution of the DAC output itself does not change. For our instrument configuration, the physical resolution of the DAC output is fixed at 5000 mV \( 2^{-14} \) bits or 0.305 mV bit\(^{-1}\). Data from the automated calibration system during the 2005 field season showed a typical change in \( a_{\text{new}} \) of \( \sim 0.003 \text{ mV} \) \( \mu \text{mol CO}_2 \text{ mol}^{-1} \) over a 5-day period. This resulted in a total loss of c resolution over the entire 300–650 \( \mu \text{mol CO}_2 \text{ mol}^{-1} \) range of 15 \( \mu \text{mol CO}_2 \text{ mol}^{-1} \). For any point measurement (measured mV), however, the change in resolution was only 0.001 \( \mu \text{mol CO}_2 \text{ mol}^{-1} \), which was small compared with the other sources of uncertainty (i.e., primary and secondary gas standards and the IRGA polynomial). When the automated calibration system was used, instrument drift was eliminated from the overall uncertainty and was replaced by the uncertainty due to DAC conversions, which were two respective orders of magnitude smaller.

c. Estimating the effect of span drift on calculated carbon fluxes

The effect of span drift on carbon fluxes measured using a closed-path IRGA was modeled with data collected by our PECS during the 2005 site comparison at Harvard Forest. For this modeling exercise, we compared a true carbon flux calculated from our original data to a “span drifted” carbon flux that was modeled. The true carbon fluxes were calculated from the original time series data as described in section 2c. The raw mV signal from the closed-path IRGA DAC channel was converted to \( \mu \text{mol mol}^{-1} \) using Eq. (3) and then
used to calculate $\overline{w^c}_\text{true}$ [cf. appendix A, Eq. (A2)]. The true carbon fluxes were calculated by holding $a$ in Eq. (2) constant to simulate a stable IRGA with no instrument drift. Span-drifted fluxes were estimated based on actual measured drift measured by the automated calibration system. Because the measured span drift was nearly linear, a simple linear model was used to calculate the drift for each 20-Hz record. Then the span-drifted flux was modeled by adding the drift to $a$ to obtain $a_{\text{new}}$ in Eq. (3a) prior to calculating $\overline{w^c}_\text{drift}$. In other words, the difference between the original slope $a$ and $a_{\text{new}}$ provided a measure of the span drift over a 7-day period. Using the 20-Hz data, true and span-drifted fluxes were calculated and compared.

d. Relative flux measurement error

The RFME has been estimated using aircraft data (Lumley and Panosky 1964; Lenschow et al. 1994; Mann and Lenschow 1994):

$$\frac{\sigma_f(L)}{\overline{F}} = \left( \frac{2\pi}{L} \right)^{0.5} \left( \frac{1 + r_{wc}^2}{r_{wc}^2} \right)^{0.5} \left( 1 - a_{\omega^c} \right) r_{wc}^2 = \frac{\overline{w^c}^*}{\sigma_w \sigma_c}, \quad \text{and}$$

$$\frac{\sigma_f(T)}{\overline{F}} = \left( \frac{2r_{wc}}{T} \right)^{0.5} \left( \frac{1 + r_{wc}^2}{r_{wc}^2} \right)^{0.5}$$

(7a)

