ACCURACY OF THE RELAXED EDDY-ACCUMULATION TECHNIQUE, EVALUATED USING CO_2 FLUX MEASUREMENTS*

E. PATTEY, R. L. DESJARDINS and P. ROCHETTE

Centre for Land and Biological Resources Research, Research Branch, Agriculture Canada, Ottawa, Ontario K1A 0C6, Canada

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Abstract. A system capable of measuring the fluxes of trace gases was developed. It is based on a simpler version of the eddy-accumulation technique (EA), known as the relaxed eddy-accumulation technique (REA). It accumulates air samples associated with updrafts and downdrafts at a constant flow rate in two containers for later analysis of the trace gas mean concentration. The flux integration is based on the durations of updraft and downdraft events, rather than on the vertical wind velocity (W) as is the case for EA and eddy-correlation (EC) techniques. The flux, calculated by the REA technique, is equal to the difference in the mean concentration of the trace gas of interest between the upward and downward moving eddies, multiplied by the standard deviation of the vertical wind velocity and an empirical coefficient. CO_2 fluxes measured for 162 half-hour periods over a soybean field by both EC and REA techniques showed excellent agreement (coefficient of determination, $R^2 = 0.92$). The slope (0.985) and the intercept ($-0.042\ \mathrm{mg\ m^{-2}\ s^{-1}}$) were not significantly different from 1 and 0, respectively, at the 5% level; and the standard error of estimate was $0.074\ \mathrm{mg\ m^{-2}\ s^{-1}}$. It is also shown that the empirical coefficient can be calculated from either latent or sensible heat fluxes. A model describing the effect on this empirical coefficient of not sampling around W equal to zero is proposed.

1. Introduction

The global atmospheric concentration of trace gases is steadily increasing and the contribution from various sources is uncertain due to the lack of accurate field measurements of trace gas exchange. Such information is needed to develop process-based models and to obtain regional and global flux estimates (Stewart *et al.*, 1989).

The most direct approach to flux measurement is the eddy-correlation technique (EC). This technique is based on the mean product of the fluctuations of vertical wind velocity (W) and concentration of the gas of interest (S). This requires fast-response vertical wind velocity and trace gas sensors. However, for several gases, fast-response sensors are not readily available (Anderson *et al.*, 1989); hence other measuring techniques are needed.

The eddy-accumulation technique (EA) proposed by Desjardins (1972) overcomes the need for fast-response gas sensors without adding other uncertainties, since it is based on the same physical principle as EC. EA relies on the conditional sampling of air in proportion to the vertical wind velocity (positive or negative).

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Gas samples can be analyzed after each sampling period with a slow-response sensor; however, EA requires fast-response proportional sampling valves. A version of these valves developed by Buckley *et al.* (1988) has recently been improved.

Businger and Oncley (1990) modified the EA method by collecting air at a constant rate for updrafts and downdrafts. This approach, called the relaxed eddy-accumulation technique (REA), expresses the covariance of W with a scalar, S ($\overline{W'S'}$), as the product of an empirical coefficient (A), the standard deviation of W (s_W) and the difference in the mean concentration of the scalar associated with updrafts ($\overline{S^+}$) and downdrafts ($\overline{S^-}$):

$$F_S = \overline{W'S'} = A s_W (\overline{S^+} - \overline{S^-}) , \tag{1}$$

where F_S is the flux of S, primes indicate deviations from the mean and overbars denote the mean values over the sampling period. The coefficient "A" was found to be about 0.6 in simulations of the REA method (Businger and Oncley, 1990; MacPherson and Desjardins, 1991).

Only a few field experiments have been carried out on EA and REA techniques (Speer *et al.*, 1985; MacPherson and Desjardins, 1991; Baker *et al.*, 1992; Majewski *et al.*, 1993) due to technical difficulties. The absence of a bias in W during conditional sampling is essential, since biased flux measurements cannot be corrected by later data manipulation. In addition, the analysis of the gas concentration requires high accuracy because differences in concentration associated with updrafts and downdrafts are generally small (Hicks and McMillen, 1984; Businger, 1986; Businger and Delany, 1990). For most gases, this high accuracy can only be obtained under laboratory conditions; hence air samples must be stored in containers for subsequent analysis.

In this study, field measurements of CO_2 fluxes obtained with a REA system are compared to fluxes measured with the EC technique to test the feasibility of measuring trace gas fluxes by the REA technique.

2. Materials and Methods

The measurements were carried out over a 40-ha soybean (*Glycine max* [L.] Merill) field at the Greenbelt farm of Agriculture Canada (Ottawa, Canada). The instruments were mounted on a tower at a height of 3.2 m above the crop. Observations were made on 13 days during the 1992 growing season from calendar day 197 to 238. Fluxes were calculated on a 30-min basis. Measurements were taken mainly under unstable atmospheric conditions; that is, 84% of the observations had a z/L parameter ranging from -0.5 to -0.05.

