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Field-scale application of flux measurement by conditional sampling

J.M. Baker[a], J.M. Norman[b] and W.L. Bland[b]
[a]*US Department of Agriculture, Agricultural Research Service, St. Paul, MN 55108, USA*
[b]*Department of Soil Science, University of Wisconsin–Madison, Madison, WI 53706, USA*

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ABSTRACT

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Increasing concerns about atmospheric transport of agricultural chemicals and the diffuse emission of greenhouse gases are motivation for development of accurate, straightforward methods for measurement of trace gas fluxes. A recently proposed hypothesis suggests that the flux of a substance is directly proportional to the product of the standard deviation of the vertical wind velocity (σ_w) and the difference between mean concentrations of that substance in upward- and downward-moving eddies (ΔC). Reported simulations indicate that the coefficient of proportionality (β) is unaffected by atmospheric stability and may be similar for heat, water vapor, and, presumably, other scalars. This research was conducted to evaluate the validity of this hypothesis and the utility of the method at the farm field scale. The system we developed samples air from the immediate vicinity of a one-dimensional sonic anemometer. There are two sample lines; one is open only when vertical velocity (w) is positive, and the other is open only when w is negative. These lines are routed to a differential gas analyzer, which simultaneously measures ΔC for both CO_2 and H_2O. A data-logger samples w at 10 Hz, controls the solenoid valves, and computes σ_w. It also samples a fine-wire thermocouple to allow computation of sensible heat flux by both eddy correlation and conditional sampling. Field tests were conducted in a soybean (*Glycine max*) field at Rosemount, MN. Two data sets of sensible heat flux, each with more than 250 observations, both produced estimates of $\beta = 0.56$, comparable with the previously reported estimate of 0.6 $\pm$ 10%. We show that this is not an altogether empirical value, but is derivable from statistical considerations. The value of 0.56 was used in subsequent measurements of latent heat flux (LE) and carbon exchange rate (CER) with an IR gas analysis-based system. There are discretization errors in the sample system that caused systematic underestimation of ΔC, for which we derived an approximate correction. Even with this correction, measurements of LE still tended to be somewhat lower than residual energy balance estimates of LE. In one 4 day trial, the slope of measured LE vs. residual-estimated LE was 0.96, whereas in a second trial the slope was only 0.86. Although such results indicate that further research is necessary, they also provide encouragement that such work will be worthwhile.

Correspondence to: J.M. Baker, US Department of Agriculture, Agricultural Research Service, St. Paul, MN, USA.

INTRODUCTION

Measurement of gas-phase transport is necessary in a wide variety of process-oriented research, and seems certain to assume increasing importance in regulatory environmental monitoring as well, given the ever-lengthening list of anthropogenic gases. Historically, at least in agricultural and ecological research, primary emphasis in gas-phase flux measurement has been on CO_2 and H_2O, but many of the methods employed have limitations when used for trace gases. We describe the development and testing of a system, based on a recent hypothesis by Businger and Oncley (1989) and hereafter referred to as conditional sampling, that seems particularly suited to trace gas transport measurement. The results encourage further use, and also indicate specific points which may admit improvement.

Comprehensive reviews of existing gas exchange methodology can be found elsewhere (e.g. Baldocchi et al., 1988), but a brief overview is necessary to place conditional sampling in proper context. There are three principal approaches to gas transport measurement: flux/gradient, mass balance, and eddy correlation. All techniques are limited when used for trace gases by the availability of sensors with sufficient resolution and accuracy for measurement of ambient concentrations, and consequently they require samples integrated over time for subsequent laboratory analysis. This precludes the use of eddy correlation.

Flux/gradient techniques include the aerodynamic method and the Bowen ratio/energy balance method. The aerodynamic approach requires sampling at multiple heights (preferably four or more), with concurrent measurement of windspeed and temperature. An eddy diffusivity for momentum is calculated from the wind profile, with a correction for stability effects based on the temperature profile (Dyer and Hicks, 1970; Pruitt et al., 1973). An eddy diffusivity for the compound of interest is then calculated on the assumption of similarity in transport. Depending on the specific characteristics of the sampling protocol employed, corrections for density effects caused by concurrent transport of heat and/or water may be necessary (Webb et al., 1980), although this has not always been appreciated. The number of samples required, the dependence of the method on ancillary measurements, and the need for empirical stability correction are the principal limitations of this technique.

The Bowen ratio energy balance method is attractive because it requires concentration measurement at only two heights. Sensible and latent heat fluxes are determined from the residual of the energy balance (net radiation minus soil heat flux) and the ratios of the gradients of temperature and specific humidity at the two heights. Transport coefficients are calculated by dividing the measured flux by the respective gradients, then similarity is assumed in calculating a transport coefficient for the companion gas of interest. The product of this coefficient with the measured concentration gradient then yields the flux. Unfortunately, the Bowen ratio is often indeterminate or subject to large errors when $R_n - G$ (where R_n is net radiation flux and G is soil heat flux) is near zero, as at night.

In the mass balance approach (Denmead et al., 1977), mean windspeeds and concentrations are measured at several heights (preferably five or more) above the surface and the flux is computed as the integral of their product from the surface to the uppermost measuring height, divided by the distance to the leading (windward) edge of the field. As with the aerodynamic method, the number of samples required can be a limitation. A generalization of this approach, based on trajectory simulation modeling (Wilson et al., 1982) requires measurement of windspeed and concentration at one height only, but it must be at the center of a circular source plot, and the roughness length of the surface must be known. Some correction (up to 20%) may be necessary to account for the use of mean rather than instantaneous windspeeds and concentrations (Wilson and Shum, 1992).

In eddy correlation, the mean vertical turbulent flux is determined by measuring and computing the covariance of the vertical wind velocity and the mixing ratio of the constituent of interest at a single height within the constant-flux layer. Over a suitable averaging period (approximately 20 min–1 h) the product of this covariance with the mean density of dry air yields the flux, on the assumption that there is no net transport of dry air. In practice, concentrations are typically measured rather than mixing ratios, so the Webb et al. (1980) corrections must be applied to account for correlated density fluctuations. Eddy correlation is theoretically attractive, as it requires no assumptions regarding similarity, is not dependent on accurate energy balance measurements, and does not require stability correction. However, its use has been limited by the need for sensors with sufficient frequency response and resolution to measure accurately the covariances of vertical velocity and concentration of the species of interest. This has been a severe limitation to its use for compounds whose ambient concentrations fall below or scarcely exceed the detection limits of available sensors.

Desjardins (1977) suggested a variant of eddy correlation more suitable for trace gases, known as eddy accumulation, in which air might be drawn from the immediate vicinity of an anemometer measuring vertical windspeed (w) and diverted into one of two 'accumulators' on the basis of the sign of w, at a pumping rate proportional to the magnitude of w. Over a suitable averaging time the difference in concentration between the two accumulators should yield the flux as

$$F = (\alpha T)^{-1}(M_u - M_d) \qquad (1)$$

where T is the time length of the sampling period, M_u and M_d are the masses of the constituent of interest accumulated in the updraft and downdraft sample containers, and α is the pump coefficient (pumping rate per unit of vertical windspeed). Hicks and McMillen (1984) conducted a detailed simulation of the method and concluded that successful application would depend on satisfaction of rather stringent requirements. Resolution of deposition velocities to within 0.1 cm s^{-1} would require accuracy in sampled gas volume measurement of 0.1% and linearity in proportional sampling over two orders of magnitude in the standard deviation of wind velocity σ_w. Apparently for these reasons, demonstration of practical application of this method has thus far been elusive (Speer et al., 1985), although Beier (1991) has recently described theoretical development and simulation of a new variation.