where $L$ is the length of the flight leg (m), $\tau$ is the Eulerian integral length scale (m), $r_{wc}$ is the correlation coefficient (dimensionless) between the vertical wind velocity, $w$ (m s$^{-1}$), and the scalar $c$, and $a_{\omega^c}$ is the height of the aircraft above ground (m). For tower measurements, $L$ is replaced with the averaging time $T$ (s) and $\tau$ is replaced with the integral time scale of $\overline{w^c}^*$ ($\tau_{wc}$; Katul et al. 1997 and their appendix C) and $a_{\omega^c} = 0$, that is, Eq. (7b). Term I of Eq. (7b) estimates the error associated in our ability to measure the turbulent transport over a finite averaging period. Here, $\tau_{wc}$ is the mean size of turbulent structures, in units of time, that contribute most to $\overline{w^c}^*$ for each 30-min period, which also corresponds to the peak of the cospectral density (Kaimal and Finnigan 1994). Larger errors in term I occur when the production of turbulence increases, thereby reducing the overall number of turbulent events that are measured during one averaging period and decreasing our certainty in mean quantities. Term II is an estimate of all the systematic and random errors associated with the measurement system, and the error associated with any violation of the assumptions that are fundamental to the eddy covariance method, for example, Taylor’s hypothesis. Because we attempt to remove or minimize all systematic errors, the remaining and assumed predominate source of error are from random sources. RFME is calculated here for 30-min averaging periods.

Relative measurement errors of carbon fluxes were calculated for both the closed- and open-path sensors at three sites: deciduous hardwood (Harvard Forest), grassland (Konza Prairie), and evergreen conifer (Gainesville) (see appendix C). The data included in this analysis were from the PECS only and not from the permanent instrumentation installed at these sites. Here, $\overline{w^c}^*$, $\sigma_w$, and $\sigma_c$ for each 30-min averaging period were calculated as described in section 2a and used to calculate RFME values using Eq. (7b). The $\tau_{wc}$ for each 30-min averaging period was calculated by integrating the area under the autocorrelation function of $\overline{w^c}^*$ to the first zero crossing using a trapezoid function (Lenschow and Stankov 1986; appendix C in Katul et al. 1997). The results of the RFME analysis were separated into three stability classes according to the stability parameter ($s$): neutral ($-0.1 < s < 0.1$), stable ($s > 0.1$), and unstable ($s < -0.1$) [see appendix A, Eq. (A1)].

4. Results

a. Uncertainty in $c$

1) IRGA POLYNOMIALS

There are three sources of uncertainty in determining the IRGA polynomials: the use of primary standards, inherent variability in the measurement system, and least squares polynomial fit (Table 3). The Climate Monitoring and Diagnostics Laboratory reports the uncertainty in the near-ambient WMO-CMDL $c$ standards to be $\pm 0.07$ $\mu$mol CO$_2$ mol$^{-1}$ (D. Kitzis 2006, personal communication). The uncertainty in the least squares polynomial fit was generally small and could be reduced by adding more primary standards to the calibration cycle. Here, $u$ was $\pm 0.23$ $\mu$mol CO$_2$ mol$^{-1}$, and $U$ was $\pm 0.46$ $\mu$mol CO$_2$ mol$^{-1}$ for the IRGA polynomial using Eqs. (4) and (5), respectively (Table 3). The certainty in $u$ and $U$ was only applied using the range of sampled gases, in this case the range was 0 to $\sim 501$ $\mu$mol CO$_2$ mol$^{-1}$, the uncertainties may be larger if a broader range of standards were used.

2) SECONDARY $c$ STANDARDS

Using Eqs. (4) and (5), respectively (Table 3), $u$ was $\pm 0.37$ $\mu$mol CO$_2$ mol$^{-1}$, and $U$ was $\pm 0.74$ $\mu$mol CO$_2$ mol$^{-1}$ for the secondary $c$ standards.
Table 3. The expanded uncertainty $U$ for three different types of measurements associated with the PECS is presented: calibration of secondary $c$ standards and field measurements of $c$ without and with the use of an automated calibration system, respectively. All uncertainties are reported in units of $\mu$mol CO$_2$ mol$^{-1}$. Each component uncertainty $u_i$ is also given, as per Eq. (3), and $u_{\text{precision}}$ for both the LI-6262 and LI-7000 was measured using 1-Hz data of five WMO–CMDL standards averaged over two 60-s periods. Residual standard errors from the least squares regression analysis were used for $u_{\text{polynomial}}$. The sd of the mean $c$ in the secondary standard for each automated calibration system calibration cycle were measured 18 times over 3 days and used in Eq. (3) to calculate $u_{\text{reproducibility}}$.

