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THE ROBUSTNESS OF EDDY CORRELATION FLUXES FOR AMAZON RAIN FOREST CONDITIONS

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Abstract. We analyzed errors and uncertainties in time-integrated eddy correlation data for sites in the Amazon. A well-known source of potential error in eddy correlation is through possible advective losses of CO_2 emissions during calm nights. There are also questions related to the treatment of low frequencies, non-horizontal flow, and uncertainties in, e.g., corrections for tube delay and frequency loss, as well as the effect of missing data. In this study, we systematically explore these issues for the specific situation of flux measurements at two Amazon forest sites. Results indicate that, for this specific environment with tall forest and tall towers, errors and uncertainties caused by data spikes, delay corrections, and high-frequency loss are small (<3% on an annual basis). However, sensitivities to the treatment of low frequencies and non-horizontal flow can be large, especially if the landscape is not homogeneous. Given that there is no consensus on methodology here, this represents an uncertainty of 10–25% on annual total carbon uptake. The other large uncertainty is clearly in the nighttime fluxes. Two different ways to evaluate the validity of these fluxes resulted in at least a 100% difference of annual totals. Finally, we show that uncertainty (standard errors) associated with data gaps can be reduced to <0.5 Mg·ha^{-1}·yr^{-1} if data are covering at least half of the time, with random spread. Overall uncertainty, on annual CO_2 fluxes, excluding the nighttime dilemma, is estimated at ±12% (central Amazon site) to ±32% (southwest Amazon site). Additionally, the nighttime uncertainty is of similar magnitude as the time-integrated fluxes themselves.

Key words: coordinate rotation; delay corrections; flux uncertainty; frequency corrections; low frequency turbulence; nighttime fluxes; non-stationarity.

Introduction

The use of eddy correlation techniques to assess the exchange of momentum, energy and mass between vegetated land surfaces and the atmosphere has been dramatically gaining support over the past five years (Baldocchi et al. 2001). In the "early days" of eddy correlation, some studies were done to assess errors and uncertainty, leading to the notion that there is a stochastic error of ~10% on individual half-hourly fluxes, which rapidly vanishes if multiple data points are averaged (Lumley and Panofsky 1964, Dyer and Hicks 1972, Moncrieff et al. 1996). The basic methodology has not changed since then, but because eddy correlation is now being used to estimate annual totals and spatial variability of carbon and water exchange (Wofsy et al. 1993, Grace et al. 1995, Valentini et al. 2000), it is more important than ever to assess the absolute accuracy and uncertainty ranges of measured surface–atmosphere exchange. This need for error assessment is exacerbated by the fact that, at least for the carbon balance, the long-term sums are small differences between large daytime uptake and large nighttime emission.

One of the most frequently cited sources of uncertainty in the eddy correlation method is the uncertainty about CO_2 fluxes at night. This is based on the observation that during periods of low wind speed and low turbulence intensity, CO_2 emission fluxes measured above canopies at night are usually much lower than expected from the respiratory plant and soil source which is supposed not to depend on turbulence. Rigorous CO_2 flux studies include in the analysis of nighttime fluxes an estimate of in-canopy storage changes of CO_2, through spatial integration of measured concentration profiles followed by differencing over time (Grace et al. 1996). These storage fluxes in some cases are large enough to recover the apparent "nighttime losses," but often a (smaller) difference remains between measurement and expectation.

Somewhat outside the perception of the wider community, there are still important uncertainties in the basic calculation of fluxes from the high-frequency sig-

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nals. Currently there is rather vigorous debate on whether data should be high-pass filtered, what is the best averaging time, whether corrections for tilt in the mean flow are needed and how to best correct for instrument inertial response and high-pass filtering (Lee 1998, Finnigan 1999, Baldocchi et al. 2000, Paw U et al. 2000). Final answers have not been satisfactorily given yet, and it is useful to at least be aware of the uncertainties in the fluxes associated with the undecidedness of this debate.

The objective of this paper is to explore the effects on fluxes associated with these methodological uncertainties, including systematic and conceptual errors. This will be applied to the specific situation of flux measurements above Amazon forests, to assess how robust measured fluxes in these conditions are to choices and uncertainties in the processing, and to define an overall uncertainty for fluxes measured under these conditions.

Data Sets, Instrumentation, and Data Acquisition

In this study we will mainly make use of data collected at the K34 site near Manaus (Araújo et al. 2002) and at the Rebio Jarú site in Central Rondônia (von Randow et al. 2004). Although both are in ''Terra firme'' forest, these sites differ in their degree of seasonality (with the Jarú forest being more seasonal) and to some extent in forest structure (as yet poorly defined at Jarú but visually more uneven-aged at that site). At K34, the topography is one of a dissected plateau and valley landscape, with height differences of about 50 m, and the flux tower is situated on the top of a plateau. To the northeast, which is the main wind direction, the altitude of the plateau increases slightly and the valleys become less wide and deep. To the southwest, the landscape gradually slopes down, with wider valleys, toward the lowlands and floodplains of the Rio Negro and tributaries. More information can be found in Araújo et al. (2002). In Jarú, the site is in the (flat) footplains between a low hill range, at several kilometers to the east and south, and the Rio Machado at ~1 km to the west (see also Andreae et al. 2002). Recently, there have been invasions in the forest at about 1 km to the north that were stopped, but now a few medium-sized clearings remain.