2.1. EDDY-CORRELATION MEASUREMENTS

Wind velocities and temperature fluctuations were measured with a three-dimensional ultrasonic anemometer/thermometer (DAT-310, Kaijo Denki Ltd., Tokyo, Japan) and the CO_2 and H_2O density fluctuations by an open-path fast-response infrared gas analyzer (IRGA) developed at Agriculture Canada (Chahuneau *et al.*, 1989; Desjardins, 1991). The CO_2 fluxes were corrected for the IRGA sensitivity to water vapour and for air density fluctuations, using sensible and latent heat fluxes (Webb *et al.*, 1980). The vertical wind velocity signal was high-pass filtered at 0.001 Hz with a digital filter. No rotation of axes correction (Chahuneau *et al.*, 1989) was applied to the fluxes in order to compare them with fluxes computed by the REA technique. All signals were recorded at a sampling frequency of 20 Hz with an A/D converter (Labmaster card DMA TM-40, Scientific Solutions, Solon, Ohio) connected to a microcomputer.

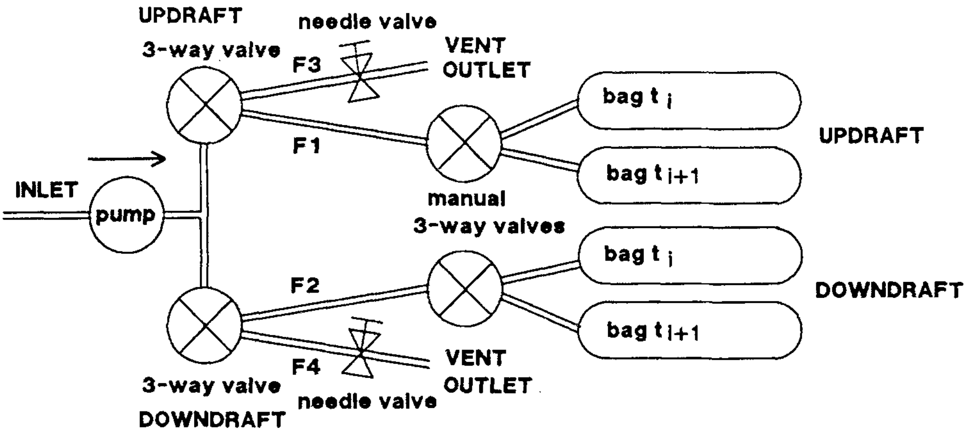
2.2. SIMULATION

Raw signals of vertical wind velocity (W), air temperature (T), horizontal wind velocity (U), water vapour (ρ_V) and CO_2 (ρ_C) densities were simultaneously recorded at 20 Hz. These data files were processed to compute fluxes by EC and REA techniques. The data analysis program permitted the following: (1) simulation of different intervals of suppressed sampling (deadbands) centred around W equal to zero, (2) high-pass filtering of the W signal, (3) introduction of various time lags between W and the other channels and (4) quantification of the effect of a bias on $\overline{W}$.

2.3. RELAXED EDDY-ACCUMULATION MEASUREMENTS

The REA system is illustrated in Figure 1. It consists of an inlet Teflon tube of 0.11 m length, connected to a diaphragm pump (micropump KNF, type NMP 08L, Neuberg Inc., Princeton, New Jersey) that pushes air through two fast-response 3-way valves (TFE 1-30-900 solenoid 3-way valve, General Valve Corp., Fairfield, New Jersey). This small assembly was mounted at the top of the tower, 0.15 m behind the sonic anemometer. The tubing between the inlet and the valves was kept small (1 mm inner diameter) and short (0.18 m). This limited the delay between the W signal and the effective conditional sampling to 14 ms for each reversal of W. The response time of the solenoid valves was 20 ms, leading to a total time lag of 34 ms per reversal of W, for the sampling device. The REA system is designed to have a continuous flow rate (0.600 L min^{-1}) through the pump. Needle valves on the vent outlets (F3 and F4 in Figure 1) were used to balance the flow rates (0.400 L min^{-1}) through the sampling tubing (F1 and F2 in Figure 1) in order to keep the time lag identical on both sides.

The W signal recorded for the EC method also controlled the two 3-way valves operating the conditional sampling (Figure 1). An assembler language routine was used to high-pass filter the W signal at a 0.001 Hz cutoff frequency in order to remove any bias on $\overline{W}$ and to activate the valves via a control port of the data acquisition system. This setup reduces the delay between W and the control of the valves to less than 1 ms. The sampling frequency of 20 Hz generated a time lag ranging from 0 to 50 ms. This variable time lag corresponds to the period between the effective change of the sign of W and its measurement. Air samples



FLOW	F1	F2	F3	F4
+D < W	1	0	0	1
-D ≤ W ≤ +D	0	0	1	1
W < -D	0	1	1	0

Fig. 1. Schematic of a relaxed eddy-accumulation device to measure trace gas fluxes. The status of flows F1 to F4 indicates if there is a flow (1: yes, 0: no) through the tubing depending on the vertical wind velocity (W) compared to the negative and positive value of the deadband ($\pm D$). Air is collected in bags that are changed from one period (t_i) to another (t_{i+1}).

associated with updrafts and downdrafts were accumulated in 6.5-L bags made of Curlam 9003 (Curwood Inc., New London, Wisconsin) equipped with double-end shutoff quick connectors to avoid contamination when connecting and disconnecting the bags. To allow continuous sampling from one half-hour period to another (t_i and t_{i+1} in Figure 1), two bags can be connected on each side (i.e., downdraft and updraft) of the sampling system (Figure 1). The bags were flushed with dry air having a CO_2 concentration of 360 μmol mol^{-1}, before use in order to avoid any contamination of the air samples.