Businger and Oncley (1989) suggested that the demands of eddy accumulation might be 'relaxed' by sampling at a constant rate, rather than proportionally, retaining the binary switching in response to changes in sign of w so that eddies with positive and negative vertical velocities are sampled separately. They proposed that the flux of the compound of interest should be given by

$$J = \beta\sigma_w(\bar{C}_u - \bar{C}_d) \tag{2}$$

where $\bar{C}_u$ and $\bar{C}_d$ are the mean concentrations of the upward- and downward-moving eddies, and β is an empirical constant. Simulations using wind, humidity, and temperature signals from a previously collected eddy correlation data set led them to the tentative conclusion that β was approximately equal to 0.6 $\pm$ 10% for both heat and water vapor, with little apparent dependence on stability. Although not explicitly mentioned in their original discussion, it should be apparent that density fluctuations caused by sensible or latent heat transport will give rise to spurious fluxes unless the Webb et al. (1980) corrections are applied. If eqn. (2) is rewritten in terms of a difference in mean mixing ratio $(\chi_u - \chi_d)$ multiplied by the mean dry air density, $\bar{\rho}_a$, no correction is necessary:

$$J = \bar{\rho}_a\beta\sigma_w(\chi_u - \chi_d) \tag{3}$$

For simplicity, we shall refer to measurement of concentration differences, with the implicit understanding that either the samples are brought to a common temperature and humidity or the appropriate corrections are made.

MacPherson and Desjardins (1991) reported simulations similar to those of Businger and Oncley (1989), using eddy correlation data for CO_2, H_2O, and sensible heat. They obtained mean estimates of β ranging from 0.579 to 0.596, and then proceeded to conduct the only direct test of the method reported thus far, with measurements collected with an aircraft-based system. They used a single sampling line leading from a sonic anemometer on a noseboom to a switching manifold in the cabin that directed air to sampling bags for subsequent determination of CO_2 concentration by IR gas analysis (IRGA). Comparison of flux values computed by conditional sampling with eddy correlation measurements produced disappointing results. MacPherson and

Desjardins speculated about possible sources of error, including laminar flow-induced longitudinal mixing in the sampling line in front of the switching valve. However, they noted that such mixing would diminish ΔC, leading to underestimation of the flux, and in a number of cases the conditional sampling estimate was higher than the eddy correlation result. They suggested leakage in the sampling system and bag contamination as other possible sources of error.

We describe a different approach, designed for ground-based application at the field scale within a few meters of the exchange surface. This extends the potential applicability of the method, but it imposes more rigorous demands on the switching circuitry and plumbing, as eddy frequency increases with decreasing height about the surface.

MATERIALS AND METHODS

System design

A schematic diagram of the system used for CO_2 and H_2O flux measurements is shown in Fig. 1. The anemometer is a one-dimensional CSI CA27 sonic anemometer (Campbell Scientific, Logan, UT)[1] with a path length of 10 cm. Air from the upward- and downward-moving eddies is sampled through separate lines of Bevaline IV tubing of 3.2 mm i.d. This is in contrast to approaches in which air is drawn through a single inlet and subsequently routed; this change eliminates errors associated with a lag volume between the sampling and switching points. The tubing inlets are within the sphere described by an axis extending between the two sonic transducers, and they each lead to two-way solenoid valves (Clippard Minimatic, Clippard Engineering, Cincinnati, OH). These valves have low power consumption (60 mW), short stroke, and correspondingly rapid response time (10–15 ms). Separate lengths of tubing lead from the solenoid valves to a weatherproof enclosure (NEMA type 4X, Hoffman Engineering, Anoka, MN) containing the remaining equipment. There are 100 ml ballasts in the tubing lines, which serve to dampen high-frequency fluctuations in concentration and temperature. Quick-release fittings are employed at the junction of the tubing with the enclosure, which allow the sample lines to be disconnected and replaced with gas lines from standard gases of known CO_2 and/or H_2O concentration for adjustment of the zero and span potentiometers on the gas analyzer.

Inside the enclosure, the airstreams are first passed through 1 μm filters (Gelman ACRO-50, Cole-Parmer, Chicago, IL) to remove particulate matter.

[1] Mention of commercial products and sources is for the convenience of the reader and implies no endorsement on the part of the authors or their respective institutions.

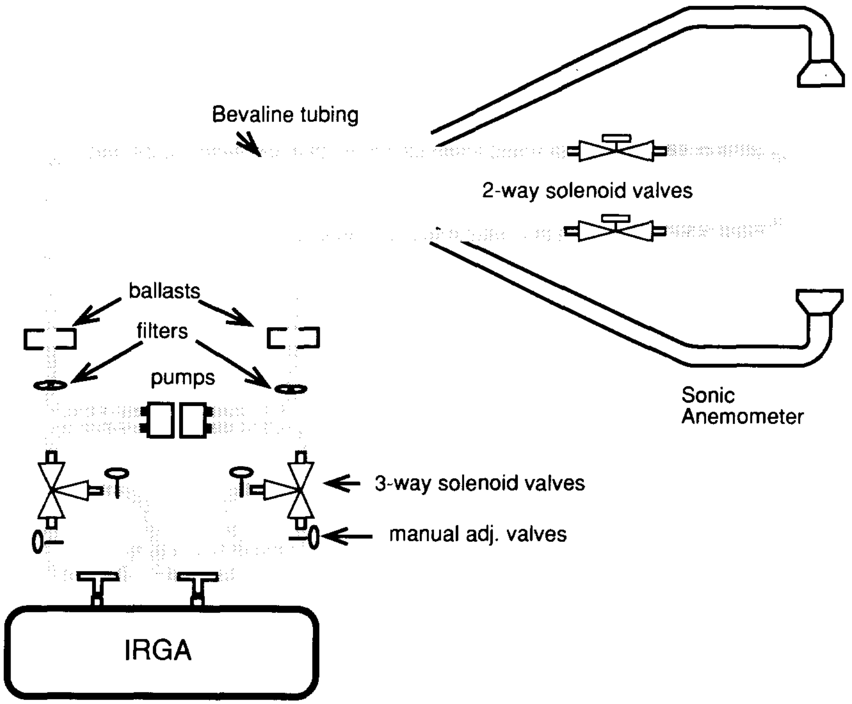

Fig. 1. Schematic diagram of the conditional sampling system designed for field-scale use. There are two inlets in the airstream, one for sampling from upward-moving eddies and one for sampling from downward-moving eddies. The solenoids on the two inlets are controlled by a data-logger in response to the sign of the vertical velocity. The IRGA system, data-logger, pumps, filters, etc., are all housed in a NEMA type 4X weatherproof enclosure.