The flux towers at K34 and Jarú, as well as the additional Manaus C14 (formerly identified as the ZF2 or Cuieiras tower by Malhi et al. [1998] and Kruijt et al. [2000]) and the pasture site at Fazenda Nossa Senhora, Rondônia (Andreae et al. 2002), were all equipped with nearly identical measurement systems, similar in design to the Edisol system (Moncrieff et al. 1997) and the EUROFLUX standard (Aubinet et al. 2000). These were closed-path eddy-correlation systems, consisting of a three-axis sonic anemometer (Solent 1012R2; Gill Instruments, Lymington, UK), a fast-response (0.3 s response time) infrared gas analyzer (IRGA, Li-6262, Li-Cor, Lincoln, Nebraska, USA) and ~5 m of 4 mm inner diameter Teflon tubing and a pump to pull air at 7 L/min from an inlet near the sonic to the IRGA. Tubes were not heated because the lowered pressure inside the tubes prevents condensation. Pure nitrogen gas was bled through the reference cell at low flow rate (0.02 L/min). The sonic wind paths and tube inlets were positioned several meters above the tall towers on telescopic masts attached to the tower tops, minimizing effects of flow distortion by the towers. More details of the system setup can be found in Araújo et al. (2002).

Water vapor and CO_2 signals from the IRGA were fed into the built-in AC/DC converter of the sonic via a 1:1 amplifier circuit designed to prevent voltage drops across the analog signal wires. The concentration signals recorded by the sonic at 10.4 Hz plus temperature and wind velocities measured at 20.8 Hz were read into a palmtop computer (HP 200LX; Hewlett Packard, Palo Alto, California, USA) at 10.4 Hz through serial communication, and the computer then stored the signals on a small PCMCIA card hard disk for later off-line flux calculations.

Calibration of the IRGA was performed infrequently, but when done, drift usually had been very small. A continuous cross-check of the concentrations was performed, in the post-processing phase, by comparing the Li-Cor signal with that of a second, slow response but low drift IRGA (CIRAS-SC; PP systems, Herts, Hitchin, UK) that was used to monitor in-canopy concentration profiles of H_2O and CO_2. This IRGA was stable because the single analysis cell was thermostated, and zeroed on a half-hourly basis with a chemically scrubbed air circuit.

The physical robustness of such an eddy correlation system in a tropical rain forest turned out to be quite high. A frequently occurring problem was that tubes weathered quickly under high radiation load and frequent wetting-drying cycles, causing leaks. Calibration, which was done in the field because transport to the research base carried risks of rough handling and bumpy roads, was difficult, especially under high temperature and radiation conditions. Especially the zero reading of the Li-6262 seems to be sensitive to temperature gradients within the instrument. For the rest, several disasters occurred caused by lightning and violent winds, but generally the damage was limited to the repair of two or three instruments. In two cases, the tower structure was compromised by a fallen tree, but this was also repaired.

Methods

Processing steps and analysis of uncertainty

There are a number of processing steps between the collection of ''raw'' 10.4-Hz data and the final hourly and long-term water and carbon fluxes. The following

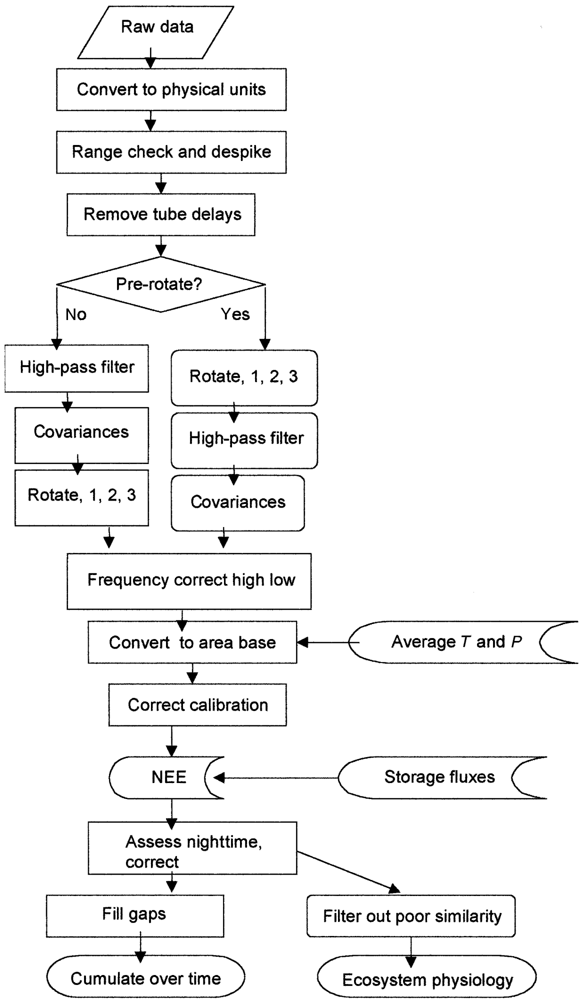

FIG. 1. Flow chart of all processing steps between raw eddy correlation data and final generalized fluxes. T is temperature, P is atmospheric pressure, NEE is net ecosystem carbon exchange.

serves both as a methodology description for the specific setups of the Manaus and Rondônia flux stations and as an inventory of possible sources of error and uncertainty. The order of processing is outlined in Fig. 1. As far as the standard methodology is concerned, we used an in-house developed FORTRAN program, called EDDYWSC, which closely follows the procedures described in Moncrieff et al. (1997) and Aubinet et al. (2000). The robustness (or uncertainty) of the processing steps has been investigated using the Manaus K34 and Jarú data sets, applying either variations of the EDDYWSC software or an analysis package developed by R. Clement at the University of Edinburgh (EdiRe).