The difference in CO_2 concentrations between the bags was incorporated in the equation described by Pattey *et al.* (1992) that corrects the flux for density fluctuations:

$$F_C = \left[\frac{P - \bar{e}}{T}\right] A\, s_W \frac{M_C}{R}\left[(\overline{C_m^{+}} - \overline{C_m^{-}})\left(1 + \frac{\bar{e}}{P}\right) + \right.$$
$$\left. + (\overline{C_m} - \alpha)\left(\frac{\overline{e^{+}} - \overline{e^{-}}}{P}\right)\right] 10^{-3}, \qquad (2)$$

where F_C is the flux of CO_2 (mg m^{-2} s^{-1}) corrected for the density fluctuations and for the sensitivity of the CO_2 analyzer to water vapour; T (K) is the absolute

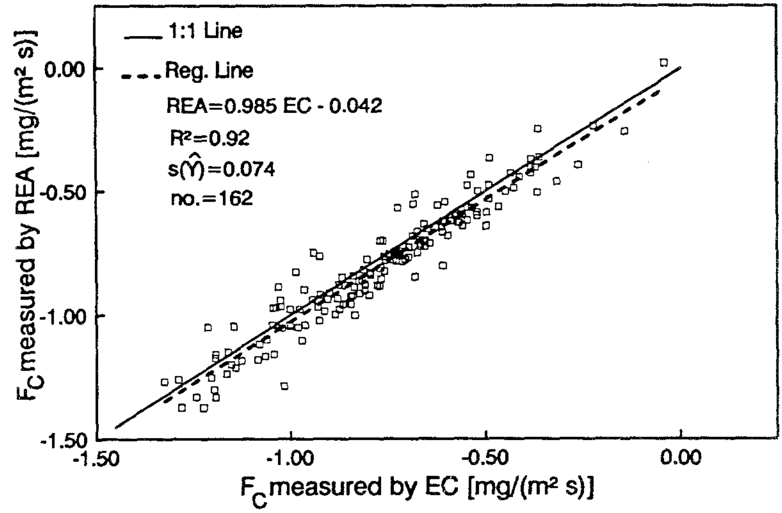


Fig. 2. Comparison between Relaxed Eddy-Accumulation (REA) and Eddy-Correlation (EC) techniques based on 30-min CO_2 flux (F_C) measurements carried out over a soybean field ($s(\hat{Y})$: standard error of the estimates; R^2: coefficient of determination).

air temperature; P (Pa) and e (Pa) are the atmospheric and water vapour pressures, respectively; C_m (μmol CO_2 mol^{-1} air) is the measured molar fraction of CO_2 and M_C (g mol^{-1}) the CO_2 molar mass; R (J mol^{-1} K^{-1}) is the gas constant and α (μmol^{-1} CO_2 mol^{-1} H_2O) is the sensitivity coefficient to water vapour of the CO_2 analyzer. Sensitivities to water vapour were 270 μmol CO_2 mol^{-1} H_2O for the slow-response CO_2 analyzer (ADC-MK3) and 289 μmol CO_2 mol^{-1} H_2O for the open-path analyzer. Measurements from the ADC-MK3 CO_2 analyzer are considered insensitive to air temperature fluctuations because the density of gas accumulated in bags had time to equilibrate before analysis. The empirical coefficient "A" was computed from Equation (1) for each run using the signals of the fast-response sensors. The empirical coefficient was calculated for air temperature (A_T), water vapour (A_V), CO_2 (A_C) and vertical wind velocity (A_W). "A_C" was used in Equation (2) for the comparison illustrated in Figures 2 and 3, because it accounts for several factors that affect the conditional sampling such as the use of a deadband, the time lag due to sampling frequency and the high-pass filtering of W. The only effect that is not accounted for by the real-time computation of "A" is the impact of the time lag due to valve opening and closing and of the air mixing in front of the valves. These potential problems were minimized by the design of the system. The time lag due to the system hardware design (34 ms) is equivalent to less than one sampling period (50 ms). Based on eight 30-min simulations of a 50-ms lag between W and CO_2 signals, the flux reduction was small, about 3%, and was considered negligible for our REA device.