<table>
<thead>
<tr>
<th>Expanded uncertainty</th>
<th>Uncertainty component</th>
<th>sd</th>
<th>$\alpha$</th>
<th>$u_i$</th>
<th>$U$</th>
</tr>
</thead>
<tbody>
<tr>
<td>*Primary $c$ standards</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>±0.07</td>
<td>na</td>
</tr>
<tr>
<td>LI-6262 precision</td>
<td>0.07</td>
<td>0.13</td>
<td>±0.11</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>LI-6262 polynomial</td>
<td>0.45</td>
<td>0.45</td>
<td>±0.02</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>LI-6262 calibration</td>
<td>na</td>
<td>na</td>
<td>±0.20</td>
<td>±0.40</td>
<td>na</td>
</tr>
<tr>
<td>**Secondary $c$ standards</td>
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<td>0.12</td>
<td>±0.11</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>LI-7000 precision</td>
<td>0.07</td>
<td>0.13</td>
<td>±0.11</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>LI-7000 polynomial</td>
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<td></td>
<td>±0.02</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>LI-7000 reproducibility</td>
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<td>0.25</td>
<td>±0.48</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>**Secondary $c$ standards</td>
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<td>0.12</td>
<td>±0.11</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>Field measurements with 3 days of instrument drift</td>
<td>na</td>
<td>na</td>
<td>±0.79</td>
<td>±1.58</td>
<td>na</td>
</tr>
<tr>
<td>*Primary $c$ standards</td>
<td>na</td>
<td>na</td>
<td>±0.07</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>LI-7000 precision</td>
<td>0.14</td>
<td>0.10</td>
<td>±0.11</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>LI-7000 polynomial</td>
<td>0.05</td>
<td></td>
<td>±0.02</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>**Secondary $c$ standards</td>
<td>0.08</td>
<td>0.12</td>
<td>±0.31</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>DAC conversion</td>
<td>&lt;0.01</td>
<td></td>
<td>&lt;0.01</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>Field measurements with automated calibration system</td>
<td>na</td>
<td>na</td>
<td>±0.51</td>
<td>±1.04</td>
<td>na</td>
</tr>
</tbody>
</table>

** The precision of secondary $c$ measurements.

### 3) FIELD MEASUREMENTS

The zero drift ranged from $-0.82$ to $0.34$ $\mu$mol CO$_2$ mol$^{-1}$ and the span drifted from $-1.78$ to $0.73$ $\mu$mol CO$_2$ mol$^{-1}$ over a 3-day period (Fig. 5). Drift of this magnitude corresponded to the uncertainty in the LI-7000 reproducibility of $\pm 0.10$ $\mu$mol CO$_2$ mol$^{-1}$ (Table 3). Without correcting for instrument drift, $u$ of our field measurements of $c$ is $\pm 0.85$ $\mu$mol CO$_2$ mol$^{-1}$, and $U$ was $\pm 1.70$ $\mu$mol CO$_2$ mol$^{-1}$. This analysis was made over a 3-day period, a much shorter interval than what is common at field sites (e.g., calibration intervals of 7 days or longer). When the automated calibration system was used for measurements of $c$, $u_i$ was $\pm 0.6$ $\mu$mol CO$_2$ mol$^{-1}$ for field measurements of $c$, and $U$ was $\pm 1.2$ $\mu$mol CO$_2$ mol$^{-1}$ (Table 3).

**b. The effect of span drift on carbon fluxes**

The effect of an uncorrected span drift was larger than anticipated. Over a 7-day period the span drift was equal to $\sim 10\%$ of the measured $c$ and drifted linearly during this period (Table 4). After 7 days, the difference between the true and span-drifted integrated $\vec{w}'\bar{c}'$ was $\sim 5\%$. Because the span drift changed the slope of the polynomial used to convert the IRGA absorptance to $c$, $\bar{c} - \bar{c}'_{\text{drift}}$ is not equal or in the same direction over the entire range of ambient $c$.