Post-field calibrations

Although the signal from the Li-6262 analysis cell is pressure and temperature corrected, zero and span calibrations are necessary every month or so. Whenever a drift in zero or span was detected, corrections were not applied a posteriori to the raw or processed data. Instead, linear corrections were derived from comparison with the stable CIRAS analyzer and applied to the processed data. Span calibration errors and uncertainty in the derived correction values linearly translate into uncertainties in the calculated fluxes. As high quality reference gases were used most of the time, the main uncertainty is in the procedure of comparison with the CIRAS, which was assessed using linear regression techniques.

Cleaning the raw data series

Since eddy correlation fluxes essentially are covariances between vertical wind and another signal, as long as the average vertical wind speed is (forced to) zero, the calculations should be on average insensitive to spikes, step changes in zero offset, or any other noise on one signal as long as this noise is absent from the other signal. The effects of spikes and ''despiking'' on uncertainty are related to the degree to which spikes are correlated, and to the decrease in the degrees of freedom in the estimate of the average covariance as a result of removing records. As these effects are hard to determine directly, an experiment was done, showing the effect of engineered spikes in the CO_2 signal on the resulting fluxes.

Calculation of and correction for tube delays

A ''closed path'' eddy correlation system pulls air to be analyzed through a tube from the sonic anemometer to the IRGA. The result of this is that detection of the H_2O and CO_2 signals is delayed relatively to the directly measured vertical wind signal, and thus these time series need to be realigned. The tube delay is a function of pumping speed and tube geometry, but also of less easily predictable air properties such as degree of turbulence in the tube, viscosity, and adhesion to tube walls. Therefore it is usually considered best to estimate the delay empirically, for CO_2 and H_2O separately, assuming that the cross-correlation between these two signals and vertical wind speed is maximum at the appropriate time delay. Uncertainty in fluxes arises when the cross-correlation is weak and thus the delay poorly defined.

Averaging and high-pass filtering

Usually in combination with rotations (see next subsection), all data series are detrended by subtracting periodic means (Reynolds averaging), a mean linear trend, or a moving average, removing covariance and thus flux represented by slowly fluctuating or mean signal components, or large meteorological structures (Von Randow et al. 2002). In the EDDYWSC software, a recursive running mean filter is used. In the case of Reynolds averaging and linear detrending the cutoff of this high-pass filter is defined by the averaging time, whereas with moving average detrending a cut-off frequency can be defined independently of averaging time. The diversity and controversy in averaging and high-pass filtering presents an uncertainty to all eddy correlation results. Although the assumption is often made that flux at low frequencies is either negligibly small or undesirable because it is associated with ''advection,'' this is not necessarily the case. First, the amount of flux represented by low fluctuation frequencies increases as wind speeds decrease, so any cutoff in the time domain cannot be assumed constant, and second, the separation between advection and local flux is not necessarily defined by temporal or spatial scales.

Coordinate rotations

Streamlines are usually not exactly parallel to the underlying surface, but sonic anemometers are rarely exactly aligned with either surface or streamlines. A nonzero average vertical wind speed leads to large ''vertically advective'' terms in the calculated fluxes. As is clear from recent discussions in literature, this situation is complicated, because if finite vertical advection is taken into account, horizontal advection terms not measured should also be considered, with unpredictable values (Lee 1998, Finnigan 1999, Baldocchi et al. 2000, Paw U et al. 2000). The mainstream approach to flux calculations includes a geometrical rotation of the three orthogonal wind components to transform them onto a new frame aligned with the mean streamlines (McMillen 1988, Aubinet et al. 2000). The result of this operation is that the transformed vertical wind component is set to zero. The procedure generally consists of three trigonometric operations, successively projecting the wind components to the mean horizontal streamline, to the mean vertical tilt of the streamline, and then to the lateral tilt, defined by the direction in which average lateral momentum transport is zero. The algorithms and backgrounds have been outlined in detail by Kaimal and Finnigan (1994). Recently, this approach is being revisited, with studies suggesting that rotations should only be done to the long-term streamlines, thus allowing nonzero average vertical wind speeds. Also, the appropriateness of the lateral rotation is being questioned (J. Finnigan and R. Leuning, *personal communication*). In any case, the effect of rotations will depend on the averaging period over which mean wind components are being calculated. Also, many studies calculate the lateral rotation on the basis of detrended variances and covariances of vertical and lateral wind speed (Aubinet et al. 2000). This is an incorrect procedure, as raw statistics should be used here (Kaimal and Finnigan 1994), but the magnitude of errors caused by this is as yet unclear.

Frequency corrections

Eddies that carry flux are of an enormous range of sizes, from very large down to the size of the viscous dissipation range, but eddy correlation systems can only capture part of that range. At the low-frequency side, limitations to averaging time, nonstationarity, and other issues already covered in the sections above mean that there is a likely loss of signal there. If the damping characteristics of the system can also be predicted, it is relatively straightforward to correct fluxes for ''high-frequency loss'' using procedures first proposed by Moore (1986) and expanded by Leuning and Judd (1996). However, all corrections depend on the assumption that similarity relations and ''standard'' spectra (Kaimal et al. 1972) apply, and scale with the difference between measurement height and zero-plane displacement. Such conditions are usually not strictly valid above rough forest canopies (Raupach et al. 1996), where length scales do not simply scale with height above an (also estimated!) zero-plane displacement, and at lower frequencies the actual situation often diverges widely from standard theory.

