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Abstract. Fluxes of carbon dioxide, water and sensible heat were measured using three different eddy covariance systems above the forest floor of a closed deciduous forest (leaf area index ≈ 6). The primary objective was to examine the representativeness of a single eddy covariance system in estimating soil respiration for time scales ranging from one-half hour to more than one week. Experiments were conducted in which the eddy covariance sensors were in one of three configurations: i) collocated, ii) separated horizontally or iii) separated vertically. A measure of the variation between the three systems (CV', related to the coefficient of variation) for half-hour carbon dioxide fluxes was 0.14 (collocated systems), 0.34 (vertically separated systems at 1, 2 and 4 m above the surface), and 0.57 (systems horizontally separated by 30 m). A similar variation was found for other scalar fluxes (sensible and latent heat). Variability between systems decreased as the number of half-hour sampling periods used to obtain mean fluxes was increased. After forty-eight hours (means from ninety-six half-hour samples), CV' values for carbon dioxide fluxes were 0.07, 0.09 and 0.16 in the collocated, vertically separated and horizontally separated experiments, respectively. The time dependence of variability has implications on the appropriateness of using short-term measurements in modelling validation studies. There are also implications concerning the appropriate number of half-hour samples necessary to obtain reliable causal relationships between flux data and environmental parameters. Based on the longer-term measurements, we also discuss the representativeness of a single eddy covariance system in long-term monitoring of soil respiration and evaporation beneath forest canopies using the eddy covariance method.

Keywords: Ameriflux, Carbon flux, Deciduous forest, Eddy covariance, Soil respiration, Spatial variability.

1. Introduction

Special research networks have been initiated that depend on eddy covariance measurements to provide reliable half-hour to annual estimates of water and carbon exchange between vegetation and the atmosphere (Baldocchi et al., 1996; Aubinet et al., 2000). At several forested sites, two flux measurement systems are deployed; one above the canopy to determine net ecosystem exchange rate (NEE) and a second immediately above the forest floor to estimate soil respiration (Wilson et al., 2000a; Baldocchi et al., 2000a). An implicit assumption is that the soil respiration estimated at the forest floor is representative of the mean air/surface exchange for a region directly comparable to the NEE measurements above the canopy. A similar assumption is also made when attempting to separate soil evaporation from evapotranspiration (Wilson et al., 2000b). The short and long-term uncertainty associated with this assumption is essential to understanding the processes and component contributions of energy and carbon fluxes.

Three pertinent questions are raised in addressing the representativeness of eddy covariance measurements at the forest floor. The first relates to errors inherent in using a single-point measurement over short time periods (i.e., typically one-half hour) to estimate ensemble averages of turbulent quantities. Because all realizations of the turbulent flow cannot be measured at a single point, the random error associated with this assumption is present even over uniform surfaces and within (statistically) uniform geophysical flows (Wyngaard, 1973; Wesely and Hart, 1985). If the flow and surface are uniform, the magnitude of the error decreases as the inverse of the square root of the number of half-hour samples and eventually approaches zero (Moncrieff et al., 1996). Nevertheless, uncertainty at the shorter time scales remains, especially at the scale in which mean turbulent quantities are estimated (one-half hour). The expected statistical accuracy of these short-term measurements has crucial implications in our understanding of ecological and atmospheric processes. For example, short-term eddy covariance data are often used to evaluate or initialize ecological and canopy turbulence models (Meyers and Paw U, 1986; Katul and Alberson, 1999). Eddy covariance data at the forest floor are also often compared with chamber data, or eddy covariance data above the canopy, or are used to examine short-term relationships between biophysical fluxes and environmental conditions (Norman et al., 1997; Law et al., 1999; Kelliher et al., 1999; Hollinger et al., 1999; Janssens et al., 2000; Wilson et al., 2000b). Quantifying the uncertainty of short-term measurements is necessary to examine the validity and/or the appropriate averaging times in which to make these comparisons.

A second question relates to the spatial variability of biological and physical properties at the forest floor and specifically addresses the validity of using a single eddy covariance system to estimate longer-term carbon exchange rates, or the long-term ‘location bias’ (Schmid and Lloyd, 1999). The forest floor is often heterogeneous in solar and net radiation (Baldocchi et al., 2000a), soil temperature and moisture (Hanson et al., 1993), quality and quantity of decomposing litter (Edwards et al., 1989; Trettin et al., 1999), fungal and bacterial biomass (Morris and Boerner, 1999) and litter wetness (Schaap et al., 1997). Heterogeneity at the forest floor is especially important because the surface area contributing to the measured fluxes, or the ‘flux footprint’, can be several orders of magnitude less than that above the canopy (Baldocchi, 1997a). Therefore, the subcanopy measurements may not integrate over variability within the spatial scales represented by the above-canopy footprint, which is a necessary condition if the above and below-canopy measurements are to be comparable. Because increasing the length of the measurement period decreases random errors, differences in long-term fluxes between multiple systems will reflect biological and physical variability among the different footprint regions.

The two previous questions concerning short-term random errors and the longer-term location bias can be addressed by spatially separating multiple eddy covariance systems and evaluating variability across a range of time scales. A third question relates to how these systems are separated. For instance, it is important to understand the difference between horizontal and vertical separations and whether there is an ideal height to place systems to avoid drainage flows, weak turbulence or high frequency loss of flux. Although both vertical and horizontal separations will generate dissimilar footprints between systems, the two types of separation affect footprint characteristics differently. Horizontal separation will primarily alter the footprint location, but a vertical displacement will change the size, shape and location of a footprint. In both types of separation, some overlapping of footprints is possible and the measurements may not be completely independent, depending on the actual displacement distances and flow characteristics. Experiments with vertically separated sensors have an additional benefit of evaluating whether vertical sensor placement introduces bias in flux estimates, resulting from drainage flow, changes in turbulent length and time scales (high frequency loss of flux) or storage calculation errors (Lee, 1998; Mahrt, 1999; Baldocchi et al., 2000b).

An eddy covariance study that addresses these questions concerning variability of carbon dioxide and energy fluxes at the floor of a fully-leafed deciduous forest is described. At different times during the experiment, three eddy covariance systems were either collocated, displaced horizontally or displaced vertically. A recent study investigated a few of these questions above an even-aged pine plantation (Katul et al., 1999), and Yang et al. (1999) compared fluxes using only two different eddy covariance systems above the understory of a boreal aspen forest. In this study, we focus on fluxes beneath virtually all vegetation using three different eddy covariance systems within a small region surrounding our above-canopy tower measurements. We also address how overlapping of footprints, drainage flow and high frequency loss of flux may affect interpretations of below-canopy fluxes and the conclusions in our study. Because of the direct relevance to carbon sequestration studies, we primarily focus on the variability of carbon dioxide flux, but we also address other scalar and velocity components.

2. Site and Methodology

2.1. Site

The experiments were performed during a fifty-three day period (days 253 through 305) in late summer and early autumn of 1999 beneath the canopy of a forest located at Walker Branch Watershed, Oak Ridge TN, USA (35°57′30″ N, 84°17′15″ W, 365 m asl). This Ameriflux site, located on the Oak Ridge National Laboratory reservation, continuously monitors energy and carbon dioxide exchange above and below the forest and is one of the longest operating eddy covariance flux systems that measures net ecosystem exchange (NEE) and energy fluxes (Greco and Baldocchi, 1996; Baldocchi, 1997b; Baldocchi et al. 2000b; Wilson and Baldocchi, 2000; Wilson et al., 2000a,b). The top of the mixed deciduous stand, dominated by oak, maple and hickory, is approximately 26 m above the surface and has a maximum leaf area index (LAI) of approximately 6.0. The upwind fetch of forest extends several kilometres in all directions and the terrain slopes about 3% to the south-southwest, the predominant wind direction. The soil is well drained, and a litter layer of decomposing leaves and small branches covers the soil surface. During the experiment, the forest was at maximum leaf area and was essentially closed. Other than the trunks of larger trees, below 4 m there was very little vegetation and less than 5% of the total leaf area. All eddy covariance measurements at the forest floor were within a 75-m radius of the tower system used for measuring above-canopy fluxes and were on a gradual slope facing the south and west. A more detailed description of the canopy architecture, species composition and soil properties is provided by Luxmoore et al. (1981), Hutchison et al. (1986) and Johnson and van Hook (1989).

2.2. Instrumentation

Mean vertical flux densities were evaluated by computing the mean covariance of scalar and horizontal velocity fluctuations with the fluctuating vertical velocity (Baldocchi et al., 1988). Fluctuations of velocity components and scalars were calculated as the difference between the instantaneous and mean quantities. Mean scalar and velocity quantities were determined using a digital recursive filter with a 400 s time constant. Coordinate axes were rotated so that the mean vertical velocity was zero (McMillen, 1988). Fluxes were corrected for the effect of density fluctuations (Webb et al., 1980; Paw U et al., 2000). The wind vector components were determined using a sonic anemometer (model R3 Gill Instruments, Hampshire, England), whose symmetric head design and slender support structure of the R3 produces little flow distortion (Grelle and Lindroth, 1994). Fast response water vapour and CO_2 concentrations were measured using an open-path infrared gas analyzer (Auble and Meyers, 1992). Carbon dioxide density calibrations were performed before and after the experiment using gas standards prepared by NOAA's Climate Monitoring and Diagnostic Laboratory. Water vapour calibrations were referenced to a dew point hygrometer. Changes in calibration coefficients before and after the experiment were less than 5% and had almost no effect on the difference in calculated fluxes between the three systems. The infrared gas analyzer (IRGA) was mounted directly to the sonic in a vertical configuration with a horizontal separation of about 0.1 m, such that the top of the IRGA was level with the bottom of the vertical struts of the R3 array (Figure 1). This provided the most horizontally symmetric projection for the wind field.