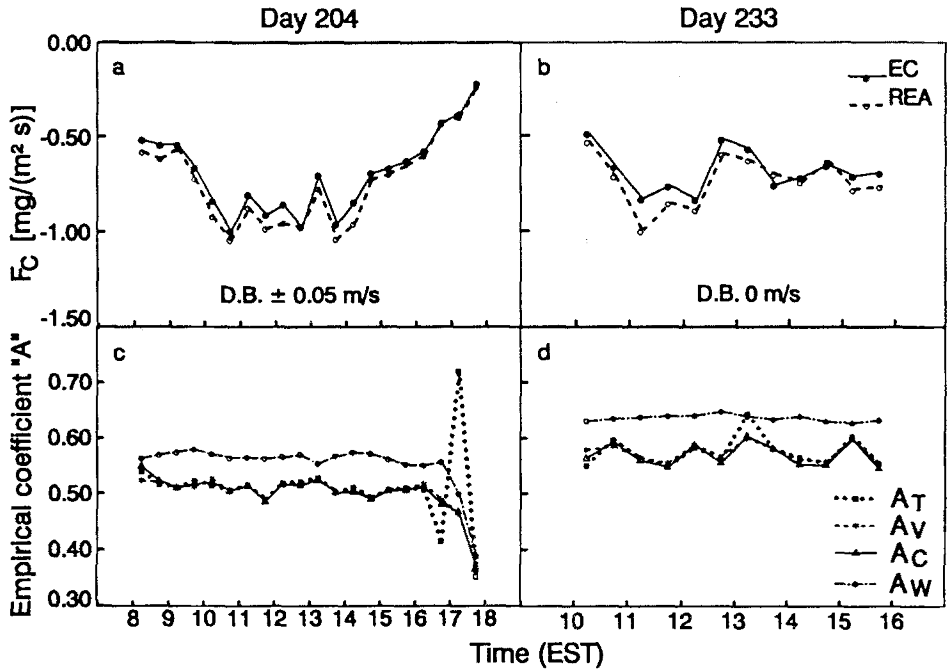


Fig. 3. (a, b) Temporal variations of CO_2 flux (F_C) measured using REA and EC techniques, (c, d) of empirical coefficient "A" for temperature (A_T), water vapour (A_V), CO_2 (A_C) and vertical wind velocity (A_W), illustrated for two days, with and without deadband (D.B.).

2.4. ANALYSIS OF THE DIFFERENCE IN CO_2 CONCENTRATION (ΔC)

Air collected in bags during the conditional sampling was analyzed using an infrared gas analyzer in differential mode ($\Delta C = \overline{C^+} - \overline{C^-}$). The CO_2 analyzer (ADC 225 MK3, Analytical Development Co. Ltd, Hoddesdon, UK) was kept in the laboratory to minimize vibration and temperature changes during measurements. A zero adjustment was made at the beginning and at the end of a series of ΔC measurements. Span adjustments were performed at the beginning and end of each ΔC analysis to account for the drift of the instrument. Dry air with a CO_2 concentration of 360 μmol mol^{-1} was used as a calibration gas. In this range, a change of 10 μmol mol^{-1} of the background concentration caused a sensitivity change of 1.6%. This effect was neglected in our calculations. The output of the CO_2 analyzer was sampled at 5 Hz for 20 s to compute the mean and standard deviation of each measurement. To analyze ΔC, a four-way valve connected at the inlet of the two cells was used to interchange the flow from the bags to the cells, permitting the determination of an implicit zero value without disconnecting the bags. The switching was done twice to account for the drift during each measuring period of ΔC. The equation used to compute ΔC is as follows:

$$\Delta C = K\frac{(V_1 + V_3 - 2V_2)}{(4V_S - V_1 - V_3 - 2V_2)}, \tag{3}$$

where K is the difference in CO_2 concentration used for span adjustment (18 μmol mol^{-1} in our experiment); V_S (V) is the mean of the two span readings before and after ΔC determination; V_1, V_2, V_3 (V) are the three consecutive steady-state readings of the ΔC between a pair of bags corresponding to each time that the air samples to the analyzer cells were interchanged.

Several tests were carried out to evaluate the overall precision of the CO_2 analysis with this experimental setup. The precision was about 0.03 μmol mol^{-1}, which corresponds to a CO_2 flux of 0.015 mg m^{-2} s^{-1}, under typical conditions.

3. Results and Discussion

3.1. COMPARISON OF CO_2 FLUX MEASUREMENTS

A linear regression curve was performed on the 162 observations of CO_2 flux measured by REA (Equation 2) using calculated A_C against those measured by EC (Figure 2). Excellent agreement was found between the techniques (R^2 = 0.92), giving a slope and an intercept, which were not significantly different from 1 and 0, respectively, at the 5% level. The standard error of the estimates was 0.074 mg m^{-2} s^{-1}, indicating small dispersion. The limited scattering, which is random, can be caused by errors associated with measuring ΔC by the bag-analyzer assembly, and imprecisions in sensible heat flux measurement used to correct EC estimates of CO_2 fluxes for density fluctuations.

REA is not as exact as EC or EA. However, the good agreement between REA and EC suggests that integrating the sampled air by the duration of updraft or downdraft events as is the case for the REA technique is a good approximation to a flux integration based on the vertical wind velocity as is the case for EA and EC techniques.

Fluxes measured by REA and EC had a very similar pattern of temporal variation as illustrated for two typical days in Figures 3a and 3b. These flux values were based on A_C values calculated for each run. This did not improve the agreement in the temporal flux pattern variation because A_C was relatively constant during most of the day. It will normally not be possible to calculate A_C but it is not serious because calculated values of A_T, A_V and A_C were identical except for one case at the end of day 204 (Figure 3c). It should be noted that the A_W values were considerably larger.