Nighttime fluxes

Poorly developed turbulence mostly occurring during very calm nights does *not* preclude a correct measurement of the local flux near an eddy correlation sensor. However, it does complicate its interpretation in terms of average surface fluxes. Assessment of apparent nighttime losses of CO_2 flux can be done in two ways. First, a threshold value is defined for the friction velocity, $u*$, as a measure of the turbulent mixing rate below which storage corrected nighttime ecosystem flux starts to be depressed (Goulden et al. 1996). All nighttime fluxes coinciding with $u*$ values lower than that threshold are then rejected and replaced by an estimate based upon either the mean of values associated with high $u*$, or some independent estimate of nighttime ecosystem respiration fluxes. The uncertainty in the replacement value then defines an uncertainty on the flux. A different approach explored here, is to consider long-term (daily or longer) totals of fluxes as the main value of interest, and investigate whether these depend on the average degree of nocturnal mixing, avoiding effects of rapidly changing turbulence or poorly representative and variable storage measurements.

Gap filling, growth of uncertainty with the amount of gaps

To investigate how quickly the uncertainty of gap fills increases with increasing size and frequency of gaps, the full 1.5–2-yr data sets from Manaus K34 and Jarú were used. First, a periodic function of time of day and date was fitted to all available flux data, without the use of other independent variables. This function was a summation of modified sine functions (see Appendix), and had 18 empirical parameters of varying sensitivity and interdependence. Then, artificial, regular gaps of multiples of 10-d periods were introduced

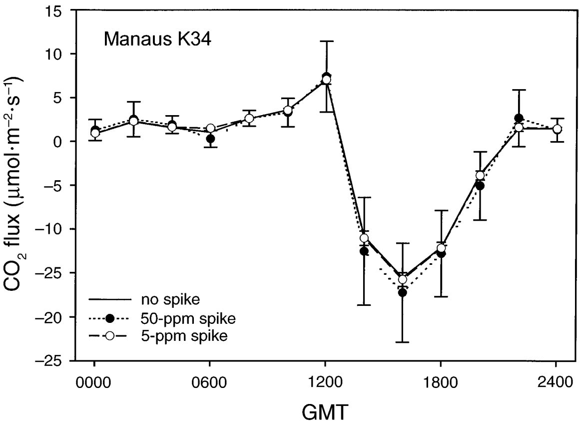

FIG. 2. Effect of two intensities of spiking on the CO_2 signal on the average diurnal course of the CO_2 flux. The error bars show the uncertainty associated with the occurrence of spikes, as standard deviation of the differences with a no-spike control. The inner error bounds represent the less intense spikes. The *x*-axis shows GMT, which is 4 h ahead of local time in Manaus and Rondônia, Brazil.

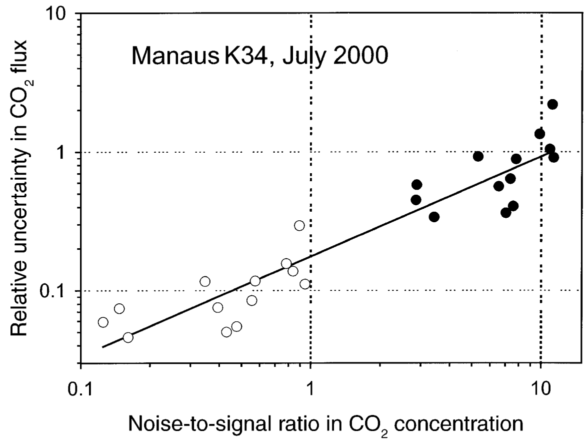

FIG. 3. Dependence of the relative half-hourly uncertainty (calculated as the standard deviation of the CO_2 flux error resulting from spikes, divided by the flux itself) on the noise-to-signal ratio. Open circles represent the 5-ppm spike, and closed circles the 50-ppm spike. The regression line is $y = 0.18x^{0.72}$.

in the data, and the fit was repeated. The growth of the confidence interval with decreasing data coverage thus provided an index of internal statistical robustness of the data set as well as a feeling of the minimum required size and spread of a flux data set necessary to achieve a given degree of precision in means or totals.

RESULTS AND DISCUSSION

Spikes

To analyze the effect of spikes in the CO_2 signal, regular, one-minute-interval spikes of various magnitudes were simulated in the raw data signal. Fig. 2 shows that minor spikes, such as might be caused by interference from other instruments, result in almost negligible errors in the fluxes. Only if such spikes become very large there is an effect on individual fluxes, because for every period a recurrent spike will result in a random correlation with the wind signal. In an attempt to generalize the effect of such spikes on fluxes, we expressed their magnitude as a ''noise-to-signal ratio'', dividing the standard deviations of the simulated spikes by the standard deviation of the clean signal. The average biases associated with this noise are 1.8% and 1.1% for a 5- and 50-ppm, 1-min spike, respectively. The random noise error was best predicted by a power function of the noise to signal ratio (see Fig. 3).

Tube delay

The sensitivity of CO_2 fluxes to the value of the estimated delay time has been explored for a limited period of 10 d at Manaus K34, and the result is a 7% change in flux for every second of change in delay estimate. The occurrence of periods where a tube delay could not be calculated by EDDYWSC is plotted for Manaus K34, for the whole period of 1999 and 2000 against the time of day in Fig. 4. This frequency is clearly larger at night, increasing the uncertainty in calculated fluxes. The product of sensitivity to delay value and the proportion of periods where a default delay was chosen gives an estimate of the real uncertainty associated with accounting for tube delays. Absolute uncertainties are shown in Fig. 4 along time of the day. The average one-sided relative uncertainty for each half-hourly period was 2.3% per second of delay range.