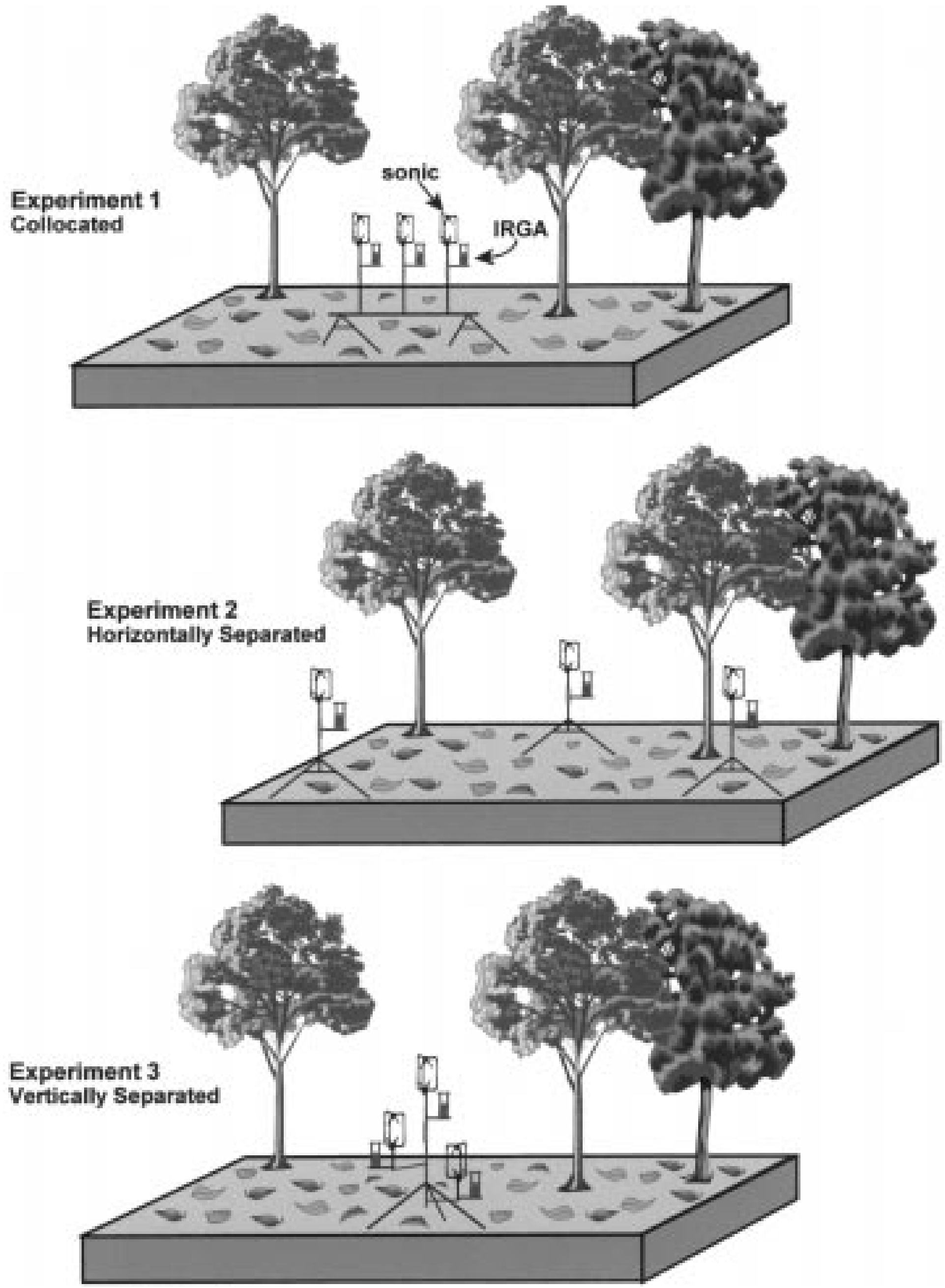


Figure 1. Schematic of the three experiments in this study. In experiment 1, the sensors were collocated. In experiment 2, the sensors were separated by 30 m in a triangular fashion. In experiment 3, the sensors were at nearly the same horizontal position, but separated vertically at 1, 2 and 4 m above the ground surface.

Mean carbon dioxide concentrations were computed with a LiCor 6262 (LiCor Inc. Lincoln, Nebraska) infrared gas analyzer located within 75 horizontal metres from the forest floor eddy covariance systems. This analyzer sequentially measured CO_2 concentrations at four heights (0.75 m, 9.10 m, 21.7 m and 36.6 m) within and above the canopy. A zero calibration was performed each half-hour, and a span calibration was performed at midnight. The volume-averaged storage of carbon dioxide (Wofsy et al., 1993; Greco and Baldocchi, 1996) below the eddy covariance sensors was estimated directly from temporal changes in concentration measured at 0.75 m. Storage was usually small because flux calculations were performed close to the surface, and the contribution of storage to the flux calculations was assumed to be identical for eddy covariance systems placed at the same vertical position. However, the magnitude of storage is discussed in the vertically separated experiments because the storage contribution can vary with height.

2.3. EXPERIMENTS

Three sets of experiments were performed to evaluate the variability of forest floor fluxes (Figure 1).

Experiment 1: 'Collocated systems'

Instrument bias was evaluated by 'collocating' the three flux measurement systems (Figure 1). In this configuration, the sonics were in a linear array with a separation distance of 0.20 m, and their sensing volumes were about 2.0 m above the ground surface. The collocated experiment was repeated, using the same spatial separation of 0.20 m, but at 1.0 m above the forest floor. Both experiments were performed for over 100 half-hour periods.

Experiment 2: 'Horizontally separated systems'

In the second experiment, the systems were separated horizontally at the forest floor (Figure 1). The three systems were at 2.0 m above the forest floor and horizontally separated by approximately 30 m in a triangular configuration. The sensors were in this configuration for more than 500 half-hour periods.

Experiment 3: 'Vertically separated systems'

In the third experiment, the sensors were at approximately the same horizontal position but were separated vertically (Figure 1). The three heights above the floor were approximately 1.0, 2.0 and 4.0 m. This configuration was repeated at a distance of 25 horizontal metres from the first vertical separation. Both of these vertically separated experiments include more than 350 half-hour periods. There was virtually no vegetation beneath the sensors at any height.

2.4. Analysis Tools

The mean turbulent vertical flux density obtained from a single eddy covariance system for a single half-hour is $\overline{w'\chi'}$, where w is vertical velocity and χ represents a scalar (heat, water vapour, carbon dioxide) or horizontal velocity. The single over-bar denotes a temporal (half-hour) mean, and the single prime denotes deviations from the mean. Sensible heat (W m^{-2}), latent heat (W m^{-2}) and carbon dioxide (μmol m^{-2} s^{-1}) fluxes will be denoted H, LE and F_c respectively. The standard deviation of a fluctuating quantity ($\sqrt{\overline{\chi'\chi'}}$) is denoted by σ_χ.

Double-primed quantities denote deviations among the three systems from the three-system mean, and $\langle\ \rangle$ denotes the mean of the three systems. Letting s represent any turbulent quantity (such as $w'\chi'$ or $\chi'\chi'$) measured by each of the three systems, the coefficient of variation (CV) is the standard deviation divided by the mean

$$CV(s) = \frac{\sqrt{\langle \bar{s}''^2 \rangle}}{\langle |\bar{s}| \rangle}, \tag{1}$$

and is an indicator of variability between the three systems. When $\bar{s} \to 0$, a condition that is not unusual at the forest floor, CV can become spuriously large. Therefore, we report a related variable CV', which is calculated over the entire experimental period for each turbulent quantity s

$$CV'(s,m) = \frac{\sum_{n/m} \sqrt{\langle \bar{\bar{s}}''^2 \rangle}}{\sum_{n/m} \sqrt{\langle \bar{\bar{s}} \rangle}}, \tag{2}$$

where the total period of n half-hourly samples was subdivided into n/m blocks with each block having an equal number (m) of half-hour samples. The double bar denotes the mean within each of the blocks ($\bar{\bar{s}} = 1/m \sum_m \bar{s}$, where $\bar{s}$ is the half-hour mean). For example, if $m = 1$, CV' is calculated directly from each of the half-hour samples. With $m = 2$, CV' is calculated only after averaging all half-hour samples into hourly quantities, and if $m = n$, CV' is calculated only after averaging over the whole data set.

2.5. Lagrangian Trajectory Model

Assuming a ground (z = 0) source, the flux density (F) at the measurement height (z_m) can be written (Baldocchi, 1997a)

$$F(x, y, z_m) = \int_{-\infty}^{\infty}\int_{-\infty}^{x} Q(x_\tau, y_\tau, 0)\cdot f(x - x_\tau, y - y_\tau, z_m)\,\mathrm{d}x_\tau\,\mathrm{d}y_\tau, \tag{3}$$

where $Q(x_\tau, y_\tau, 0)$ is the source strength at the ground and $f(x - x_\tau, y - y_\tau, z_m)$ is the normalized flux footprint, or the probability distribution function that the flux measured at x, y, z_m originates from $x - x_\tau, y - y_\tau, 0$.