The similarity between the coefficients calculated from temperature, water vapour and CO_2 data was examined for the entire data set (Figure 4). Values of A_T, A_V and A_C agreed closely, within the limitations of the large scatter for A_T and one value of A_V. These cases occurred when the flux of the scalar was small and when the rate of convergence towards zero of $\overline{W'S'}$ was different from that of

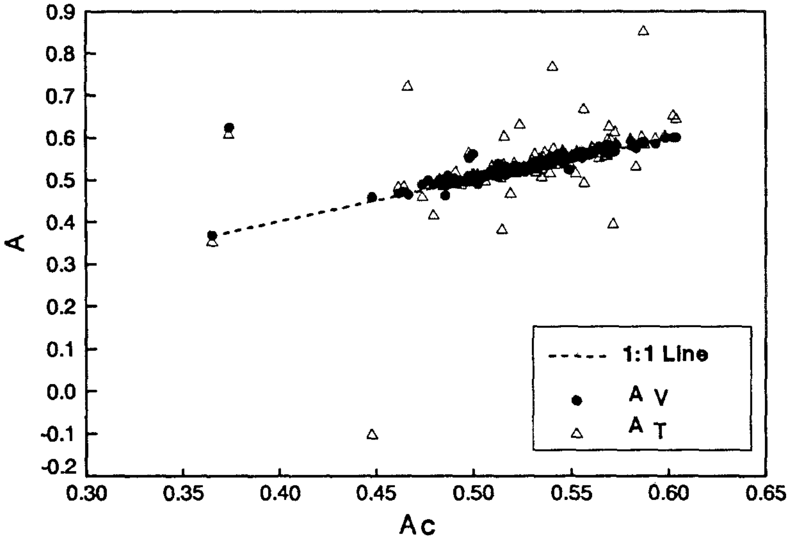


Fig. 4. Similarity between the empirical coefficients for CO_2 (A_C), water vapour (A_V) and temperature (A_T) for the entire data set. The range of values reflects the effect of a deadband of ±0.05 m s^{-1} used for 67% of the observations.

$(\overline{S^+} - \overline{S^-})$. This situation is illustrated (Figure 5) by the increased dispersion of A_T when F_T was between 1 and -25 W m^{-2}. Most of the difference between A_C and A_T (Figures 3c, 4) is related to the change in the sign of F_T that occurred earlier in the afternoon, rather than the change in sign of F_C. A_C, A_T and A_V appear to be interchangeable except when the scalar used to calculate the coefficient has a flux tending towards zero. The CO_2 fluxes were therefore calculated again using A_T instead of A_C in Equation (2) and were compared to EC fluxes (Figure 6). If we exclude the 20 runs when $-25 \leqslant F_T \leqslant 1$ W m^{-2}, the same regression coefficients and statistics were found. The standard error of estimate is also of the same magnitude, i.e., 0.078 mg m^{-2} s^{-1}. A_T can therefore be used for most cases to characterize the empirical coefficient for a specific experimental setup. For the case of CO_2, A_V gave even better results than A_T but the ease of obtaining A_T justifies its use.

For observations that were taken without deadband (42 obs.), A_C averaged 0.57, which agrees with previous estimates (Businger and Oncley, 1990; MacPherson and Desjardins, 1991; Baker *et al.*, 1992). The coefficient of variation was 5%, indicating that the empirical coefficient is relatively constant between runs.

The similarity between the empirical coefficients does not extend to A_W. The values of A_W were higher than those of A_C by an average of 13% (Figure 7). This difference can be explained by the fact that the derivation of A_W (MacPherson and Desjardins, 1991) relies on the W frequency distribution only, while the other coefficients are calculated by accounting for the characteristics of the joint

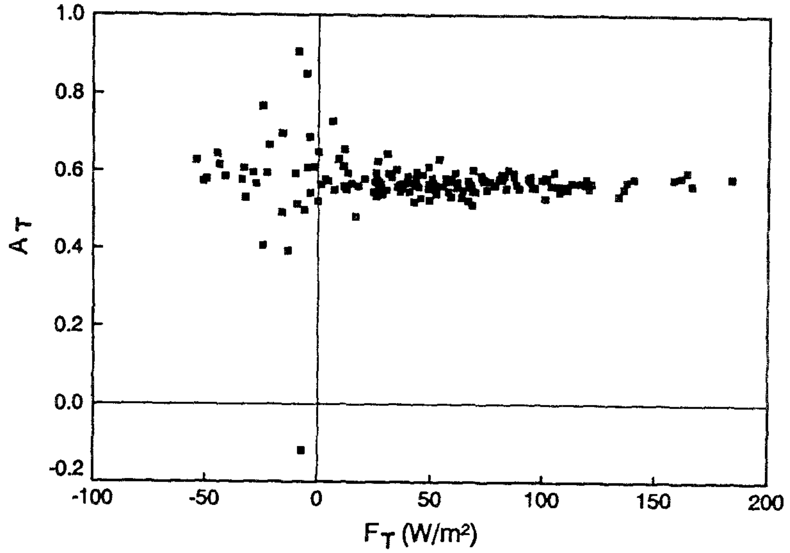


Fig. 5. Variations of the empirical coefficient for temperature (A_T), corrected for the deadband effect using Equation (5), with respect to the sensible heat flux (F_T), for 162 observations.