Detrending, rotation, and averaging

The sensitivities of calculated CO_2 fluxes to the basic processing options for detrending, averaging, coordi-

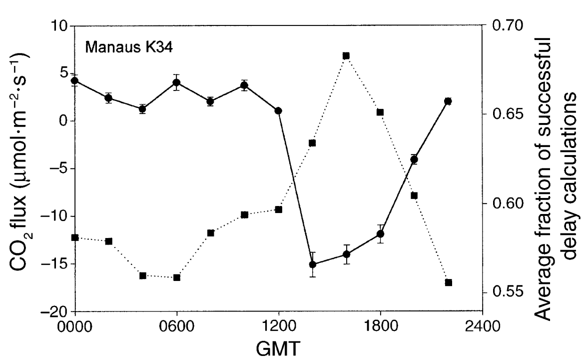

FIG. 4. Sensitivity of CO_2 fluxes to erroneous or inconclusive calculations of tube delays. The solid lines and circles show the mean diurnal trend of CO_2 flux over the test period (1–10 October 1999) with error bars representing the absolute error range associated with the delay range of 0.5–3.5 s. The dotted line and squares show the variation of the mean fraction of successful delay calculations over the day. The *x*-axis shows GMT, which is 4 h ahead of local time in Manaus and Rondônia.

TABLE 1. Average uncertainty in daily total CO_2 fluxes (F_c; kg C·ha^{-1}·d^{-1}) and latent heat fluxes (E; MJ·m^{-2}·d^{-1}) resulting from uncertainty in flux calculation methods for different sites and periods.

Site and period	F_c CV	E CV	F_c SD	E SD	Total R_{net}
Manaus K34, average	0.10	⋯	1.97	⋯	⋯
Jarú, average	0.25	⋯	3.47	⋯	⋯
Manaus C14, wet		0.10		0.56	13.0†
Manaus K34, wet	0.14	⋯	3.29	⋯	⋯
Jarú, wet	0.43	0.09	7.56	0.63	12.7
Manaus K34, dry	0.15	0.08	2.24	0.61	14.6
Jarú, dry	0.27	⋯	2.83	⋯	⋯

Notes: Uncertainties are expressed as standard deviations (SD) and coefficients of variation (CV = SD/mean daily total flux) of the set of fluxes calculated using the range of options given in *Results: Detrending, rotation, and averaging.* To illustrate the importance for the energy budget closure, average daily total energy input is also given (R_{net}, MJ·m^{-2}·d^{-1}).

† Estimate from the nearby Manaus K34 tower.

nate rotation, and the low-frequency correction for detrending were analyzed in a number of combinations, using four arbitrarily chosen 10-d data periods for Manaus and Jarú, during wet and dry seasons. For detrending, we studied no detrend (block averaging), 200-s recursive running mean, and 800-s recursive running mean. Linear detrending was not considered here, but its effect is likely to be intermediate between running mean and block averaging. For averaging, we used either 30 or 120 min. For rotation, the options were no rotation, only horizontally, horizontally and vertically, full three-dimensional, and three-dimensional but on the basis of detrended second moments of wind components. Finally, fluxes were either corrected for loss of low frequency components or not corrected. Fluxes were calculated for most combinations of these options, and average diurnal trends were calculated from this. Then the relative sensitivities of daily total CO_2 and H_2O fluxes to processing options were calculated from the diurnal trends, by normalizing with the simplest analysis option (no detrend, 30 min averaging, no rotation, no low-frequency correction). The results of this operation show that there is no clear, general pattern, and that sensitivities are often correlated. Sensitivities are often fairly small (5–10%), but, especially for the Jarú site, they can be as large as 60% or even reverse the sign of daily total fluxes. Most combinations of these options represent existing or reasonable choices for eddy correlation systems over forest, where clear theoretical guidelines about the proper choice are lacking. Therefore, an uncertainty index was calculated from these results, as the standard deviation of all absolute and relative sensitivities, and shown in Table 1. First, the uncertainties in daily water vapor exchange are smaller than those in daily CO_2 exchange. Second, uncertainties are larger for individual seasons than for the average of seasons, i.e., the sensitivities are not consistent, depend on conditions, and appear to partly cancel over longer time periods. Fig. 5 summarizes the distribution of this aggregate uncertainty over time of the day for two sites and two seasons, showing that absolute uncertainty is largest during daytime and at the Jarú site. Derived from the same exercise, the sensitivity of CO_2 and H_2O fluxes to averaging time and rotation, averaged over all other processing options, are shown in Table 2. This analysis stresses effects of the nonlinear interaction of rotation and averaging time. Table 2 also shows that sensitivities are largest at Jarú. The difference between Jarú and Manaus is likely to be related to meso-scale topography. Although both towers are situated in moderately complex terrain, the topography at Manaus is of smaller scale and more homogeneous at the meso-scale. In the Jarú area, it is likely that the hill range and river promote mesoscale circulations and wind-direction dependence of turbulent flow, which would emerge mainly in the lower frequencies. It should also be noted that the tower in Jarú is about 10 m taller than the Manaus tower, increasing the average eddy size and duration.