The flux footprint was estimated using a Lagrangian trajectory model (Wilson and Sawford, 1996), which simulated 7000 particle trajectories based on measured mean turbulent statistics and random forcing. The model and the analysis of flux footprints are similar to that described previously and analyzed in detail at the forest floor (Baldocchi, 1997a). The standard deviation of the vertical velocity (σ_w) was a function of height and was estimated from measurements below and above the canopy during the experiments. Lagrangian time scales were estimated from the vegetation height as described in Baldocchi (1997a). Released particles that impinged on the surface were reflected perfectly and the turbulence was locally homogeneous near the surface, assumptions that preserve the well-mixed condition (Wilson and Flesch, 1993). Probability distributions were calculated as a function of horizontal distance by displacing the particles at the mean horizontal wind speed and computing the relative contribution of vertical fluxes to the total flux at the sensor height.

There were two purposes of the Lagrangian modelling. One was to estimate the size of the source regions contributing to the fluxes. A second purpose was to estimate an index of the overlapping of source regions for separated (horizontally or vertically) sensors. This allows some estimate on the extent of independence between the systems. Neglecting crosswind contributions (i.e., $y = y_\tau = 0$ in Equation (3)), the relative overlap (OL_h, a fraction between 0 and 1) between systems separated by a positive horizontal distance (Δx) is calculated from the intersection of the probability distributions defined in Equation (3) between x and $x + \Delta x$,

$$OL_h = \int_{-\infty}^{x} \min[f(x - x_\tau, z_m)\,\mathrm{d}x_\tau,\ f(x + \Delta x - x_\tau, z_m)\,\mathrm{d}x_\tau]. \tag{4}$$

OL_v is calculated from systems separated vertically by Δz as,

$$OL_v = \int_{-\infty}^{x} \min[f(x - x_\tau, z_m)\,\mathrm{d}x_\tau,\ f(x - x_\tau, z_m + \Delta z)\,\mathrm{d}x_\tau]. \tag{5}$$

Because the simulations ignore potentially important crosswind velocity perturbations, the footprint probability functions were only a function of streamwise distance, an assumption that will overestimate the extent to which multiple footprints overlap. The model still provides an index of footprint size at the forest floor relative to the separation distances. The model also provides an upper boundary on the extent to which multiple footprints are expected to overlap and the relative independence of the displaced systems in each of the experiments. Calculation of OL_h implies that the wind direction is parallel to a line connecting two separated systems separated by Δx, which further overestimates the actual footprint overlap.

As long as wind direction does not vary significantly with height in the lowest few metres, no such assumption is necessary when calculating OL_v.

3. Results

3.1. Lagrangian Model Estimates of Flux Footprints

The simulated flux footprint is a function of the mean wind speed and turbulent statistics for any given half-hour, which vary between half-hours, between days and between day and night (Figure 2). Figure 3 illustrates the estimated footprint characteristics for mean midday and nocturnal conditions. The normalized flux footprints are computed from the probability that particles released upwind contribute to the measured flux, at the three heights used in this experiment (1, 2 and 4 m). Although there was a small difference between midday and nocturnal mean wind speed (0.30 m s^{-1} and 0.24 m s^{-1}), the primary difference between the two scenarios was the value of σ_w (Figure 2). During the night, the mean σ_w was 0.04 m s^{-1} near the forest floor compared to 0.10 m s^{-1} during midday.

The horizontal distances of the peak in the footprint probability distribution during typical daytime conditions were approximately 2 m (1-m height), 6 m (2-m height) and 10 m (4-m height) (Figure 3a). The peak distances increased by almost a factor of three (6, 16 and 29 m) at night (Figure 3b). The general characteristics of the footprints (location of peak, general shape) were repeatable using different random number seeds.

The distances separating systems in the ‘collocated’ experiment were at least an order of magnitude less than the peak distances contributing to the flux and OL_h (Equation 4) was nearly 1.0, suggesting that the footprints were almost identical in these experiments. In contrast, for systems separated by 30 horizontal metres the daytime value of OL_h was 0.16, indicating very little overlap between systems. However, during the night only 44% of the cumulative fluxes occurred within 30 m, and OL_h was 0.47, implying the possibility of greater overlapping footprints at night compared to day. Contradicting this theoretical conclusion, we observed more variability at night for all scalar fluxes compared to day (diurnal variation of CV' for F_c shown in Figure 4). Intermittent turbulence and localized drainage flows at night may be two reasons for the increased variability in eddy covariance measurements that are not considered in the Lagrangian simulations.

A similar analysis was performed for vertically separated systems. In the daytime simulations, OL_v was 0.79 between systems at 1-m and 2-m heights. The one-dimensional (streamwise) footprints at 2 m and 4 m overlap by 73% (OL_h = 0.73), and between 1 m and 4 m OL_v was 0.55. With the nighttime conditions, the footprint sizes increase dramatically (Figure 3), but the relative overlap is not substantially altered, 0.72 (1 and 2 m), 0.64 (2 and 4 m) and 0.49 (1 and 4 m).

The Lagrangian model results suggest that there is limited overlap of source regions in the horizontally separated experiment, but is possibly greater at night.

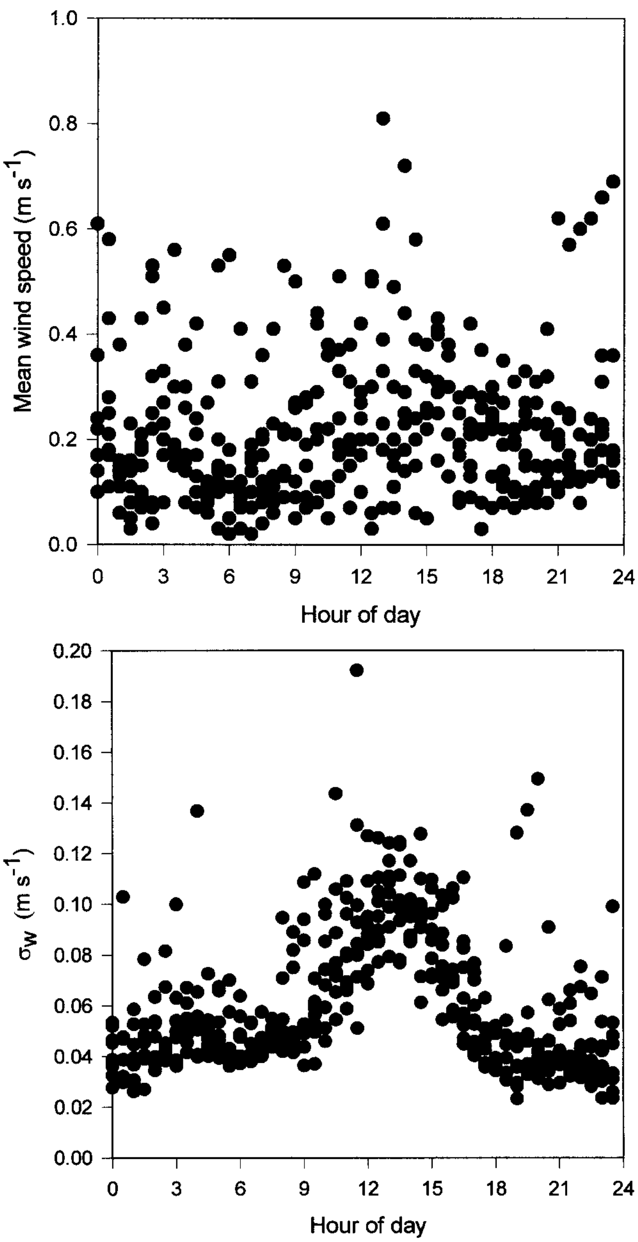


Figure 2. (a) Mean wind speed and (b) σ_w as a function of hour of day, 2 m above the forest floor between days 280 and 292, 1999.

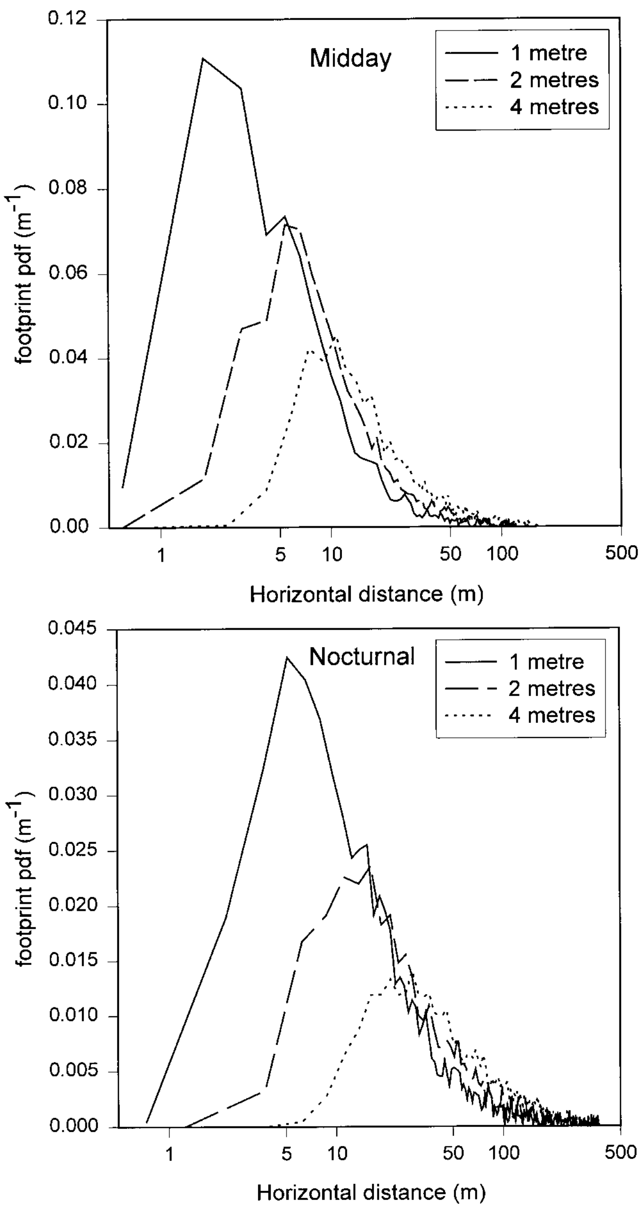


Figure 3. The horizontal distribution of the 'flux footprint' probability distribution based on Lagrangian trajectory simulations for the three vertical measurement heights used in this study. Simulations are for (a) mean daytime conditions and (b) mean nighttime conditions.