**c. Relative flux measurement error**

RFME values from the three sites were generally larger during periods of neutral and stable atmospheric conditions (Table 5) compared to conditions when the surface layer was well mixed (unstable conditions). During unstable conditions term II [Eq. (7b)] was smaller than during neutral and stable conditions, but the integral time scales did not differ greatly (data not shown). The PECS had higher RFME values at the Gainesville and Harvard sites than at Konza Prairie. This was a result of the smaller integral time scales at the grassland site due to the higher-frequency turbulence above the short, uniform canopy (Table 5).

RFMEs from the open-path IRGA signals were generally smaller than those found from using the closed path. Integral time scales from the two sensors were nearly identical. Therefore, the larger closed-path RFMEs were the result of a larger term II [Eq. (7b)] compared to those found by the open-path sensor.

### 5. Discussion

Here, we present a comprehensive and robust EC measurement system that serves as the AmeriFlux network standard, all the sources of uncertainties in $c$, the effects of drift in $c$ measurements on flux measure-
Drift in $c$ can increase errors in turbulent flux measurements (cf. Fig. 5) to $\sim5\%$ after 5 days between calibrations (Table 4), which does not appear to scale similarly (e.g., with the same sign) in both uptake and efflux (i.e., daily integrals, Table 4). For example, in our modeling exercise the span drift caused respiration to be overestimated at night and carbon uptake to be underestimated during the day (data not shown). A linear regression between drifted and measured $\overline{w^2}c$ resulted in a slope of 1.025, which is a small source of error for any 30-min average, but summed over a day, week, or month may have a significant effect on flux estimates. Approximately 75% of AmeriFlux sites do not have the WMO–CMDL primary standards to calibrate their secondary $c$ standards used in the field. The reported uncertainty in many purchased secondary tanks are 1% or larger, increasing the uncertainty in accuracy to $\pm 4$ $\mu$mol CO$_2$ mol$^{-1}$ for a standard close to ambient values. Moreover, most EC measurement sites do not employ an automated calibration of their closed-path IRGA and rely on manual calibrations at intervals of $>7$ days. If long-term accuracy and precision is ensured with frequent calibrations (from hours to days), minimizing the effects of drift on flux measurements, then the largest single source of uncertainty in field $c$ estimates is in the secondary $c$ standards and the ability to automate the calibrations. Identifying and reducing this source of uncertainty among research sites is a tangible goal.

During unstable conditions, the RFME estimated here ranged from 0.05 to 0.37, within the range reported by Hollinger and Richardson (2005), which was $\sim0.05$ to 0.6 for any individual 30-min period. In all cases, the RFME increased significantly for measurements in neutral atmospheres. Our study also showed a smaller RFME at Konza Prairie suggesting differences in site characteristics can also affect RFME, that is, $z \geq 35$ $d$ [Eq. (A1)], and cospectral peaks shifted toward higher respective frequencies. Moreover, Hollinger and Richardson (2005) found that the relative flux uncertainty from the closed path decreased with increasing uptake.

Table 4. The effect of span drift on calculated turbulent fluxes, where $\overline{w^2}c_{\text{true}}$ and $\overline{w^2}c_{\text{drift}}$ are 24-h integrals and units converted. Span drift was modeled in the turbulent exchange, $\overline{w^2}c_{\text{drift}}$, over a 7-day period using data collected by the PECS at Harvard Forest 2005. The percent difference in $c$ measurements between original data and span-drifted data is the percent difference at the end of each day.