Frequency corrections

The magnitude of and uncertainties in corrections for underestimation at high and low fluctuation frequencies were studied by calculating fluxes and corrections for a 10-d period in October 1999 at the K34 site, and varying settings for zero-plane and tube characteristics. As shown in Fig. 6, the magnitude of corrections for the present data is small both in relative and in absolute terms, and so is the uncertainty associated with uncertainty in assumptions of zero-plane displacement and tube parameters. In annual terms, for

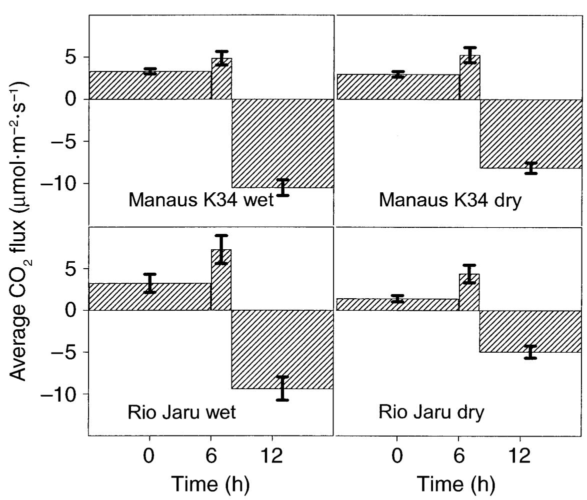

FIG. 5. Average CO_2 fluxes and uncertainties resulting from sensitivities to averaging and rotation options, for two sites and two periods (dry and wet). The plots show how uncertainties are distributed over time of day, but it should be realized that these are not independent over the days, so that uncertainties in the small daily differences of daytime uptake and nighttime emission can be more important than suggested here.

TABLE 2. Average effects on daily total CO_2 and water vapor fluxes, of (1) increasing averaging time and (2) applying the lateral coordinate rotation. Effects are expressed as (affected/not affected).

Site and variable	Increasing averaging time 30–120 min: Vertical rotation only	Vertical and lateral rotation	Vertical and detrended lateral rotation	True lateral rotation: 30 min	120 min	Detrended lateral rotation: 30 min	120 min
Manaus K34, F_c	0.96	0.95	0.95	0.94	0.93	0.97	0.95
Jarú, F_c	0.74	0.71	0.85	0.84	0.92	1.00	1.15
Manaus K34, E	0.99	1.08	1.03	0.94	1.01	0.99	1.02
Jarú, E	0.98	1.13	1.07	0.88	0.99	0.97	1.04
Manaus C14, E	1.04	1.10	1.09	0.92	0.97	0.93	0.98

the towers studied, with their height of 55–65 m and low wind speed regime, these corrections in total represent about 0.7 $Mg \cdot ha^{-1} \cdot yr^{-1}$, and the uncertainty associated with estimating the zero-plane displacement height is about one order of magnitude less than that: 0.27% per meter. Per unit of relative uncertainty in tube flow rate, there is a bias of just 1% in the high-frequency corrections. The additional effect of doubling

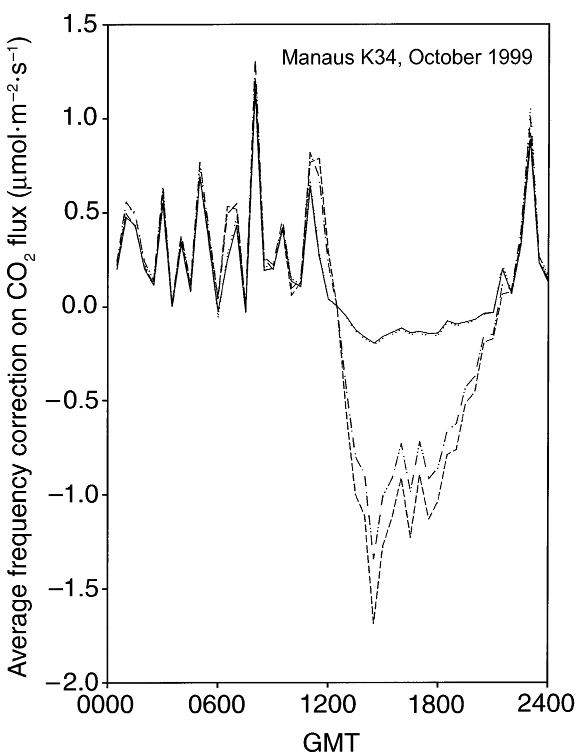

FIG. 6. Analysis of average absolute frequency corrections ($\mu mol \cdot m^{-2} \cdot s^{-1}$) for a 10-d test period in October 1999, and how these change by halving tube flow rate and increasing the estimate of d, the zero-plane displacement height, from 20 to 30 m. The cases shown are high-frequency corrections only (solid line), high-frequency corrections with low flow rate (dotted line), all frequency corrections (dashed line), and all frequency corrections with $d = 30$ m (dot-dashed line). The x-axis shows GMT, which is 4 h ahead of local time in Manaus and Rondônia.

tube length was negligible. However, choices on whether or not to apply low-frequency corrections do make a significant difference, especially during daytime, as was clear from the previous section.