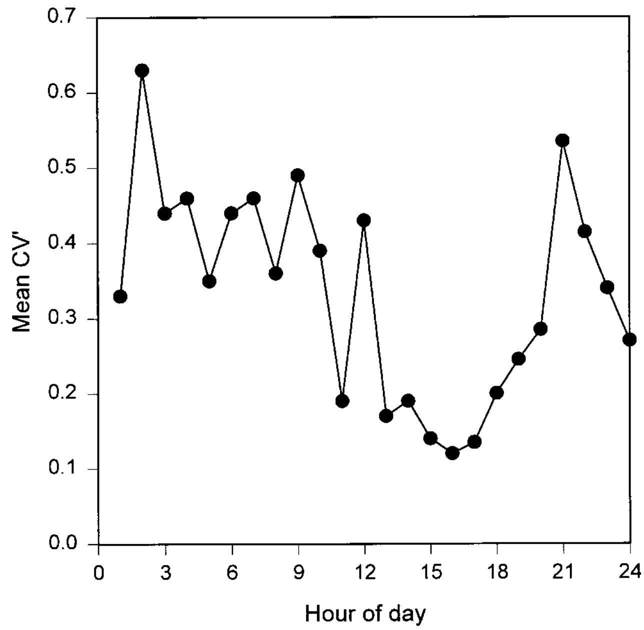


Figure 4. Mean diurnal CV' (Equation (2), $m = 1$) for F_c in the horizontally separated experiment.

There is likely less independence between systems separated vertically compared to systems separated horizontally, at least for the separation distances used in this study, although the actual overlap in our analysis is likely overestimated in both cases because crosswind velocity perturbations were not considered. These results do not consider the possibility of shallow sub-canopy nocturnal drainage flows very close to the surface, which would influence the degree of independence between vertically separated sensors.

3.2. Spectral corrections

Separation between the sonic anemometer and gas analyzer will result in the loss of high frequency contributions to the fluxes of carbon dioxide and water vapour (Moore, 1986; Massmann, 2000). It is particularly relevant to evaluate the effect of measurement height on high frequency flux loss in this study to ensure compatibility between flux estimates at the three measurement heights. Because the vertical velocity and sonic temperature are determined within the same finite volume, the assumption was made that the temperature flux approximated that of an ideal sensor. Although this idealization is not completely accurate because of path averaging, the errors resulting from sensor separation are normally much greater (Moore, 1986; Laubach and McNaughton, 1998). A normalized cospectral low frequency fraction ($F_{w\theta}$) was computed as

$$F_{w\theta} = \frac{\Delta f_{w\theta}}{f_{w\theta}} = \frac{\int_0^{n_1} C_{w\theta}(n)\,\mathrm{d}n}{\int_0^{n_2} C_{w\theta}(n)\,\mathrm{d}n}, \tag{6}$$

where the denominator represents an integral over the entire spectrum (i.e., total flux) and the numerator is integrated to a lower frequency ($n_1 \approx 0.1$ Hz in this study) and comprises the larger scale contributions to the vertical turbulent heat flux. If cospectral similarity is assumed, the normalized cospectra will have the same shape, and the cospectral fractions of heat ($F_{w\theta}$) and other scalars ($F_{w\chi}$) are identical. Assuming low frequency contributions are accurate, corrections can be made by matching the cospectral fractions such that

$$F_{w\chi} = \frac{\Delta f_{w\chi}}{(1+\alpha) f_{w\chi}} = F_{w\theta}, \tag{7}$$

where α is the fractional increase in the measured scalar flux necessary to match the spectral fraction of the temperature flux (i.e., the relative correction). Normalized cospectral estimates for heat and water fluxes for the three measurement heights are shown from day 261 when the three sonic anemometers were in a vertical configuration (Figure 5). The relative correction decreased slightly with height above the surface. For the lower (1 m) system, α was 0.10 and it was 0.06 at 2 m and 0.05 at 4 m.

3.3. Experimental Results

Experiment 1: Systems collocated

Figure 6 shows the half-hour carbon dioxide flux densities (F_c) when the three systems were collocated at 2 m above the forest floor. The fluxes from the three systems closely track each other. The average half-hourly standard deviation between systems $\sqrt{\langle F_c''^2 \rangle}$ was 0.27 μmol m^{-2} s^{-1}, and the average half-hour value of CV' (m = 1, Equation (2)) was 0.14 (Table I). As the number of half-hour samples (m) used to compute the mean fluxes increased from one to ninety-six (from a half-hour to forty-eight hours), the variation (CV', Equation (2)) was reduced by a factor of two, to 0.07 (open squares in Figure 7; Table I). There were no statistical differences in the overall mean carbon dioxide fluxes between the three sensors over the experimental period. Using these overall means from each of the three systems, the mean ecosystem flux was 1.88 ± 0.07 μmol m^{-2} s^{-1} (Table II).

Table I (under columns labeled 'Collocated') shows CV', using either single or ninety-six half-hour samples (m = 1 or m = 96), for all of the turbulent fluxes ($\overline{w'\chi'}$)

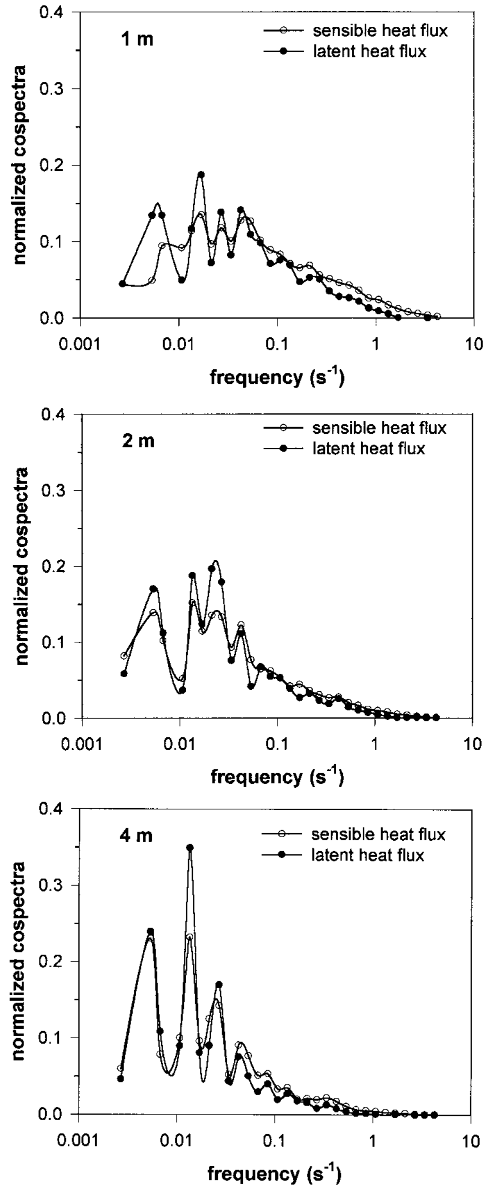


Figure 5. Normalized cospectra of temperature and water vapour flux for instruments at (a) 1 m, (b) 2 m and (c) 4 m heights above the ground surface. All data was acquired when the systems were vertically separated on day 261.

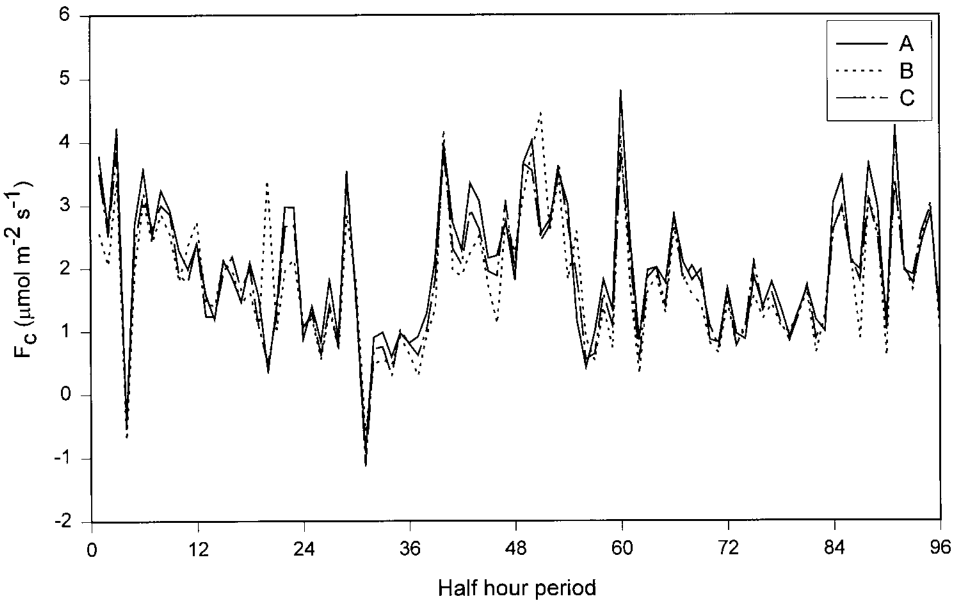


Figure 6. Carbon dioxide flux density versus half-hour period for each of the three eddy covariance systems (labeled A, B and C) during the collocated experiment at 2 m above the surface. Measurements were made between day 257 and day 259, 1999.