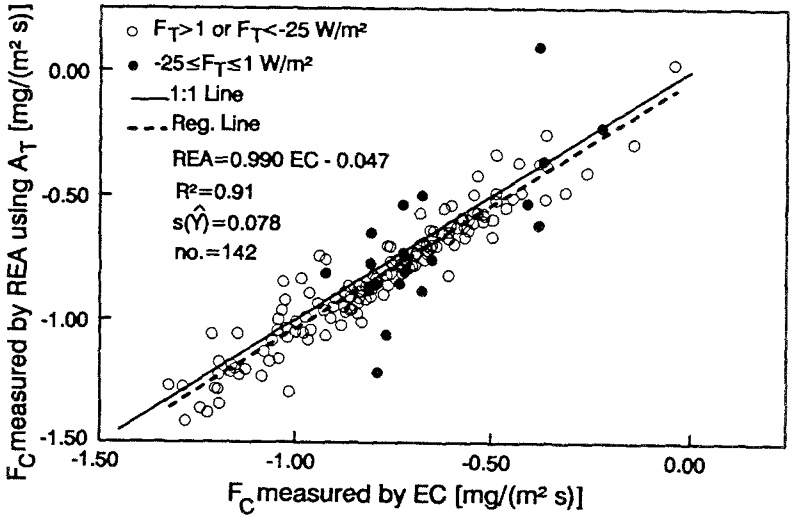


Fig. 6. Comparison between CO_2 flux (F_C) measured by Relaxed Eddy-Accumulation (REA) using the empirical coefficient for air temperature (A_T) and Eddy-Correlation (EC) techniques based on 30-min measurements. The linear regression applies to 142 observations. It excludes A_T values associated with $-25 \leq F_T \leq 1\ \mathrm{W\,m^{-2}}$.

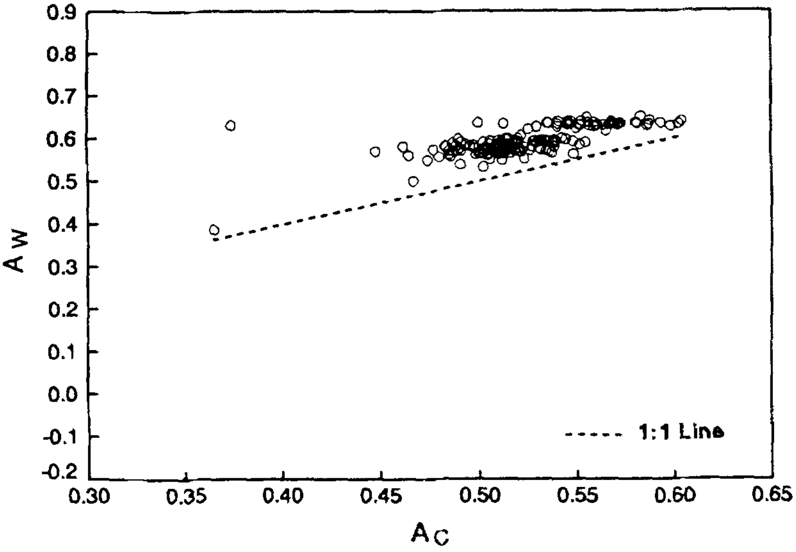


Fig. 7. Comparison between the empirical coefficients for CO_2 (A_C), and vertical wind velocity (A_W) for the entire data set. The range of values reflects the effect of a deadband of ±0.05 m s^{-1} used for 67% of the observations.

probability distribution of W with the scalar. Therefore, the derivation of the empirical coefficient cannot be based only on the frequency distribution characteristics of W.

3.2. SIMULATION STUDIES

3.2.1. *Deadband Effect*

A deadband is an interval defined on the W signal, centred at $W = 0$, in which no air sampling takes place. It can be used to prolong the life of the valves driven by the conditional sampling system and to increase the difference in trace gas concentration between updrafts and downdrafts ($\overline{S^+} - \overline{S^-}$). However, using a deadband can bias the sampling towards larger eddies as it first removes air samples having a concentration close to the mean. The increase of the differences in concentration is then compensated by the decrease of A_S. This effect is illustrated in Figure 3, when lower coefficients A_C were computed on day 204 (Figure 3c), for which a deadband of ±0.05 m s^{-1} was used, than on day 233 when no deadband was used (Figure 3d). In addition, the deadband removed many more observations (20 to 50%) during light horizontal wind conditions (at 17:00), leading to a strong reduction of "A" values, than during normal daytime conditions (~5% of the observations) (Figure 3c). In Figure 4, the range of A_C values (0.36 to 0.60) reflects the effect of a fixed deadband from run to run. A deadband of ±0.05 m s^{-1}

TABLE I

Values of the coefficients (b_0, b_1) for the nonlinear model describing the effect of a deadband normalized with s_W ($\beta_S(D/s_W)$) applied on the filtered signal of W (high-pass filter of 0.001 Hz), for the relaxed eddy-accumulation coefficients for temperature (T), CO_2 (ρ_C) and water vapour (ρ_V). The coefficient of determination (R^2) applies to the linear regression between the predicted and observed data, and $s(\hat{Y})$ represents the standard error of the estimates. The model is: $\beta_S(D/s_W) = 1 - b_0[1 - e^{(-b_1 D/s_W)}]$

	$\beta_S(D/s_W)$		
	T	ρ_C	ρ_V
b_0	0.437	0.412	0.432
b_1	1.958	2.125	1.947
R^2	0.985	0.981	0.988
$s(\hat{Y})$	0.012	0.013	0.011

was used for 67% of the data set while no deadband was used for the remaining runs.