Gap filling

Average diurnal variation of gaps was not always uniform, with more gaps in daytime than at night. Daily gap frequencies were usually evenly distributed over environmental conditions such as daily radiation, precipitation, or windiness and when they were more frequent, such conditions occurred infrequently. This leads to the conclusion that smaller gaps in the data can be filled with averages or interpolations without much risk of bias, as long as the mean diurnal and preferably seasonal variation in fluxes is adequately covered. Functions fitted to the K34 and Jarú data sets, using 100%, 50%, 25%, 12.5%, and different subsets of all available half-hourly data, suggest that uncertainty in estimates for interpolation purposes does not deteriorate strongly down to ~25% data coverage, but that uncertainty becomes unacceptably large when only as little as 12.5% of time is covered with measurements (Fig. 7, Table 3). Fig. 8 shows that uncertainties on annual totals resulting from gap filling are mainly a function of the data coverage, for a given filling strategy. The similarity in this relationship between Jarú and Manaus suggests that the variation in fluxes is similar. The analysis also shows that for an approximate 95% confidence band (four standard errors) of 1 Mg/ha on annual totals (of up to 5–8 Mg/ha in this case), we need ~70–80% data coverage. For the actual data coverage realized during 1999 and 2000 the uncertainty associated with gap filling was only 3% or 0.25 Mg/ha at Manaus K34 but as much as 20% or 1 Mg/ha at Jarú. Of course, this still excludes all other sources of uncertainty.

Nighttime fluxes

Ecosystem CO_2 exchange, calculated as the sum of above-canopy eddy flux and the change in CO_2 storage between the eddy correlation sensors and the ground, was calculated for all periods at K34 and Jarú, and plotted for nighttime periods only against u^* (a measure

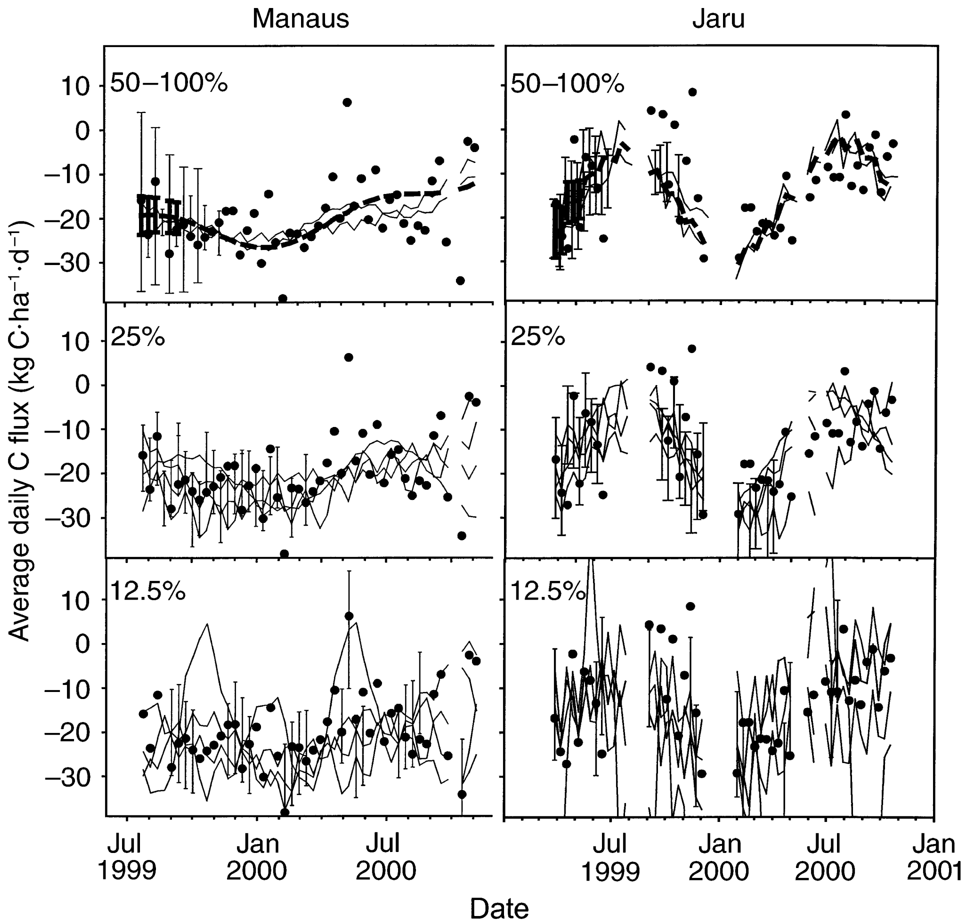

FIG. 7. The effect of discontinuously sampling CO_2 fluxes on the consistency and uncertainty of a simple fitted interpolation function. The dots are 10-d average daily total measured CO_2 fluxes, and the bundles of lines and error bars represent fits and 95% CI of fits to several subsets (regular samples of the percentage are given in the top left of each panel and are offset by 10-d periods) of the measured data. The left-hand column represents data from Manaus K34, and the right-hand column data from Jarú, whereas the three rows represent, from top to bottom, increasingly less data used in the fit. In the top row, the thick line is a fit to 100% of the data.

TABLE 3. Dependence of gap-fill uncertainty on data coverage, for the particular fitting function and total time period used here.

Site	Period (d)	Total coverage (%)	Data in fit (%)	Test fit length (d)	Daily SE of prediction, (kg C·ha^{-1}·d^{-1})	Average SE of prediction at one day of fit (kgC·ha^{-1}·d^{-1})
Jaru	580	64	100	370	2.54	48.91
			50	185	3.55	48.26
			25	93	4.53	43.58
			12.5	46	5.96	40.52
Manaus K34	480	84	100	405	2.03	40.95
			50	202	5.07	72.16
			25	101	3.53	35.50
			12.5	51	4.48	31.86

Notes: The daily standard error of estimate is the average given with each fit, and the average standard error at one day of fit is inferred from the fit and number of days used in the fit.