TABLE I

The mean value of CV' for m = 1 (0.5 h) and m = 96 (48 h) when the systems were placed 2 m above the forest floor and either collocated or separated by 30 m. Also shown is CV' for the entire experiment when the sensors were separated (303 h).

	0.5 h (m = 1)		48 h (m = 96)		303 h
Variable	Collocated	Separated	Collocated	Separated	Separated
σ_u	0.02	0.09	0.00	0.03	0.02
σ_w	0.05	0.16	0.02	0.05	0.04
σ_T	0.08	0.12	0.05	0.02	0.01
σ_{CO_2}	0.06	0.23	0.03	0.08	0.03
σ_q	0.03	0.21	0.01	0.07	0.04
$\overline{u'w'}$	0.55	0.86	0.08	0.14	0.11
H	0.14	0.57	0.06	0.07	0.07
LE	0.13	0.53	0.06	0.09	0.10
F_C	0.14	0.57	0.07	0.16	0.15

TABLE II

Mean turbulent quantities of the three systems for all experiments in this study. Standard errors are calculated from the means of the three systems. CL indicates 'collocated' experiment and 'S' indicates horizontally separated experiment. '2-m' and '1-m' indicate the vertical heights above the forest floor. 'Vertical' indicates vertically separated experiments (A and B indicate the two replications). (*) indicates the means between the three sensors are statistically different. Also shown for reference is the mean u_* (friction velocity) measured above the canopy during the respective experiments.

	Units	2-m CL	2-m S	1-m CL	Vertical A	Vertical B
u_*	m s^{-1}	0.61	0.24	0.21	0.31	0.33
σ_u	m s^{-1}	0.30 ± 0.000	0.20 ± 0.003	0.20 ± 0.000	0.19 ± 0.003	0.21 ± 0.004
σ_w	m s^{-1}	0.09 ± 0.001	0.07 ± 0.002	0.06 ± 0.000	0.06 ± 0.006*	0.07 ± 0.001*
σ_T	K	0.334 ± 0.008	0.285 ± 0.002	0.262 ± 0.004	0.300 ± 0.002	0.270 ± 0.004
σ_{CO_2}	μmol m^{-3}	110 ± 2.2	162 ± 2.6	118 ± 1.8	106.7 ± 5.9*	152.7 ± 16.6*
σ_q	kg m^{-3}	0.22 ± 0.002	0.23 ± 0.005	0.24 ± 0.005	0.18 ± 0.006	0.20 ± 0.014*
$-\overline{u'w'}$	m^2 s^{-2} × 100	1.13 ± 0.05	0.56 ± 0.034*	0.325 ± 0.023*	0.622 ± 0.163*	0.594 ± 0.054*
H	W m^{-2}	11.3 ± 0.38	3.7 ± 0.15	5.91 ± 0.26*	5.21 ± 0.35*	4.37 ± 0.55*
LE	W m^{-2}	11.2 ± 0.40	8.1 ± 0.54	7.45 ± 0.30	8.87 ± 1.11*	7.77 ± 0.22
F_C	μmol m^{-2} s^{-1}	1.88 ± 0.07	1.51 ± 0.13*	1.84 ± 0.02	1.52 ± 0.07	1.99 ± 0.11*

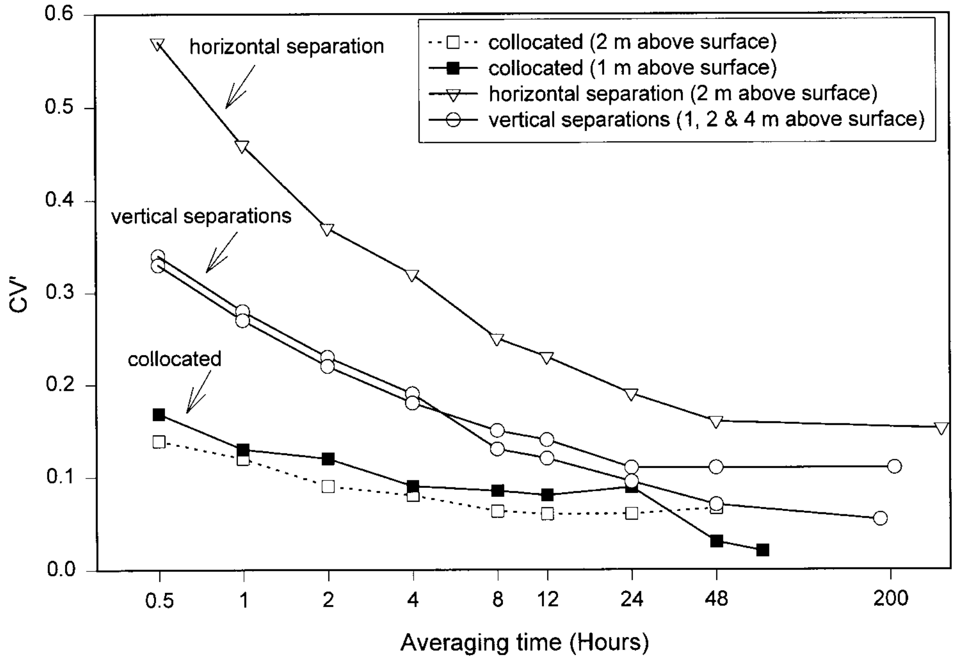


Figure 7. CV' (Equation 2) calculated for F_c as a function of averaging time (averaging over half-hour samples). Collocated experiments at one-metre (■) and two-metre (□) heights are shown. Also shown is the horizontally separated experiment (▽) and both sets of vertically separated experiments (○).

and standard deviations of turbulent fluctuations (σ_χ). At the half-hour time scale ($m = 1$, Equation (2)), CV' ranged from 0.02 (σ_u) to 0.55 for the momentum flux ($\overline{w'u'}$). When computed over forty-eight hours ($m = 96$, the mean of the ninety-six half-hour samples), CV' did not exceed 0.08 for any of the turbulence variables. There were no statistical differences in the means of any turbulent parameter when averaged over forty-eight hours.

The same patterns discussed above also generally applied when the sensors were collocated at a lower height above the surface (1 m), but with slightly greater differences between systems at 1 m (closed squares in Figure 7; Table III). When evaluated from forty-eight hour means ($m = 96$), both collocated experiments indicate similar variations with CV' less than 0.10.

Experiment 2: Systems horizontally separated

Figure 8 shows F_c for the three systems during the period when the three eddy covariance systems were 2 m above the surface, but horizontally separated by approximately 30 m. The half-hour deviations between systems are visually much greater than when the systems were collocated (compare Figures 6 and 8). The average half-hour standard deviation of F_c between systems was 0.91 μmol m^{-2}

TABLE III

The mean value of CV' for m = 1 (0.5 h) and m = 96 (48 h) and when the systems were collocated at 1 m above the forest floor.

Variable	0.5 h (m = 1)	48 h (m = 96)
σ_u	0.02	0.00
σ_w	0.05	0.02
σ_T	0.14	0.03
σ_{CO_2}	0.05	0.03
σ_q	0.07	0.04
$\overline{u'w'}$	0.55	0.08
H	0.24	0.09
LE	0.23	0.07
F_C	0.17	0.03

s^{-1}. The mean half-hour CV' (m = 1) was 0.57, more than four times the variability of collocated systems (Table I). Figure 7 (open triangles) shows the strong time-dependence of CV', rapidly decreasing from 0.57 for the half-hour to 0.16 over forty-eight hours. Time is on a logarithmic scale in Figure 7, de-emphasizing the rapid reductions at short time scales. There was almost no further decrease in CV' beyond forty-eight hours (CV' was still 0.15 after more than ten days, m = 606). The mean carbon dioxide fluxes were statistically different over the entire experiment and the mean forest floor flux was 1.51 ± 0.13 μmol m^{-2} s^{-1} (Table II).