A dual-channel diaphragm pump (model TD4X2N, Brailsford, Rye, NY) is used to pump both lines simultaneously, and the output sides of the pumps are connected to three-way solenoid valves. When the three-way solenoid valves are energized the upward-eddy airstream goes to the sample cell and the downward-eddy airstream goes to the reference cell, and when they are quiescent the airstreams are reversed, with the downward eddies routed to the sample cell and the upward eddies routed to the reference cell. This is necessary to remove the effects of zero drift on the concentration measurements, as the concentration differences are often small. There are manual valves in all four lines leading out of the three-way solenoids. These allow the flow rates to be matched and set at a rate low enough to produce sufficient back-pressure to dampen pressure fluctuations caused by the cycling of the two-way solenoids as they respond to changes in polarity of w. Laboratory evaluation showed that reducing the flow from 20 to 6.7 $cm^3 s^{-1}$ was sufficient to reduce ΔP between the input lines to the IRGA system to less than 0.1 mbar in the presence of 0.5 Hz cycling of the two-way solenoids. The pressure difference decreases with increasing cycling frequency.

The gas analyzer employed is a dual-channel, non-dispersive, portable IR gas analyzer (LI-6262, Li-Cor, Lincoln, NE). It can be operated in absolute or differential mode; in our configuration the differential mode is used. The analyzer corrects the CO_2 signal for errors caused by the diluting effects of differences in water vapor concentration between channels. Further, the thermal mass of the optical bench in the analyzer, together with the long common path of the two sample lines and the relatively low flow rate, ensure that temperature differences between the two airstreams are negligible at the point of measurement. Hence, we deem it unnecessary to apply the Webb et al. (1980) corrections.

The sonic anemometer and its companion fine-wire thermocouple are sampled by a data-logger (CR21X; Campbell Scientific, Logan, UT) at 10 Hz, and the IRGA system signals are read at 1 Hz. The data-logger continually controls the solenoids in the system, holding the 'up' line open whenever the vertical velocity exceeds the mean, and holding the 'down' line open when the reverse is true. No deadband is employed; i.e. one line or the other is always open. The three-way solenoids are reversed every 2 min, after which the IRGA system signals are ignored for 20 s. Eddy correlation computations are performed at 20 min intervals, with 5 min subintervals, and the most recent 5 min mean is always used for determining the polarity of w. The data-logger also reads a barometric pressure transducer (type TJE, Sensotek, Columbus, OH) and provides a proportional analog voltage to the gas analyzer to permit internal correction for changes in ambient pressure.

Field instrumentation

The conditional sampling system was set up in a 7 ha soybean field at the Rosemount Agricultural Experiment Station of the University of Minnesota (44°45′N, 93°05′W). Fetch exceeded 100 m in all directions save south, where the field boundary was approximately 80 m distant; the surrounding area in all directions was cropland. Soil at the site is a Waukegan silt loam (mixed, mesic, typic hapludoll), and topography in the immediate vicinity of the mast is essentially level. Supplementary data collected by the logger included net radiation (model Q6, Radiation and Energy Balance Systems, Seattle, WA), air temperature (shielded thermocouple), and soil heat flux (heat flux plate at 10 cm with thermocouples at 2.5 and 7.5 cm). In addition, a Bowen ratio system similar to that described by Tanner et al. (1987) was installed 20 m north of the conditional sampling mast. Data were collected during rain-free periods of 1–5 days scattered between planting and senescence. At the start of each measurement run, and daily during each run, the zero and span settings

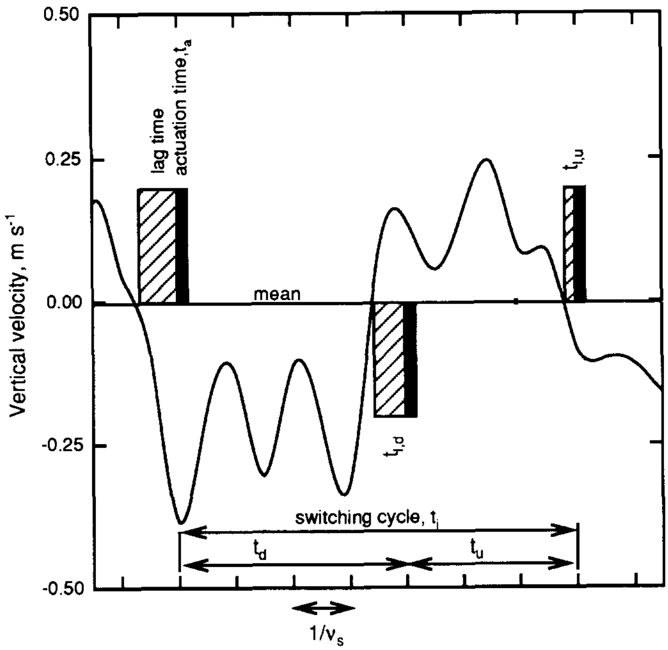

Fig. 2. Conceptual view of discretization errors. The curve is a spline fit through sonic anemometer data acquired at 20 Hz. The tickmarks on the x-axis indicate the discrete points at which the signal would be read by our system operating at v_s = 10 Hz. The lag time, t_l, is the elapsed time between a change in polarity of vertical velocity, w, and the next sampling time of the data-logger, and the actuation time, t_a, is the time required for the data-logger and solenoids to respond to a sensed change in polarity of w.

on the gas analyzer were checked using gases of known concentration, and adjusted when necessary.

Correction for discretization errors

Use of the method in a true sampling mode requires consideration of various sources of error. In our system there are two primary concerns: (1) the time lag between the change in sign of vertical velocity and the sensing of that change by the digital measurement system; (2) the elapsed time between the sensing of a change in sign of vertical velocity and subsequent actuation of the sampling valves. The combined effect of these lags is a systematic reduction of the measured ΔC, and hence underestimation of the flux of interest.

Approximate correction for this error is possible if some simplifying assumptions are made. Figure 2 illustrates the problem. The vertical velocity is sampled at a frequency, v_s, and either the 'up' or the 'down' solenoid is powered, according to the sign of the velocity. A switching cycle is defined as the time between the sensing of successive changes from positive to negative gust velocity, with variable period t_i. Each t_i contains a segment during which the data-logger shows the velocity to be positive, t_u, and a segment during which the logger shows a negative signal, t_d. For the present purpose, normality and stationarity in the instantaneous concentrations of the upward and downward eddies (C_u and C_d) are assumed at all time-scales of importance, i.e. over the sampling period of interest and within each gust. As the wind signal is sampled discretely rather than continuously, there is a time lag, t_l, between the true change in sign of the vertical velocity and the sensing of that change by the measurement system. There is also a finite actuation time, t_a, between sensing of a change in sign of w and the subsequent opening and closing of the appropriate valves. The actuation time comprises the time required for execution of the appropriate software instructions in the data-logger and the response time of the solenoid valve. Given these circumstances, over a given measurement period the mean concentrations in the upward ($[u_a]$) and downward ($[d_a]$) channels of the gas analyzer will be

$$[u_a] = \frac{1}{T_u}\sum_{i=1}^{m} (t_i - t_d - t_a - t_{l,u})C_u + (t_a + t_{l,u})C_d \tag{4a}$$

$$[d_a] = \frac{1}{T_d}\sum_{i=1}^{m} (t_i - t_u - t_a - t_{l,d})C_d + (t_a + t_{l,d})C_u \tag{4b}$$

where $T_u = \Sigma_{i=1}^{m} t_u$ and $T_d = \Sigma_{i=1}^{m} t_d$.