<table>
<thead>
<tr>
<th>Day of year</th>
<th>$c$ percent difference</th>
<th>$\overline{w^2}c_{\text{true}} - \overline{w^2}c_{\text{drift}}$ (g m$^{-2}$ day$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>193</td>
<td>0.004</td>
<td>-0.006</td>
</tr>
<tr>
<td>194</td>
<td>0.011</td>
<td>0.116</td>
</tr>
<tr>
<td>195</td>
<td>0.017</td>
<td>0.36</td>
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<tr>
<td>196</td>
<td>0.03</td>
<td>0.429</td>
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<tr>
<td>197</td>
<td>0.039</td>
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<tr>
<td>198</td>
<td>0.049</td>
<td>-0.065</td>
</tr>
<tr>
<td>199</td>
<td>0.053</td>
<td>0.574</td>
</tr>
</tbody>
</table>
rates, but the absolute uncertainty increased with increasing uptake rates. Richardson et al. (2006) also found that the absolute uncertainty increased with increasing uptake but did not report an RFME. Here, the RFME remained relatively constant for unstable conditions, but the absolute uncertainty did increase with increasing uptake rates. Generally, term I was less than term II in Eq. (7b); hence term II contributed a larger overall affect on the RFME. But, it is not apparent which variable(s) in Eq. (7b) increased the values of RFME found in other studies. The only apparent difference among closed-path IRGAs used among these studies is the higher measurement resolution, that is, mV μmol m⁻² s⁻¹ CO₂ mol⁻¹, used here. The higher resolution enabled our closed path to differentiate smaller differences in 𝜈, but this does not necessarily translate to larger 𝜎c values. Richardson et al. (2006) found that the open-path IRGA had smaller uncertainty values than the closed path, though the differences were generally small. We also found that the open-path RFMEs were generally smaller than those for the closed path. When the individual variables used to calculate RFME for open- and closed-path sensors were compared, the largest difference was found in 𝜂. The closed-path sensor had smaller 𝜎c values, which resulted in larger values for term II in Eq. (7b). This may be, in part, a result of the high-frequency loss due to air being pulled through the tubing for closed-path measurements. The RFME may not be a robust estimate under all conditions. As Richardson et al. (2006) points out, the RFME is based on the same variances and covariances as the mean flux estimate, and the integral time scale may not adequately substitute for the integral length scale and may be, at times, dependent on other physical or turbulent structures. Yet, there is often very good agreement between the closed- and open-path estimates of turbulent flux estimates once the appropriate corrections are applied (Fig. 2B). Moreover, AmeriFlux intercomparisons of turbulent carbon exchange rarely observe departure from two independent EC systems of >12% (data not shown). Taken in concert, we have high confidence in the ability of both IRGAs to measure the turbulent environment and that the RFME (because of its untested statistical derivation) should be viewed theoretically as an upper limit of the flux error for any particular averaging interval, and may be in question when used for Kalman filter approaches to optimize parameters in estimating functional relationships like light-response curves, ecosystem respiration rates, and the affects of vapor pressure deficit on carbon uptake.

All EC sites have different protocols to maintain quality control and assurance in their data products. In part, this is due to the flexibility of having multiple investigators each with an individual and site specific approach to surface atmosphere measurements. One type of system design does not fit all the necessary conditions and logistics for all sites. Here, we present a consistent, high precision method to measure 𝜈 and its associated uncertainty and to assess the turbulent exchange of carbon in a uniform way across the entire AmeriFlux network. But because of the addition of new technologies, replacement of sensors, turnover of investigators, etc., enhancing network-level QAQC is a continual process to monitor each site, and if necessary, remedy any issues that may occur.

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G. Bracher for graphic art, and the anonymous reviewers for their thoughtful comments.