Table I shows CV' for all the turbulent variables evaluated in this experiment (columns labeled 'Separated'). For single half-hour samples, CV' was generally in excess of 0.10 for all parameters except σ_u (0.09). The spatial variability of the turbulent fluxes was generally several times larger (CV' from 0.53 to 0.86) than variability of the standard deviations (0.09 to 0.23). When the turbulent statistics were averaged over ninety-six samples (forty-eight hours), the variation was reduced substantially. The value of CV' was less than 0.10 for all parameters except F_c and $\overline{w'u'}$. Across all time scales, there is greater variability in the turbulent fluxes (0.07 to 0.16) than the standard deviations (0.02 to 0.08), similar to the collocated experiment. With the exception of σ_T, variability was always greater for separated compared to collocated sensors, but this difference was more noticeable at the half-hourly (m = 1) time scale than after forty-eight hours (m = 96) (Table I). There were further decreases in CV' for σ_χ as the averaging time is increased from 48 hours to 303 hours (total length of experiment), but there were essentially no further decreases in CV' for turbulent scalar fluxes. Compared to collocated experiments, separating instruments horizontally increased the longer-term variab-

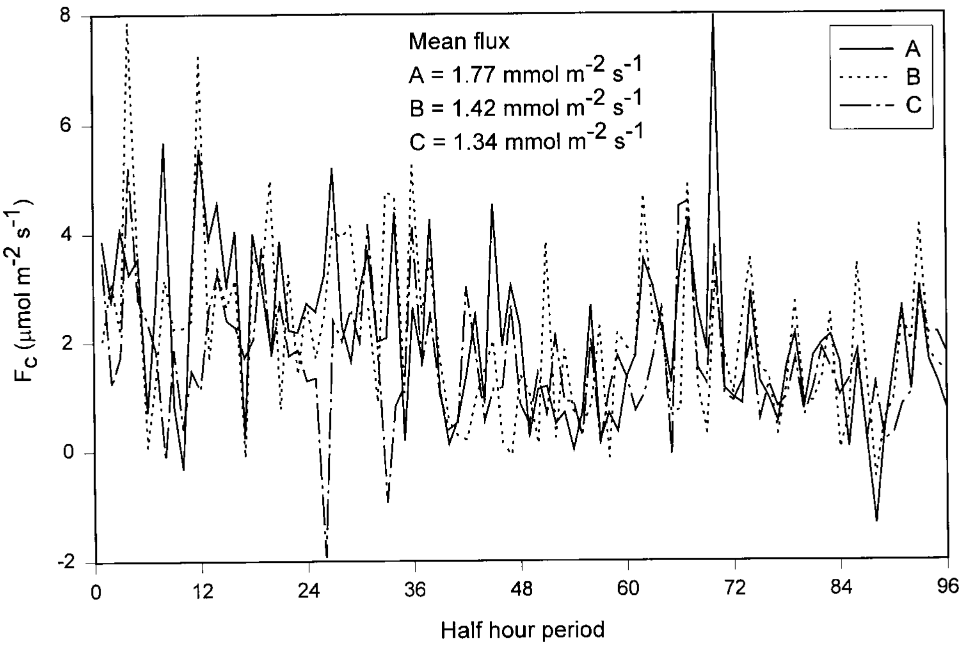


Figure 8. Carbon dioxide flux density versus half-hour period for each of the three eddy covariance systems (labeled A, B and C) for a forty-eight hour period when the systems were separated horizontally by approximately 30 m.

ility of carbon dioxide fluxes by an additional 9% relative to the total flux (CV' was 0.16 compared to 0.07 'for collocated'), but horizontal separation had less of an absolute effect on for all other turbulent quantities (Table I).

Experiment 3: Systems separated vertically

The three systems were separated vertically at two different horizontal locations and times, denoted by 'vertical separation A' and 'vertical separation B', but at the same heights (1, 2 and 4 m). The half-hour CV' values (m = 1, Equation 2) for F_c were 0.33 and 0.34 during these two periods (Table IV), a little more than half that in the horizontally separated experiment (0.57) but more than twice the collocated experiments (0.14, 0.17) (open circles in Figure 7; Tables I and III). The mean half-hour standard deviations were 0.55 and 0.68 μmol m^{-2} s^{-1}.

A problem with comparing half-hour values of F_c between systems at different heights is the potential for differences in carbon dioxide storage beneath the sensors. Any storage of carbon dioxide between 1 m and 4 m would result in different storage terms for the three systems. Because this difference was not considered, CV' might have been reduced if storage had been carefully determined. However, using the CO_2 concentration measurements at 0.75 m to represent the lowest 2 m, the average total magnitude of storage for the lowest two metres was only

TABLE IV

The mean value of CV' for m = 1 (0.5 h), m = 96 (48 h) and over the entire experiment when the systems were vertically separated at 1, 2 and 4 metres above the forest floor. 'A' and 'B' refer to the two replicated vertically separated experiments. The duration of the two experiments was 184 hours for A and 207 hours for B.

	0.5 h (m = 1)		48 h (m = 96)		Whole experiment	
Variable	A	B	A	B	A	B
σ_u	0.07	0.06	0.03	0.03	0.03	0.03
σ_w	0.20	0.18	0.20	0.15	0.17	0.15
σ_T	0.11	0.10	0.02	0.03	0.01	0.02
σ_{CO_2}	0.17	0.22	0.07	0.20	0.09	0.19
σ_q	0.12	0.19	0.05	0.14	0.05	0.12
$\overline{u'w'}$	0.70	0.49	0.56	0.18	0.46	0.16
H	0.35	0.40	0.13	0.20	0.11	0.20
LE	0.38	0.31	0.24	0.06	0.21	0.05
F_C	0.34	0.33	0.07	0.11	0.06	0.10

0.18 μmol m^{-2} s^{-1}. Because temporal changes in carbon dioxide concentration (storage) normally decrease with height, storage above 2 m is expected to be even smaller, making it unlikely that storage accounts for more than a small fraction of the observed half-hour variability.

Possible bias errors associated with measurement height were investigated further by averaging carbon dioxide fluxes (F_c) by time of day (Figure 9). During vertical separation B, there were statistical differences between the systems, but only during the early nighttime hours (Figure 9b). Some portion of this nocturnal difference is likely to be storage, but the total mean storage contribution over the lowest 2 m is generally less than 0.3 μmol m^{-2} s^{-1} (Figure 10), several times smaller than the observed flux differences (Figure 9b). During vertical separation A, the apparent bias in F_c with height is also evident but mean fluxes were not statistically different for any half-hour and are much closer to the magnitude estimated for storage (Figures 9a and 10). There was a correlation between the diurnal patterns in F_c (Figure 9) and the mean vertical velocity (Figure 11) in both vertical separations. Vertical velocity was obtained by rotating the measured mean half-hour vertical velocity to account for slope in the terrain and sensor tilt (Baldocchi et al., 2000a). The mean vertical velocity (Figure 11) was positive during midday and negative during the first half of the night, and it also increased in magnitude with height above surface. The correlation between mean vertical velocity and a potential bias in F_c is consistent with the presence of drainage flow and possible biased estimates of carbon dioxide flux, especially at night (Lee, 1998; Baldocchi et al., 2000b; Paw U et al., 2000).

The decrease in CV' with averaging time for the two vertically separated experiments is shown in Figure 7 (open circles) and Table IV. The value of CV' for F_c over forty-eight hours (m = 96, Equation (2)) was 0.07 and 0.11 for the two experiments. Extending the analysis over the entire experiments (more than one week), CV' decreased slightly to 0.06 (vertical separation A) and 0.10 (vertical separation B). During vertical separation A, the mean CO_2 fluxes over the entire measurement period were similar between the three systems (Table II, 1.48, 1.49 and 1.60 μmol m^{-2} s^{-1}at 1, 2 and 4 metres, respectively) and not statistically different. During vertical separation B, at a horizontal distance of 25 m from vertical separation A, mean F_c values were statistically different between the three systems and were greater for the system closest to the surface (2.17, 2.02 and 1.78 μmol m^{-2} s^{-1} at 1, 2 and 4 m, respectively). As shown in Figure 9b, the longer-term differences between the systems in this experiment were almost exclusively during the evening and early nighttime period (1700 to 0200 EST).

Table IV shows the values of CV' for all turbulent quantities during the two periods of vertical separation. Similar to the collocated and horizontally separated experiments, the variation in σ_u is very small when computed for the half-hour (0.06, 0.07) or longer-term (0.03, 0.03 for forty-eight hours). Alternatively, CV' for σ_w did not decrease with time, indicating that σ_w was a function of height above the surface. In both vertical separation configurations, σ_w increased with height while σ_u did not. With the exception of σ_w, the half-hour values of CV' were greater for the horizontally separated experiment than either of the vertically separated experiments (Table I and IV).

The magnitude of longer-term variability in turbulent fluxes was inconsistent between the two vertically separated experiments, but often exceeded the variability in the horizontally separated experiment (Tables I and IV). There was some tendency in both vertically separated experiments for the turbulent fluxes of momentum, heat and water vapour to increase monotonically with height above the surface (statistical differences denoted in Table II). In both vertical separations, there were statistically significant (P < 0.05) increases in mean H (CV' = 0.11 and 0.20) and $\overline{w'u'}$ (CV' = 0.46 and 0.16) with height. There was also a statistically significant increase in LE with height in separation A (CV' = 0.21), but not B. In contrast to the momentum and other scalar fluxes, the mean carbon dioxide flux *decreased* with height in separation B (CV' = 0.10).