The effect of increasing the deadband on the estimate of flux was examined by simulation studies. Deadbands up to $\pm 0.4\,\mathrm{m\,s^{-1}}$ in steps of $\pm 0.02\,\mathrm{m\,s^{-1}}$ were simulated for 20 half-hour runs, in which the W signal was high-pass filtered. The observations correspond to horizontal wind speed values ranging from 2.6 to $5.9\,\mathrm{m\,s^{-3}}$ and s_W from 0.45 to $0.84\,\mathrm{m\,s^{-1}}$. For a given run, the effect of the deadband on A_S was expressed by:

$$\beta_S(D) = \frac{[\overline{S^+(0)} - \overline{S^-(0)}]}{[\overline{S^+(D)} - \overline{S^-(D)}]} \tag{4}$$

with $0 \leq \beta_S(D) \leq 1$ and where $S(D)$ is the value of a scalar for a given deadband and $S(0)$ its value without deadband. The magnitude of $\beta_S(D)$ is expected to vary with the intensity of fluctuations in W. To compare the deadband effect on A_S between runs with different turbulence intensities, the deadband should be normalized with s_W as proposed by Businger and Oncley (1990). The following general model was used to describe the deadband effect normalized with s_W on A_S:

$$\beta_S(D/s_W) = 1 - b_0[1 - e^{(-b_1 D/s_W)}]\,, \tag{5}$$

where D is the positive half-interval of the deadband ($0 \leq \mathrm{D} \leq 0.4$ m s^{-1}) and b_0 and b_1 are nonlinear regression coefficients. The coefficients of the nonlinear model were fitted using the Marquardt iterative method (SAS, 1985) for air temperature, CO_2 and water vapour (Table I).

The general model for β_S (Equation 5) has been used to determine the maximum deadband that can be applied without invalidating the REA equation. The result-

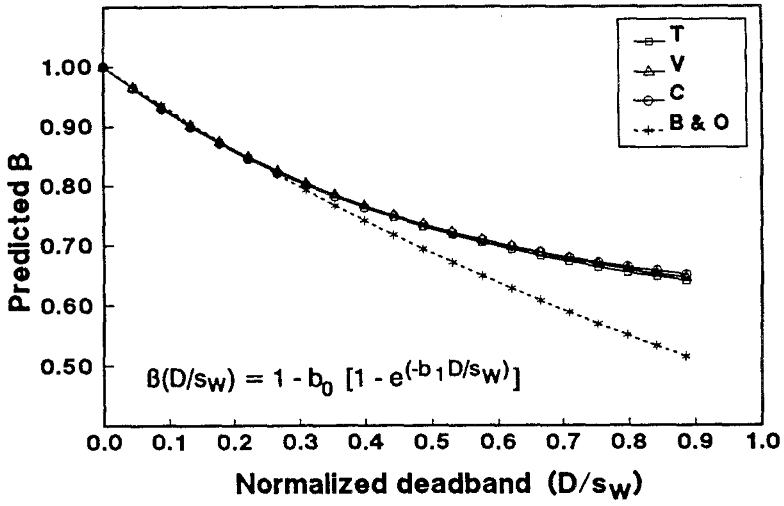


Fig. 8. Model describing the effect of the deadband (β) on the empirical coefficient "A" for temperature (T), water vapour (V) and CO_2 (C) as a function of the deadband (D) normalized using the standard deviation of the vertical wind velocity (s_W). "B & O" is the model proposed by Businger and Oncley (1990).

ing fitted curves gave similar results for the three scalars (Figure 8). The ratio of $\beta_T(D/s_W)$ over $\beta_C(D/s_W)$ was equal to one (±1%), based on the 20 half-hour runs, for D/s_W values up to 0.5. These results suggest that when run-specific A_T or A_V is calculated, they can be used to assess the deadband effect for other species, for normalized deadbands up to ±0.5. Moreover, ΔS is increased by as much as 27% (Figure 8). The difference between estimated β_s values and the observed β_S from individual runs increases as the deadband increases (Figure 9), meaning that the effect of the deadband is less predictable for these larger intervals. The variability of β_S between runs is much larger than the variation of β_S between the scalars within a run. Equation (5) should therefore be used with caution for estimating the deadband effect on the conditional sampling, when a constant "A" is used in place of A_T or A_V calculated simultaneously with actual measurements. Based on the pattern of scattering in Figure 9, Equation (5) should not be used to correct "A" when $\beta_S(D)$ is lower than 0.85 (Figure 9), or when expressed as normalized deadband, when D/s_W is greater than 0.2 (Figure 8). For D/s_W values lower than 0.2, Equation (5) and the model proposed by Businger and Oncley (1990) give similar estimates of β_S. However, the model of Businger and Oncley tends towards zero for large values of D/s_W while our model has an asymptotic value of "$1 - b_0$". We believe that the asymptotic value should be different from zero because if a large deadband is used, this is equivalent to sampling the large eddies only, for which the mean concentration difference is finite. By extending the simulations of β_C against D/s_W up to 2.5, we fitted values