APPENDIX A

Supplemental Equations to Define Quantities Expressed in the Text

To characterize the stability at the sonic anemometer height $Z$ (m) a stability parameter ($s$) was used, such that

\[ s = \frac{Z - d}{L_{MO}} \quad \text{and} \quad L_{MO} = \frac{u^3 \rho_a C_p T_u}{kg H}, \tag{A1} \]

where $d$ is the zero plane displacement (m), which is the height at which the wind profile extrapolates to $\sim 0$ m s$^{-1}$ within the canopy; $L_{MO}$ is the Monin–Obukhov length (m), ratio of convective to mechanical turbulent production, with $u_\ast$ defined as friction velocity (m s$^{-1}$) and calculated by Eq. (A3) (cf. Monteith and Unsworth 1990); $\rho_a$ is the density of air (kg m$^{-3}$), $C_p$ is specific heat capacity of air (J kg$^{-1}$ K$^{-1}$); $k$ is von Kármán’s constant (0.40); $g$ is the acceleration due to gravity (9.81 m s$^{-2}$); and $H$ is the sensible heat flux calculated using the covariance of vertical velocity and sonic temperature (W m$^{-2}$; cf. Loescher et al. 2005).

The turbulent exchange of $c$ is calculated by

\[ \overline{w'c'} = \sum_{0}^{n} \frac{(w' - \overline{w'})(c' - \overline{c})}{n}, \tag{A2} \]

where $n$ is the number of samples, $w$ is the vertical wind velocity (m s$^{-1}$) as measured by the sonic anemometer (primes denote instantaneous measurements), and the overbar is a block-averaged mean determined across the average period (to define the turbulent fluctuations; Loescher et al. 2006).

Friction velocity $u_\ast$ was calculated similarly to $\overline{w'c'}$ and substituting cross- and long-wind velocities by

\[ u_\ast = \left[ \left( \overline{w'|u_x'} \right)^2 + \left( \overline{w'|u_y'} \right)^2 \right]^{0.25}, \tag{A3} \]

where $u_x$ and $u_y$ are the cross- and long-wind velocities (m s$^{-1}$), respectively.

APPENDIX B

Changes in the Closed-Path IRGA Output Resolution as a Result of Span Drift

The uncertainty introduced by the automated calibration system into field-measured $c$ is elucidated in three different examples: 1) following a manual calibration at time 1 ($t_1$), 2) when a zero drift has occurred at time 2 ($t_2$), and 3) after a span drift and zero drift has occurred ($t_3$). Assumptions are (i) the DAC output remains linear with time, (ii) the response function (inter-

FIG. B1. Effects of drift on $c$ measurement, with (a) three examples of how the automated calibration system was used to correct for instrument drift in the field. These results were modeled from measured instrument drifts observed in the field over a 5-day period. Example $t_1$ shows the linear relationship immediately following a manual calibration in the field, setting both the zero and span values using the LI-7000 software. Examples $t_2$ and $t_3$ show the change in the linear relationship that would result from instrument drift in the LI-7000; $t_1$ was modeled with only a zero drift, and $t_2$ was modeled with both a zero and span drift. The change in the slope of the linear relationship in $t_1$ represents the change in the sensitivity of the DAC output and (b) the difference in the resolution of $c$ resulting from a span drift. The change in the resolution was modeled by adjusting $S_z$ in Eq. (1) and calculating $\sigma_{new}$ using Eq. (3b). Note the change in $c$ resolution can increase or decrease. In this case, the resolution of $c$ decreased $-0.003$ μmol CO$_2$ mol$^{-1}$ with a 50 μmol CO$_2$ mol$^{-1}$ span drift.
for zero and span as described in the LI-7000 manual. In these examples, the automated calibration system’s $C_L$ and $C_H$ were 380.43 and 452.61 μmol CO$_2$ mol$^{-1}$, respectively; the $V_{max}$ was 5000 mV; $X_f$ and $X_c$ were 600 and 300 μmol CO$_2$ mol$^{-1}$ making Eq. (4)

$$CO_2 = V(0.07) + 300.$$ (B1)

This initial relationship between DAC output and $c$ is shown in Fig. B1a (solid line).