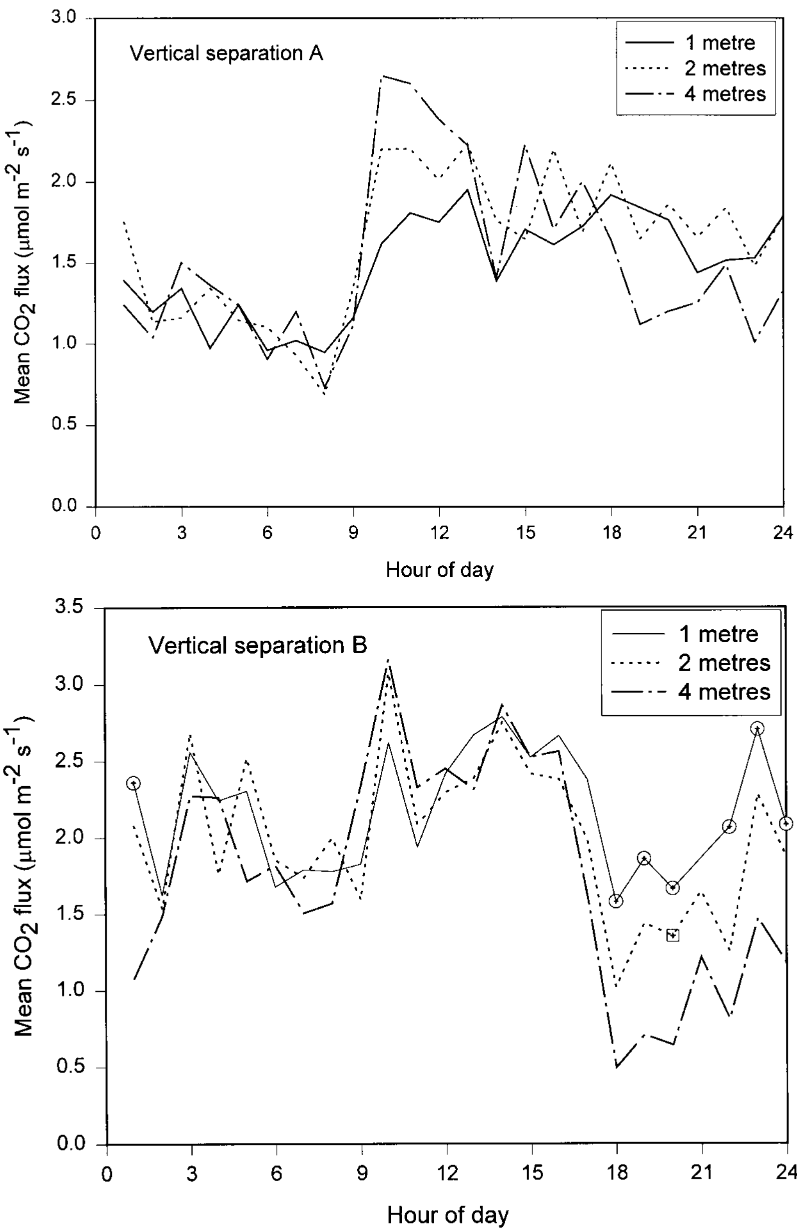


Figure 9. Mean carbon dioxide flux (F_c) as a function of hour of day during vertically separated experiments A and B. Symbols represent time periods when the mean F_c at 1-m height (O) or 2-m height (□) differs significantly ($P < 0.05$) from that at 4 m. The standard error for each half-hourly mean is variable but averaged about 0.35 μmol m^{-2} s^{-1}.

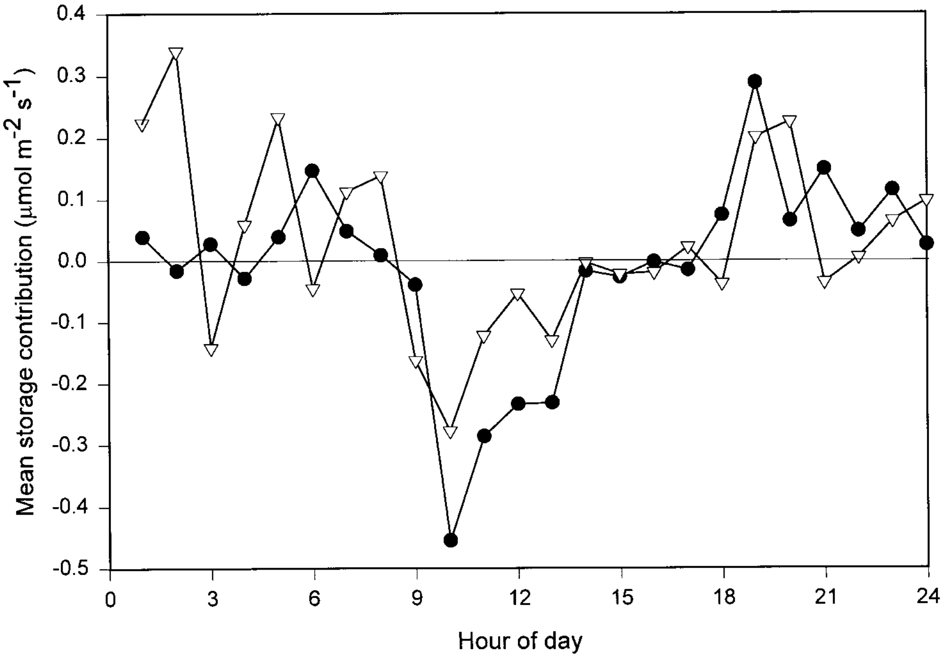


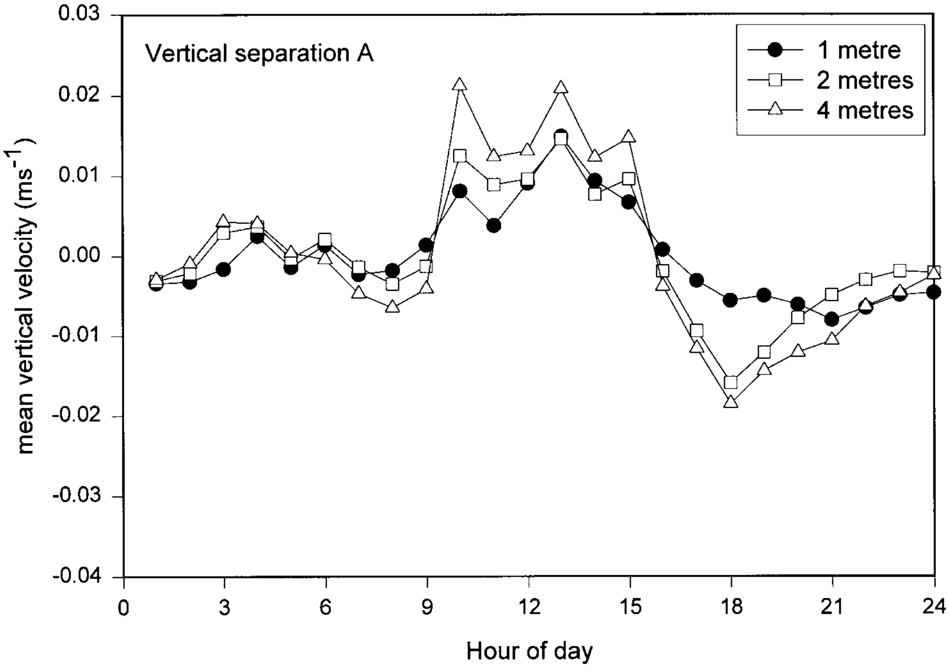
Figure 10. Estimated mean contribution of carbon dioxide storage below 2 m to total flux as a function of time of day during vertically separated experiments A (▽) and B (●).

4. Discussion

4.1. Flux footprints

Lagrangian trajectory simulations suggest that the distance between sensors in the horizontally separated experiment (30 m) is generally sufficient so that the systems probably do not significantly overlap in their footprints for any half-hour period. The analysis also suggests much greater overlapping in the vertically separated experiments, likely confounding direct analysis of spatial variability from vertically separated systems. These results are dependent on the separation distances, sensor height and canopy architecture affecting turbulence in this particular study.

The coefficient of variation for solar radiation at this forest floor approaches 100%, with a large positive skewness caused by sunflecks (Baldocchi et al., 1986). Because solar energy drives energy fluxes, and more indirectly carbon flux through changes in litter and soil temperature, these variations can be important when analyzing representativeness at the forest floor. The spatial scales of sunflecks are limited on the small scale by the tall vegetation and penumbral effects and on the large scale by the spatial scales of foliage clumping and canopy gaps. The spatial scale of larger sunflecks is generally on the order of several metres (Baldocchi and Collineau, 1994), so the calculated flux footprints will generally average over



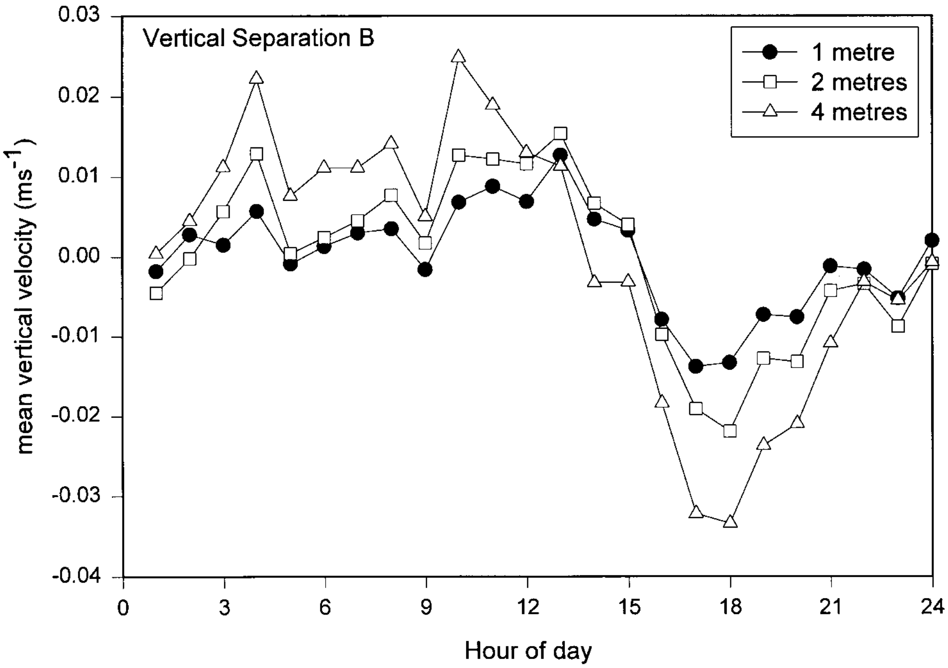


Figure 11. The average half-hour mean vertical velocity as a function of time of day in (a) vertical separation experiment A and (b) vertical separation experiment B.

scales larger than single sunflecks. However, the daytime footprints are sufficiently small to be occasionally biased by the presence or lack of sunflecks.