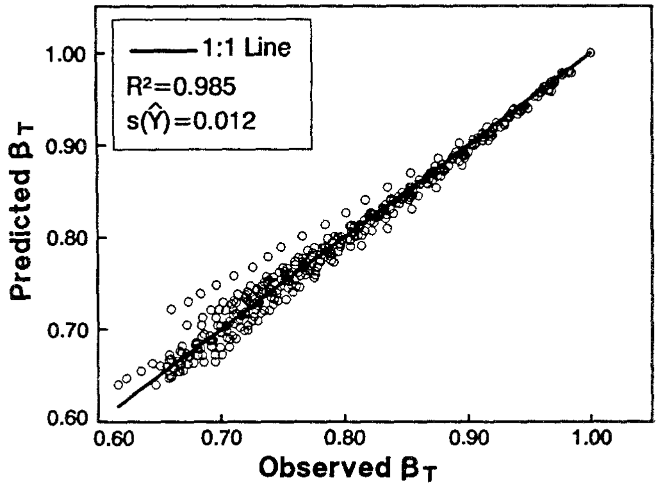


Fig. 9. Accuracy of the estimated effect of the deadband (β_T) on the empirical coefficient for temperature, evaluated from 20 30-min runs.

of b_0 and b_1 on 12 individual runs. Asymptotic values ranging from 0.48 to 0.77 were found.

3.2.2. *Effect of a Nonzero Mean W on F_C*

The conditional sampling could be biased if W is not filtered. A bias on W (W_b) could be generated by nonlevel terrain, an electrical offset or improper levelling of the sonic anemometer. Simulations were done after high-pass filtering W at 0.001 Hz and then adding a bias on W, to quantify the effect of a nonzero mean W on the REA fluxes. Simulations of W_b values ranging from -0.20 to 0.20 m s^{-1} by steps of 0.05 m s^{-1} were done on 12 runs for unstable conditions. Figure 10 illustrates the effect of a bias on W normalized with s_W on the estimate of the CO_2 flux. The simulations confirm the result of Businger and Oncley (1990) that the effect of the bias is small for a normalized bias of ±0.1. A negative bias induced an overestimation while a positive bias generated a greater flux underestimation for the same absolute value of the bias. The asymmetry of the effect of W_b seems to be due to the skewed CO_2 distribution, reflecting a difference in the shape of the C^- and C^+ distributions. The variation from run to run increased with $|W_b/s_W|$.

4. Conclusion

Excellent agreement was found between CO_2 fluxes measured by EC and REA techniques, under the experimental conditions that corresponded mostly to unstable atmospheric conditions. It confirms the potential of the REA technique, which was suggested by simulation studies (Businger and Oncley, 1990; MacPherson and Desjardins, 1991), and shows that operational REA systems can be

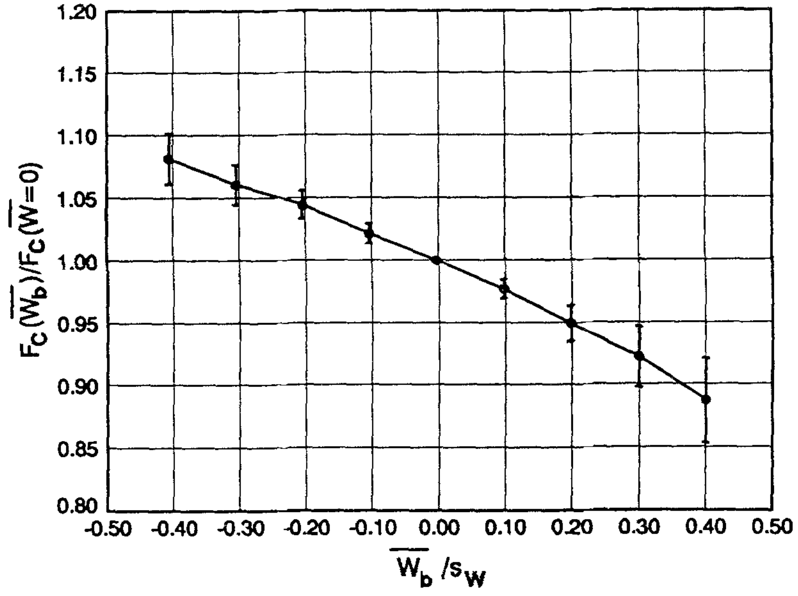


Fig. 10. Effect on the relative value of the CO_2 flux (F_C) of a bias on the mean vertical wind velocity ($\overline{W_b}$). $\overline{W_b}$ is normalized with the standard deviation of the vertical wind velocity (s_W). Intervals of confidence (95%) illustrated on the graph are based on 12 30-min runs.

developed whenever slow-response gas analyzers with adequate sensitivity are available (Desjardins *et al.*, 1993). It also shows that it is possible to minimize the effect of measurement errors such as: (1) the bias on the mean vertical wind velocity, (2) the time lag between the sign change of W and the effective conditional sampling of air, (3) the contamination of air samples collected in bags.

A model describing the effect of the deadband can be used to correct "A" for normalized deadband values not exceeding ±0.2. The effect of the deadband can also be compensated by calculating "A" with the simultaneous measurements of another scalar. Empirical coefficients calculated from CO_2, water vapour and temperature data were interchangeable for D/s_W up to 0.5. On the other hand, A_W should not be used because it does not reflect the characteristics of the joint probability distribution between W and the scalar. When no deadband was used, the empirical coefficient averaged 0.57 with a coefficient of variation of 5% between the runs. Further research should be carried out to evaluate the accuracy of REA technique under stable atmospheric conditions.

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