In example 1, immediately following this manual calibration, $V_L$ and $V_H$ were 1149 and 2180.14 mV, respectively, as output by the DAC channel (solid line in Fig. B1a). In example 2, after a zero drift occurred at $t_2$, each standard gas was plumbed through the IRGA automatically, and the zero and span values were not reset (as occurs during in situ experiments). At $t_2$, $V_L$ and $V_H$ measured by the closed-path IRGA were 1099 and 2130.14 mV, respectively (dashed line in Fig. B1a). Applying the logic in Eq. (3b), the slope did not change, $a = a_{new}$, but $b_{new} = 303.5$ μmol CO$_2$ mol$^{-1}$. In example 3, after a 1 μmol CO$_2$ mol$^{-1}$ span drift occurred at $t_3$ relative to conditions established at $t_1$ (no zero drift), the DAC output for the two standard gases were 1163.64 and 2223.22 mV, respectively (dotted line in Fig. B1a). Here, both $a_{new}$ and $b_{new}$ changed to 0.068 and 301.16 μmol CO$_2$ mol$^{-1}$, respectively, changing the range of $c$ represented by the DAC output (the dependent variable). Note that the change in $a_{new}$ and $b_{new}$ can increase or decrease.

In example 1, the resolution of $c$ is 0.0214 μmol mol$^{-1}$. After the span drift in example 3, the $c$ range was reduced from 350 to 340 μmol mol$^{-1}$ with a corresponding reduction in resolution to 0.0208 μmol mol$^{-1}$. And even though the range in the $c$ standards (10 μmol CO$_2$ mol$^{-1}$) seems large, it only corresponds to a resolution loss of <0.001 μmol CO$_2$ mol$^{-1}$. If the $c$ range represented by the DAC output increased, then the resolution of $c$ can become enhanced.

Holding all other variables constant in Eq. (2), $S_c$ was adjusted to model the change in slope [term $a_{new}$, Eq. (3)] due to span drift in the IRGA (Fig. B1b). Using an extreme example of a span drift of ~50 μmol CO$_2$ mol$^{-1}$ the DAC resolution changed by only 0.003 μmol CO$_2$ mol$^{-1}$. Including this error in any analysis of $c$ measurements is relatively small.

Data from the automated calibration system during the 2005 field season showed a typical slope change in Eq. (3) was ~0.003 mV μmol CO$_2$ mol$^{-1}$ over a 5-day period. This resulted in a total loss of $c$ resolution over the whole 5000-mV range of 15 μmol CO$_2$ mol$^{-1}$. For any point measurement (measured mV), however, the change in resolution was only 0.001 μmol CO$_2$ mol$^{-1}$, which was small compared with the other sources of uncertainty (i.e., primary and secondary gas standards and the IRGA polynomial).

APPENDIX C

Site Location and Characteristics Used for the RFME Analyses

<table>
<thead>
<tr>
<th>Location</th>
<th>Ecosystem type</th>
<th>Lat</th>
<th>Lon</th>
<th>Alt</th>
<th>Canopy height</th>
<th>d</th>
<th>$Z_m$</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harvard Forest, MA (main tower)</td>
<td>Mixed eastern deciduous/conifer</td>
<td>42°32'N</td>
<td>72°10'W</td>
<td>340</td>
<td>24</td>
<td>14</td>
<td>−0.2</td>
<td>30</td>
</tr>
<tr>
<td>Konza Prairie, KS (LTER site)*</td>
<td>Managed prairie</td>
<td>39°01'N</td>
<td>96°33'W</td>
<td>324</td>
<td>0.15</td>
<td>0.08</td>
<td>−0.02</td>
<td>2.9</td>
</tr>
<tr>
<td>Gainesville, FL (ACMF)**</td>
<td>Uneven-aged Pinus Elliottii and P. Taeda</td>
<td>29°44'N</td>
<td>82°13'W</td>
<td>50</td>
<td>22</td>
<td>19</td>
<td>−0.3</td>
<td>32</td>
</tr>
</tbody>
</table>

* LTER = Long-Term Ecological Research.
** ACMF = Austin Cary Management Forest.

REFERENCES


---, ---, ---, ---, and ---, 1996b: Measurements of carbon