The true concentration difference between the upward- and downward-moving eddies is $\Delta C = C_u - C_d$, and the gas sampling system measures the apparent concentration difference, which, from eqns. (4a) and (4b) is

$$\begin{aligned}[u_a] - [d_a] = {} & \left(\frac{C_d}{T_d} - \frac{C_u}{T_d} + \frac{C_d}{T_u} - \frac{C_u}{T_u}\right)\sum_{i=1}^{m} t_a + \left(\frac{C_u}{T_u} - \frac{C_d}{T_d}\right)\sum_{i=1}^{m} t_i \\ & + \left(\frac{C_d}{T_u} - \frac{C_u}{T_u}\right)\sum_{i=1}^{m} t_{l,u} + \left(\frac{C_d}{T_d} - \frac{C_u}{T_d}\right)\sum_{i=1}^{m} t_{l,d} \\ & + \frac{C_d}{T_d}\sum_{i=1}^{m} t_u - \frac{C_u}{T_u}\sum_{i=1}^{m} t_d \end{aligned} \tag{5}$$

If one assumes that $T_u = T_d = \Sigma_{i=1}^{m} t_i/2$ then eqn. (5) becomes

$$\begin{aligned}[u_a] - [d_a] = {} & (C_u - C_d) - 2\frac{\Sigma_{i=1}^{m} t_a}{\Sigma_{i=1}^{m} t_i}(2C_u - 2C_d) \\ & - 2\frac{\Sigma_{i=1}^{m} t_{l,u}}{\Sigma_{i=1}^{m} t_i}(C_u - C_d) - 2\frac{\Sigma_{i=1}^{m} t_{l,d}}{\Sigma_{i=1}^{m} t_i}(2C_d) \end{aligned} \tag{6}$$

As all summations are over the same range, eqn. (6) may be rewritten as

$$[u_a] - [d_a] = (C_u - C_d) - 2\frac{\bar{t}_a}{t_i}(2C_u - 2C_d) - 2\frac{\bar{t}_{l,u}}{t_i}(C_u - C_d) - 2\frac{\bar{t}_{l,d}}{t_i}(C_u - C_d) \tag{7}$$

where overbars indicate mean values over the time period. If the mean lag times for upward and downward sign reversals are taken to be equal, and if their probability density functions are uniform (equal probability that w reverses sign at any point between discrete measurements) then $\bar{t}_{l,u} = \bar{t}_{l,d} = t_s/2$. Using the sampling frequency, $v_s = 1/t_s$, eqn. (7) becomes

$$[u_a] - [d_a] = (C_u - C_d)[1 - v_e(2t_a + v_s^{-1})] \tag{8}$$

in which v_e is an eddy-reversal frequency, equal to $(0.5\bar{t}_i)^{-1}$. It is the mean frequency with which w changes sign. Thus the true concentration difference can be estimated as

$$C_u - C_d = \frac{[u_a] - [d_a]}{1 - v_e(2t_a + v_s^{-1})} \tag{9}$$

For our system, t_a is approximately 15 ms, and v_s is 10 Hz. Field data at heights between 1.5 and 2 m over bare soil and a soybean canopy have yielded v_e values ranging from 0.5 to 3 Hz. Thus our estimated relative errors range from 0.07 to 0.4, meaning that our measured concentration differences are between 60 and 93% of the true concentration differences. All data collected with the IRGA-based system were corrected using eqn. (9) with measured values of mean v_e from each run, obtainable from the data-logger with minimal additional programming.

RESULTS AND DISCUSSION

Estimation of β

Estimates of β are most readily made with sensible heat flux data, because the same raw data (w, T) can be used for calculating the flux by eddy correlation and for calculating ΔC and σ_w, without worrying about the sampling errors inherent in a system with valves and tubing. Figure 3 illustrates two separate determinations: Fig. 3(a) contains data from a 4 day period immediately after planting, whereas the data in Fig. 3(b) were obtained during a 4 day period 3 weeks later, at which point the soybean crop had reached the 4–6 leaf stage. In both cases, 20 min averaging intervals were used and all data, including night-time values, are shown. Both plots have intercepts within 1 W m^{-2} of the origin and both yield β values of 0.56, comparable