4.2. Representativeness of Half-Hour Measurements

Because half-hour values of CV' for collocated systems were non-zero, some fraction of variation in all experiments is due to instrumentation, sensor tilt angles or sensor shadowing effects. Even in ‘collocated’ experiments, the instruments were separated by a finite distance (0.20 m). However, separating the systems from several metres vertically to 30 metres horizontally nearly always increased half-hour variation, usually dramatically.

In all experiments, the half-hour CV' of σ_χ for all velocity and scalar components was less than 0.23. This is especially true for σ_u, σ_w and σ_T, which are lower than σ_{CO_2} and σ_q in the horizontally separated experiment. Therefore, it may be a reasonable to use half-hour values of σ_χ in modelling applications. For example, σ_w is needed to initialize Lagrangian models of turbulent diffusion in canopies (Raupach, 1989; Baldocchi, 1997a). The especially small variability in σ_u suggests longitudinal velocity perturbations have larger scale characteristics than σ_w. This is consistent with cospectral analyses at this forest (Baldocchi and Meyers, 1988) and so-called inactive turbulence (Katul et al., 1999).

The CV' for turbulent fluxes ($\overline{w'\chi'}$) were often much greater than for the standard deviations (σ_χ), an anticipated result when comparing second-order statistics to the square root of second-order statistics (Wyngaard, 1973; Katul et al., 1999). Because of large CV' values, individual half-hour flux measurements ($\overline{w'\chi'}$) should be used with a high level of caution in ecological, turbulent transport and atmospheric mixed-layer modelling applications. This variability will also reduce the correlation when examining causal relationships between flux and environmental data, such as the response of soil respiration to soil temperature. Averaging flux and environmental data over multiple half-hour samples will reduce these errors; CV' for carbon dioxide flux (F_c) decreased from 0.57 to 0.30 when the averaging time is increased from one-half hour to four hours (or from one sample to eight samples) in the horizontally separated experiment. After twenty-four hours it was 0.18, or only 20% greater than that for one week (0.15), suggesting that four hours (m = 8, eight samples) to one-day (m = 48) may be a reasonable averaging time. However, if the flux response to environmental forcing is non-linear and changes in environmental variables occur over these longer time periods, this approach is not practicable. Also, the number of sampling periods required may be greater at night because of the increased variability, likely a result of turbulent intermittency (Howell and Sun, 1999). A second approach to reduce the effect of variability in short term fluxes on the correlation between fluxes and environmental parameters is to average all flux data during periods of similar environmental forcing (i.e., group data by soil temperature or soil water content). This method risks multiple confounding factors if data are averaged over a time period that is too long and contains low frequency trends. Similar compromises are necessary when validating model output, because random errors associated with the eddy covariance method may confound short-term comparisons of simulated and modelled fluxes. It is probably a better approach to compare model and data using longer term averaging, but this may compromise a detailed examination of processes.

Scalar flux variability was less than for momentum, consistent with findings in previous studies above vegetation (Dyer and Hicks, 1972; Katul et al., 1999). Larger errors are anticipated for momentum fluxes, partially because of errors associated with sensor tilt and shadowing, but also because momentum flux errors are more sensitive to random errors than scalar fluxes (Wyngaard, 1973).

4.3. Longer-term representativeness

Variability between systems was greatly reduced by averaging over longer time periods, which is expected when random errors are large (Moncrieff et al., 1996). In a separate study using two eddy covariance systems within the canopy but above understory vegetation, there was little correlation between short-term CO_2 fluxes, but the long-term mean CO_2 flux agreed to within 10% after five days (Yang et al., 1999). Compared to a mean CV' value of 0.05 for F_c in the collocated experiments (mean of experiments at one and two metres), a corresponding value of 0.16 during the horizontally separated experiment suggests longer-term (several days to ten days) spatial variations of mean carbon fluxes on the order of 10% over the separation distances in this study (30 m). Some effects of random errors may remain in the measurements, but there was almost no decline in CV' when evaluated for two days or more than seven days.

Assuming an annual soil efflux $\approx$ 700 g carbon m^{-2} at this forest (Edwards et al., 1989) and a 10% error in using a single eddy covariance system to calculate long-term estimates of soil respiration, a rough approximation of absolute error due to spatial variability is on the order of $\pm$ 70 g carbon m^{-2}. Based on above-canopy eddy covariance estimates, these errors are approximately 10–15% of ecosystem NEE, but are larger ($\approx$30%) if biomass estimates are used to obtain NEE (Greco and Baldocchi, 1996).

The long-term variability in $\overline{w'\chi'}$ for all scalars, not just carbon dioxide, suggests that errors are always associated with using a single measurement to provide long-term means of heat, water and carbon fluxes. In the horizontally separated experiments, these errors did not greatly exceed 10%, at least over the small distances examined in this study, but larger errors were present in the vertically separated experiments (discussed below). The relatively small values of σ_χ over several days to a week indicate that single eddy covariance systems can provide reliable longer-term means of these statistics that are representative of a larger area, at least at specified heights above the surface.

A study using chamber methods suggests that the mean CV of soil respiration within particular regions of this watershed (e.g., ridge, south-facing slope, etc.)

is 0.36 (Hanson et al., 1993). If the longer-term estimates of CV' based on eddy covariance measurements are taken to represent spatial variability at larger scales, this suggests that the eddy covariance measurements are integrating over much, but not all, the variability seen in the chamber measurements. The eddy covariance footprint is one to several orders of magnitude greater than the surface area of the chamber measurements (0.0594 m^2), suggesting that if sampling is the only source of error, errors in long-term estimates of soil respiration will be several times smaller using eddy covariance methods compared to chamber data.

4.4. Vertical versus horizontal separations

Vertically separating systems had a smaller effect on short-term variability than horizontal separations but often had a larger effect on the long-term (several days to week) variability. Although the flux footprint is a function of vertical position, other explanations are possible for the longer-term variability of vertically separated systems. Non-zero momentum absorption and carbon and energy exchange between the vertical levels of the systems is possible, which could explain the tendency for an increase in energy and momentum fluxes with height. Because there was very little vegetation at heights between any of the sensors, this possibility is unlikely.

The decrease in measured carbon dioxide efflux with height during vertical separation B may be the result of storage, high frequency loss of flux (Moore, 1986), drainage flows (Lee, 1998; Baldocchi et al., 2000b; Paw U et al., 2000) or real differences in flux footprints. Storage of CO_2 beneath the sensors appears to be too small to account for these differences. High frequency loss of flux was only weakly height dependent (5% bias between 1 and 4 m), and would have the opposite bias, increasing the magnitude of flux with height. The diurnal pattern in mean vertical velocity and its decrease in magnitude with height may indicate that drainage flows are present in the lowest few metres, consistent with drainage flow patterns at locations (Horst and Doran, 1986). Increasing the vertical position of measurement sensors would (erroneously) decrease estimates of carbon dioxide efflux as a result of vertical advection (Lee, 1998). A correlation between apparent biases in F_c and mean vertical velocity would also be a signature of mean vertical advection at night and is consistent with the measurements presented here. Further evidence of nocturnal drainage flows is provided by chamber measurements. The magnitude of eddy covariance estimates of soil respiration is consistent with the chamber measurements of Chambers (1998) during the daytime, but not during nocturnal periods.

5. Conclusions

(1) The measured spatial variability of turbulent quantities at the forest floor over short time scales is dominated by random errors associated with using single-point measurements in a finite sampling period. The large magnitude of the

variability (CV' = 0.57 for F_c in the horizontally separated experiment) dictates that this uncertainty be considered when using half-hour turbulent fluxes in modelling applications or in developing relationships between turbulent fluxes and environmental parameters.

(2) The measured spatial variability at intermediate time scales (several hours to a day) decreases rapidly as the number of half-hour samples increases (CV' for F_c decreases from 0.57 for one-half hour to 0.30 after four hours, and 0.18 after twenty-four hours). Fluxes obtained using these time scales (or number of samples) will greatly reduce the random errors of single measurements when examining causal relationships between fluxes and environmental parameters or in model validations.

(3) The measured variability of turbulent fluxes at longer time scales (several days to a week) decreased very slowly or not at all with increased averaging time. The variability at these longer time scales is indicative of biological and physical variability at the forest floor, resulting in uncertainty if only one eddy covariance system is used. At our site, we approximate this uncertainty to be on the order of 10%, or between about 50 and 100 g carbon m^{-2} per year.

(4) There was theoretically greater footprint overlap, and less independence of flux estimates, in the vertically separated experiments than in the horizontally separated experiments. However, long-term variability was often greater in vertically, relative to horizontally, separated experiments. In addition to the flux footprint changing with sensor height, one explanation for differences in flux estimates with height is mean vertical advection associated with drainage flows.

(5) This study addressed variability of forest floor fluxes over a relatively small distance (footprints several metres to about 100 metres) within a region of similar topography, but did not account for more dramatic variations in forest floor properties that are likely to exist between coves, ridges and over different soils at Walker Branch Watershed (Trettin et al., 1999). More accurate estimates of representativeness will also require measurements over longer time scales (Nappo et al., 1982), including measurements during the leafless season.

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