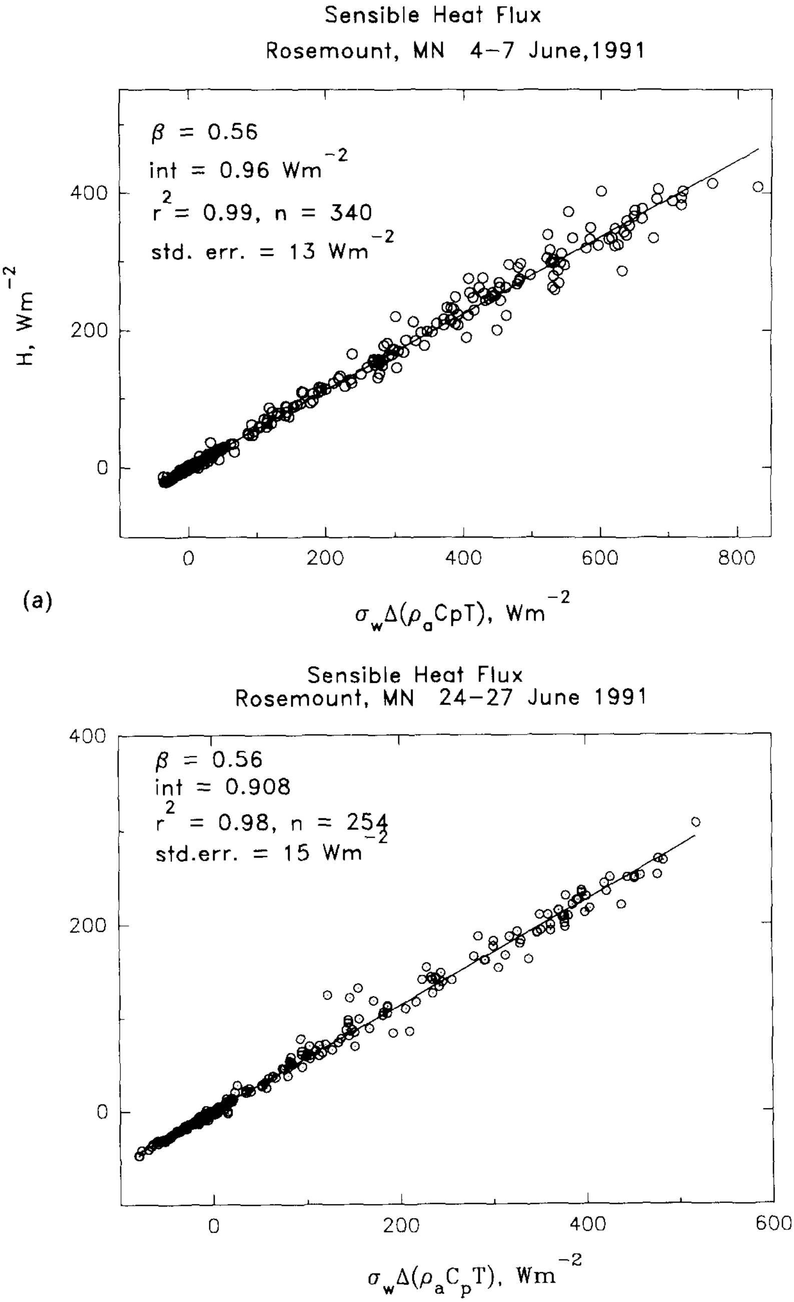

Fig. 3. Estimation of β using sensible heat flux (H) data. H was measured by eddy correlation, and the same signal was used to compute the mean difference in heat concentration between upward- and downward-moving eddies. (a) Over bare soil immediately after planting; (b) over a young soybean canopy 3 weeks after planting.

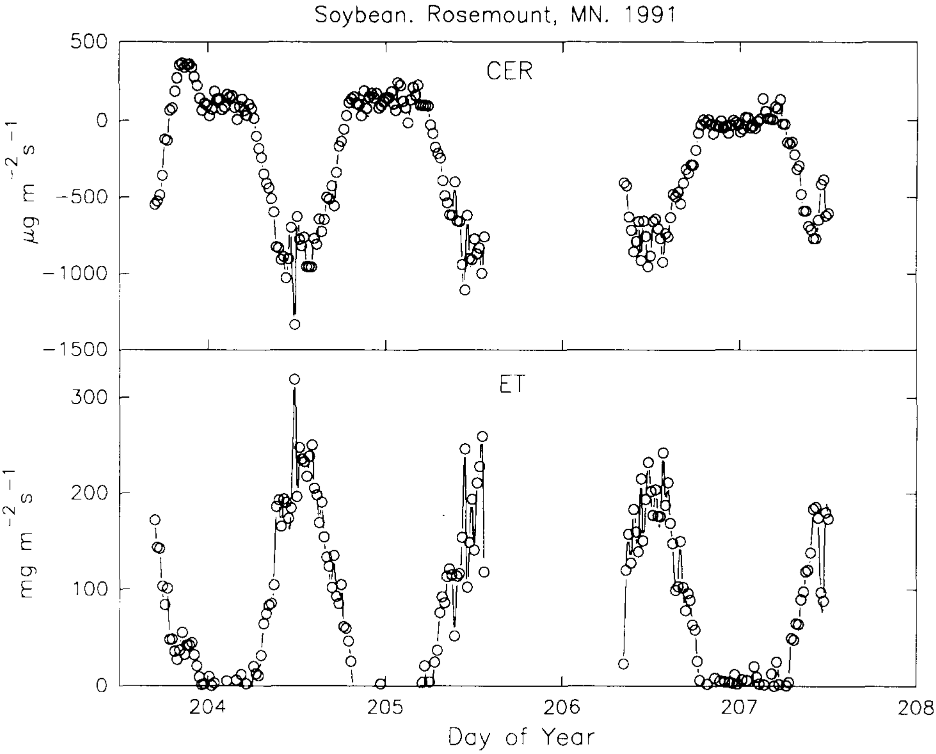

Fig. 4. Concurrent evapotranspiration (ET) and carbon dioxide exchange rate (CER) data over soybean. The crop was near canopy closure, but had not yet flowered. The interruption on day 206 was due to a rainstorm.

with the estimate by Businger and Oncley (1989) of 0.6 ± 10%. The lack of scatter and the obvious linearity support their conclusions with regard to the minimal effects of stability and turbulence intensity on the value of β.

H_2O and CO_2 flux measurements

The IRGA-based system was in place throughout the growing season, and measurements were taken during a number of rain-free periods; the data from one such period are shown in Fig. 4. The soybean crop at the time was nearing canopy closure but had not yet flowered. Figure 5 shows a comparison of the latent heat flux measured during this run by conditional sampling with the residual energy balance, $R_n - H - G$, where H, the sensible heat flux, was measured by eddy correlation. There is considerable scatter, but the slope indicates an average of 96% closure of the energy balance. In a subsequent 4 day trial, at which time the soybean crop was nearing maturity, closure was more elusive (Fig. 6), the slope being 0.84, but scatter was slightly decreased.

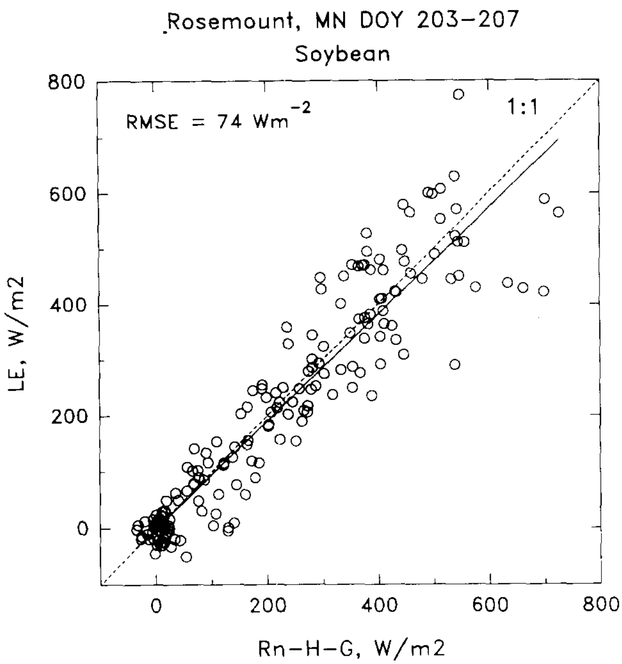

Fig. 5. Comparison of latent heat flux measured by conditional sampling (β = 0.56) with the residual energy balance (R_n − H − G) over a soybean canopy, where R_n is the net radiation flux, H is the sensible heat flux, by eddy correlation, and G is the soil heat flux.

A time series of this set indicates systematic underestimates of latent heat flux at midday (Fig. 7). This may not be entirely attributable to the conditional sampling system, as there are a number of sources of uncertainty in the residual energy balance determinations. A key factor differentiating this trial from earlier trials was the lack of turbulence; except for the final day, σ_w was consistently below 25 cm s^{-1}.

Figure 8 illustrates the behaviour of σ_w and ΔC (for H_2O) during the final 2 days of the trial. The 2 days were similar with respect to net radiation, temperature, and ambient humidity, but day 226 was considerably windier, with midday σ_w nearly double what it had been on day 225. There was a concomitant halving of ΔH_2O; consequently, the latent heat flux (LE) measured by conditional sampling was nearly identical for the 2 days, an observation corroborated by the Bowen ratio measurements and the residual energy balance data. It is also noteworthy that the H_2O signal, though smaller in magnitude, was much more stable on the second day in the presence of higher σ_w.

The corrections for discretization errors generally ranged between 7 and 40% during this measurement period (day 223–227). The size of the correction at times is a matter of concern. For our system, error caused by sampling

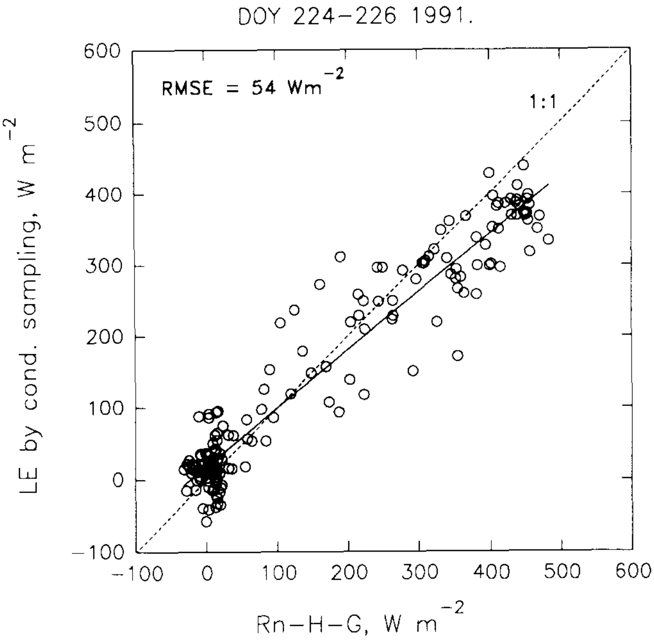

Fig. 6. Comparison of measured latent heat flux vs. residual energy balance as in Fig. 5, but at a later point in the growing season. At this point pods were filling and some lodging had occurred.

frequency is approximately three times as large as that caused by actuation speed of the solenoids. It should be possible to eliminate the dependence on the sampling frequency by switching the mast solenoid relays with a separate comparator circuit that continuously compares the analog signal from the sonic anemometer with a reference voltage (a continuous analog output provided by the data-logger) equivalent to the mean vertical velocity. This would have reduced the discretization error during the same period to a range of 1–10%. We have since designed and built such a comparator, but have not had the opportunity to test it under field conditions.

The basis of β

The similar results in estimation of β among tower-based (Businger and Oncley, 1989), aircraft-based (MacPherson and Desjardins, 1991), and near-surface, mast-based data sets (ours) beg the question of the nature of β. When the assumptions underlying eddy correlation measurement are met, the net flux, J, of the gas or particulate substance of interest is equal to the product of the mean dry air density and the covariance of the vertical velocity with the mixing ratio of the substance. If correlated density fluctuations caused by concurrent sensible and latent heat fluxes are removed or corrected for during

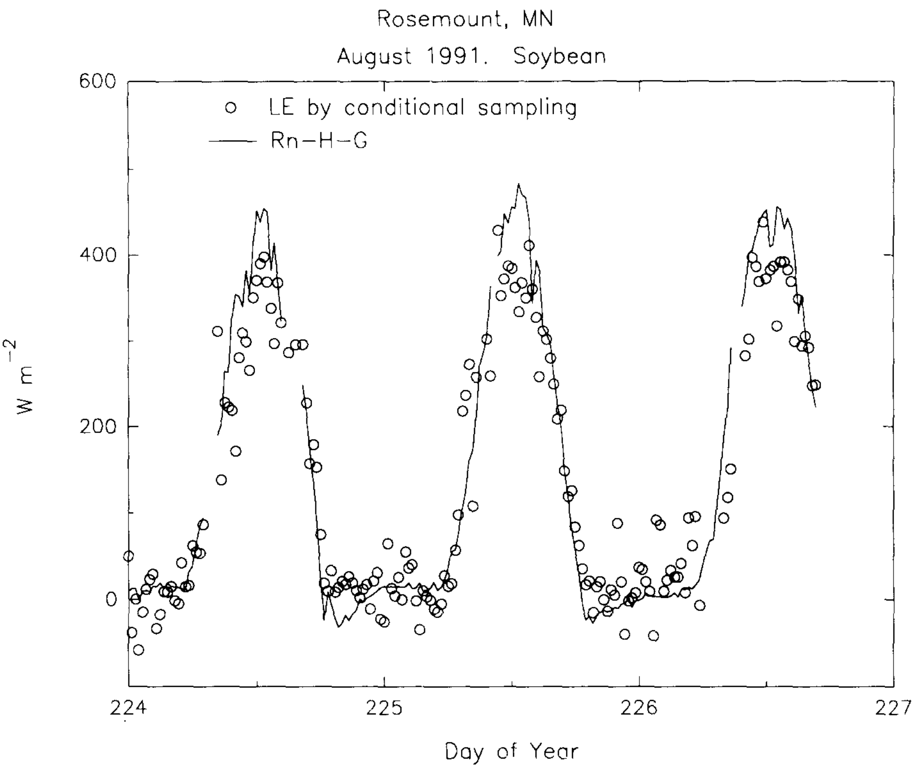

Fig. 7. Time series of the comparison of latent heat flux by conditional sampling with residual energy balance, $R_n - H - G$.

sampling, the flux may be written in terms of concentration:

$$J = \mathrm{Cov}(wc) = \overline{w'c'} \tag{10}$$

where primes indicate deviations from the mean. The correlation of w and c is

$$r_{wc} = \frac{\mathrm{Cov}(wv)}{\sigma_w \sigma_c} \tag{11}$$

Consequently, the flux may be written in terms of the correlation rather than the covariance:

$$J = r_{wc} \sigma_w \sigma_c \tag{12}$$

In linear regression, the correlation coefficient is computed as

$$r = \sum_{i=1}^{m} x_i' y_i' \bigg/ \left(\sum_{i=1}^{m} x_i'^2 \sum_{i=1}^{m} y_i'^2 \right)^{0.5} \tag{13}$$

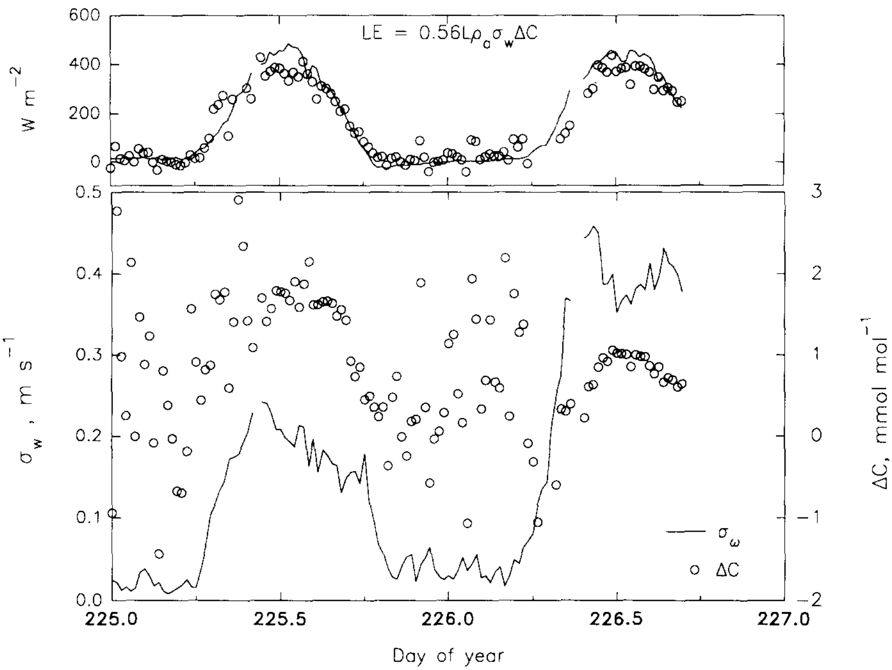

Fig. 8. Behavior of σ_w and ΔC (for H_2O) on two successive days. Latent heat flux (upper graph) was similar on the 2 days, despite indications of a substantial difference in turbulence intensity.

where $x_i' = x_i - \bar{x}$ and $y_i' = y_i - \bar{y}$. The slope, b_1, is given by

$$b_1 = \sum_{i=1}^{m} x_i' y_i' \Big/ \sum_{i=1}^{m} x_i'^2 \tag{14}$$

The ratio σ_x/σ_y is given by

$$\frac{\sigma_x}{\sigma_y} = \left(\sum_{i=1}^{m} x_i'^2\right)^{0.5} \Big/ \left(\sum_{i=1}^{m} y_i'^2\right)^{0.5} \tag{15}$$

Hence, r can be calculated as

$$r = b_1 \frac{\sigma_x}{\sigma_y} \tag{16}$$

Now we consider the problem of estimating the correlation between two variables when one is quantitatively measured and the other is defined by only two categories, drawing on the concept of biserial correlation as originally developed by Pearson (1910) and further discussed by Treloar (1942). Let us consider a dataset of (x, y) pairs sorted into two groups: (1) those in which $x < \bar{x}$ and (2) those in which $x > \bar{x}$. If the underlying regression of the quantitatively measured variable (y) on the dichotomized variable (x) is linear, then the means in each group $(\bar{x}_1, \bar{y}_1)$ and $(\bar{x}_2, \bar{y}_2)$ define points that fall on or near the regression line of y vs x. Consequently,

$$b_1 \approx \frac{\bar{y}_2 - \bar{y}_1}{\bar{x}_2 - \bar{x}_1} \tag{17}$$

Thus,

$$r \approx \frac{\sigma_x}{\bar{x}_2 - \bar{x}_1} \frac{\bar{y}_2 - \bar{y}_1}{\sigma_y} \tag{18}$$

Generally, the statistics on y are known, as y is quantitatively measured (in our case, σ_y is unknown, but unnecessary, as will become evident). The x statistics are presumably unknown, but if x is approximately Gaussian, then it can be shown that

$$\frac{\sigma_x}{(\bar{x}_2 - \bar{x}_1)} = \frac{pq}{z} \tag{19}$$

where p and q are the proportions of the number of observations in the larger and smaller of the two groups, respectively ($p + q = 1$), and z is the ordinate of the unit normal curve at abscissa $= q$. In other words, for a normally distributed variable, the ratio of the difference between the means of the two groups to the overall standard deviation is a readily evaluated function of the relative populations of the two classes. Combining eqns. (18) and (19) then yields the estimated correlation

$$r_b = \frac{pq}{z} \frac{\bar{y}_2 - \bar{y}_1}{\sigma_y} \tag{20}$$

Substituting r_b for r_{wc} in eqn. (12), and recognizing that x and y are surrogates for w and c, yields

$$J = \frac{pq}{z} \sigma_w(\bar{C}_2 - \bar{C}_1) \tag{21}$$

Comparison of eqn. (21) with eqn. (2) indicates that if the assumptions underlying biserial correlation are met, then

$$\beta = \frac{pq}{z} \tag{22}$$

The quantity pq/z is insensitive to the point of demarcation, declining only slightly from a value of 0.627 at $p = q = 0.5$ to approximately 0.620 at $q = 0.4$. In conditional sampling, q should seldom stray far from 0.5 if the system is triggering off at $\bar{w}$, provided $\bar{w}$ is recalculated frequently as a hedge against trends. In our trials, q has never been less than 0.46.

Two points are intriguing: (1) the general similarity between typically expected values of pq/z and empirically determined values of β; (2) the systematically lower values of β relative to pq/z, particularly in our case. We investigated this further with concurrent w, T, and humidity (C) data collected at 20 Hz for several 1 h time periods using a CA20 sonic anemometer with fine-wire thermocouple and a Krypton hygrometer (Campbell Scientific, Logan, UT). These data were obtained on days 225 and 226 in the same soybean field within 20 m of the conditional sampling mast. Each set was broken into 20 min intervals, and for each interval we computed the correlations (r) of w with T and C, as well as the respective biserial correlations (r_b). The results are given in Table 1. It is evident that the biserial method overestimates the true correlation. Pooling the latent and sensible heat data, the mean ratio of r/r_b is 0.885, which is essentially identical to the ratio of our β to pq/z ($0.56/0.627 = 0.893$). (This also indicates that data on latent and sensible heat transport over mature soybean produce a β that agrees with β obtained earlier from sensible heat data over bare soil.)

Why does biserial correlation apparently overestimate the true correlation? There are two principal assumptions on which biserial correlation rests: (1) approximately normal distribution of w (eqn. (19)); (2) linearity in the regression of C on w (eqn. (17)). Further processing of the raw data described in the previous paragraph permits a tentative assessment of the validity of points (1) and (2). Table 2 lists the relevant data from the nine 20 min periods. The Δ terms (ΔT, ΔC, and Δw) represent the differences in the means of the respective scalars between the upward- and downward-moving eddies. The parameter pq/z is consistently within 2% of the quantity $\sigma_w/\Delta w$, indicating that the distribution of w is sufficiently Gaussian to allow the substitution given in eqn. (19). In fact, the small errors introduced by the use of pq/z are opposite in sign to the errors in β. Comparison of $\Delta\bar{C}/\Delta\bar{w}$ with the slopes obtained from linear regression of C on w indicates that deviation from linearity is the source of the error in correlation estimation, i.e. the means in the two groups, $(\bar{x}_1, \bar{y}_1)$ and $(\bar{x}_2, \bar{y}_2)$, in the notation of eqn. (17), do not fall exactly on the regression line of y vs. x (C or T vs. w). The mean ratio of the regression slope to the differential (0.863 for temperature and 0.877 for humidity) multiplied by the slight overestimation introduced by pq/z produces the mean r/r_b of 0.885 mentioned above. Thus the empirical β apparently represents the statistical parameter pq/z, modified to account for nonlinearity in regression of C or T on w.

This leads to the question of the universality of β. There is no reason to assume a priori that the form of the c vs. w relation is insensitive to changes in such factors as stability and turbulence intensity, or that the form is similar for all scalar admixtures. In the first case, there is evidence in the original work of Businger and Oncley (1989) to suggest that stability effects are nearly negligible, and our data, which produced similar estimates of β under both highly unstable and near-neutral conditions, provide additional comfort. The

TABLE I

Data for nine 20 min sampling periods during which vertical velocity (w, m s^{-1}), temperature (T, °C), and absolute humidity (C, g m^{-3}) signals were recorded at 20 Hz over a soybean canopy

Run	σ_w	σ_T	σ_C	$w'T'$	$w'C'$	ΔT	ΔC	pq/z	r_{wT}	$r_{b,wT}$	r/r_b[a]	r_{wC}	$r_{b,wC}$	r/r_b[b]
1	0.231	0.113	1.23	0.00975	0.134	0.0749	1.01	0.626	0.373	0.414	0.901	0.470	0.510	0.920
2	0.223	0.087	1.38	0.0099	0.145	0.073	1.17	0.626	0.477	0.530	0.900	0.471	0.531	0.888
3	0.214	0.115	1.40	0.0111	0.155	0.0959	1.28	0.627	0.451	0.523	0.863	0.521	0.607	0.859
4	0.434	0.0415	0.740	0.00336	0.127	0.0139	0.527	0.627	0.1863	0.210	0.889	0.395	0.446	0.885
5	0.452	0.0350	0.745	0.00324	0.135	0.0134	0.536	0.627	0.2048	0.240	0.853	0.400	0.451	0.887
6	0.445	0.0486	0.783	0.00278	0.141	0.0141	0.572	0.627	0.129	0.147	0.875	0.405	0.458	0.885
7	0.384	0.0494	0.940	0.00488	0.143	0.0212	0.766	0.627	0.259	0.269	0.963	0.395	0.427	0.927
8	0.376	0.0665	1.11	0.00557	0.157	0.0296	0.766	0.627	0.223	0.279	0.80	0.378	0.434	0.872
9	0.355	0.564	0.971	0.00609	0.146	0.0312	0.753	0.627	0.304	0.347	0.877	0.422	0.487	0.868
Mean											0.880			0.888

σ, Standard deviations; $w'T'$, and $w'C'$, covariances of the respective variables; ΔT and ΔC, mean differences between upward- and downward-moving eddies. The correlations are labeled as r_{wT} and r_{wC}, and $r_{b,wT}$ and $r_{b,wC}$ represent the respective biserial estimates of the correlations.

[a] Ratio of correlation of w and T to its biserial estimate.

[b] Ratio of correlation of w and humidity to its biserial estimate.

TABLE 2

Additional information from the same data set, processed to determine the source of error in the biserial correlation estimate

Run	ΔT	ΔC	Δw	Regression estimate of dT/dw	$\Delta T/\Delta w$	Ratio[a]	Regression estimate of dC/dw	$\Delta C/\Delta w$	Ratio[b]	$\sigma_w/\Delta w$	pq/z	Ratio[c]
1	0.0749	1.01	0.361	0.183	0.208	0.883	2.51	2.79	0.901	0.639	0.626	1.02
2	0.0730	1.17	0.350	0.185	0.208	0.886	2.92	3.39	0.861	0.637	0.626	1.02
3	0.0959	1.28	0.337	0.243	0.285	0.853	3.41	3.79	0.898	0.634	0.627	1.02
4	0.0139	0.5267	0.679	0.0179	0.0205	0.871	0.674	0.775	0.886	0.638	0.627	1.02
5	0.0134	0.536	0.705	0.0159	0.019	0.834	0.659	0.759	0.868	0.641	0.627	1.02
6	0.0141	0.572	0.695	0.0141	0.0164	0.857	0.713	0.823	0.866	0.640	0.627	1.02
7	0.0212	0.766	0.601	0.0331	0.0351	0.942	0.967	1.07	0.908	0.639	0.627	1.02
8	0.0296	0.766	0.587	0.0395	0.0504	0.784	1.11	1.31	0.854	0.640	0.627	1.02
9	0.0312	0.753	0.556	0.0483	0.0561	0.86	1.15	1.36	0.851	0.640	0.627	1.02
Mean						0.863			0.877			1.02

[a] Ratio of true slope of the T vs. w relation to its biserial estimator.

[b] Ratio of true slope of the humidity vs. w relation to its biserial estimator.

[c] Ratio of $\sigma_w/\Delta w$ to its biserial estimator.

question of similarity requires more investigation. Our results, as well as the simulations of Businger and Oncley, indicate similar results for water vapor and sensible heat, although their data suggest that the $h(w)$ and $T(w)$ relations are more nearly linear than our data show. There is scant evidence available at this point to draw any conclusions about other gases. As mentioned above, the estimates of McPherson and Desjardins (1990) for CO_2, based on an eddy correlation data set, yielded β of approximately 0.58–0.6. The gas analyzer in our system simultaneously measured CO_2 and H_2O, so we also computed CO_3 fluxes by conditional sampling, but we had no independent measurement to serve as a yardstick. Thus we can only state that the values obtained over soybeans (Fig. 4), using a β of 0.56, were not inconsistent with expectations.

Potential applications

On-line continuous differential gas analysis is not possible for many compounds, such as pesticides, whose ambient concentrations are generally below the detection limits of available analyzers. However, the principles of conditional sampling should still apply. The compound(s) of interest must be concentrated by trapping over suitably long periods of integration (about 30–60 min) for subsequent analysis, and conversion of the data from mass to concentration requires accurate measurement of the mass flow rate through each sampling line. We have constructed and operated such a system, but laboratory analysis is unfinished at this point, and space constraints offer further argument for its description elsewhere.

It should also be noted that on-line conditional sampling does not require a differential, dual-channel analyzer. The upward and downward sample lines could be alternately switched into a single sensor or analyzer every few minutes in much the same way that Bowen ratio measurements are frequently made, although proper sizing of ballasts would then be a more critical design element than it is in a continuous differential system.

CONCLUSIONS

We have designed and successfully tested a system for conditional sampling at the field scale, incorporating a portable gas analyzer. Differential gas analyzers are particularly well suited to conditional sampling, as they can measure ΔC continuously and can prevent or correct for errors caused by density fluctuations. Elimination of the need for rapid dynamic response should allow the use of larger cells with longer optical pathlengths, and hence lower detection limits. Systematic discretization errors associated with the switching hardware and software are correctable, and may be nearly eliminated by relatively simple changes in system design.

The field data indicate that conditional sampling is a suitable alternative for measuring turbulent transport at the field scale. We conclude that the β of Businger and Oncley is not an altogether empirical coefficient, but rather is statistically derivable via the concept of biserial correlation. However, there appears to be nonlinearity in the relation between concentration and vertical velocity that induces an overestimation of correlation; hence, our estimated β is approximately 10% lower than the theoretical value. Whether this relationship is sufficiently general to allow use of a single β under all conditions for all scalar admixtures is not yet known. We invoke the familiar refrain that more research is needed, in this case a statement no less valid than banal.

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