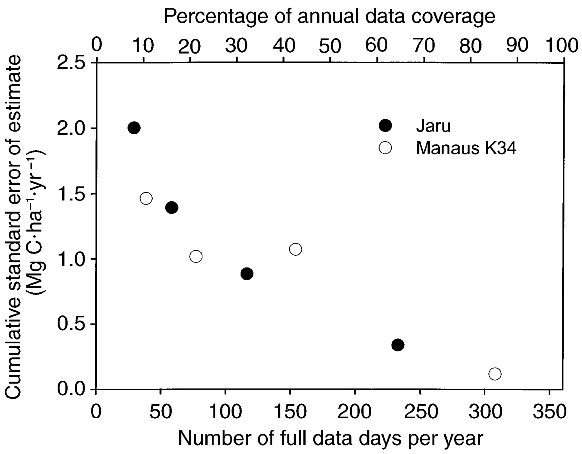

FIG. 8. Standard error of the predicted annual total NEE resulting from filling missing data gaps only, as a function of annual data coverage.

of atmospheric turbulence). Fig. 9a and 9d shows these relationships, where for clarity the flux values have been bin-averaged into classes of *u** values. The figure shows two very different patterns for the two tower sites. At K34, the net flux shows a clear downward trend as *u** decreases below ~0.2 m/s, but at Jarú such a trend is absent in the data. Although not shown here, separate analysis of such relationships for dry and wet season nights gave similar results. Especially for Jarú this diminishes a potential confounding effect of low temperatures and low respiration during windy nights, common in the dry season but not in the wet season. Since most nighttime fluxes are associated with low *u** values at these sites, the apparent underestimation at K34 affects the majority of the nighttime measurements. If it is assumed that these are real underestimates resulting from poor mixing, lateral drainage, or otherwise, then the data involved need to be rejected and replaced by an estimate of the correct net CO_2 flux. Independent estimates of total nighttime respiration fluxes can be inferred from scattered literature data, mostly of soil respiration rates. Most of these data suggest soil respiration rates between 4 and 7 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (Meir et al. 1996, Sotta et al. 2004). Meir et al. (1996) also measured bole and leaf respiration, and suggest that another 1.5 $\mu mol \cdot m^{-2} \cdot s^{-1}$ should be added, leading to estimates of between 5.5 and 8.5 $\mu mol \cdot m^{-2} \cdot s^{-1}$ average ecosystem respiration. Recent estimates of whole-ecosystem respiration from scaling up components at the Manaus K34 area were made by Chambers et al. (2004) and amount to ~8 $\mu mol \cdot m^{-2} \cdot s^{-1}$. If, as an alternative, an estimate of ecosystem respiration is obtained from the measured values at higher *u** (Goulden et al. 1996, Aubinet et al. 2000), in the case of the K34 site, this leads to higher corrections (up to ~10 $\mu mol \cdot m^{-2} \cdot s^{-1}$) to low *u** values than if independent estimates are used, but also to very high uncertainty in this estimate since only few measurements were involved. It is also questionable whether these high *u** values represent sustained periods rather than short transients. Given all these uncertainties, correction of nighttime fluxes at K34 over the range of *u** values between 0 and 0.2 m/s implies an average increase of almost all nighttime values by between 1 and ~4 $\mu mol \cdot m^{-2} \cdot s^{-1}$. On an annual basis, this represents an uncertainty of between 2 and 8 Mg $C \cdot ha^{-1} \cdot yr^{-1}$, which is of the same magnitude as or larger than the ''uncorrected'' estimates of annual carbon uptake in Jarú, Manaus, and other sites. Why fluxes do not seem to be reduced at low *u** in Jarú is somewhat puzzling. It should be noted that Grace et al. (1995) observed the same pattern from a nearby tower in that area. Given the relatively high sensitivity of fluxes at this site to averaging time (see previous sections) it may well be possible that on reanalysis of fluxes and *u** using different averaging and rotation schemes the picture changes drastically.

An alternative approach is presented in Fig. 9b and 9e. Malhi et al. (1998), for the C14 tower near K34 were also faced with apparent flux losses during low *u** periods. Subsequently, they analyzed 24-h integrals of measured carbon uptake and found that these were not related to the average *u** of the previous night, apparently contradicting the relationship based on hourly data. We have conducted a similar approach for the present data. Fig. 9b and 9e shows bin-averaged 24-h totals of measured carbon flux plotted against 24-h total photosynthetically active radiation (PAR). The relationships exhibit a characteristic saturating light-response shape, with net emission days corresponding to cloudy, low radiation days. The 24-h totals have been stratified in these plots according to the average *u** of the night preceding daytime in these 24-h periods. If emission fluxes would be underestimated by, on average, 2–6 $\mu mol \cdot m^{-2} \cdot s^{-1}$ during calm nights, then it should be expected that 24-h totals are more negative by ~10–30 $kg \cdot ha^{-1} \cdot d^{-1}$. From Table 3 it can be seen that uncertainty in daily totals is much less than this and the binned averages in Fig. 9b and 9e also show error bands that are generally narrower than 10 $kg \cdot ha^{-1} \cdot d^{-1}$. In these figures, there is no pattern of increasing daily total flux with night calmness. For Manaus, the curves are close together, whereas for Jarú there is an opposite trend: diurnal total uptake associated with turbulent nights was larger than average instead of smaller. It should be noted that this analysis cannot be conclusive as such, as net diurnal carbon uptake may be related to several other confounding parameters that are also correlated with nighttime *u**. We tested this for nighttime temperature and time of the year. We found no correlation between *u** and temperature (not shown), but Fig. 9c and 9f show that at Jarú, nighttime *u** was elevated during the wet seasons. As this is also a period of higher net uptake (Fig. 7),

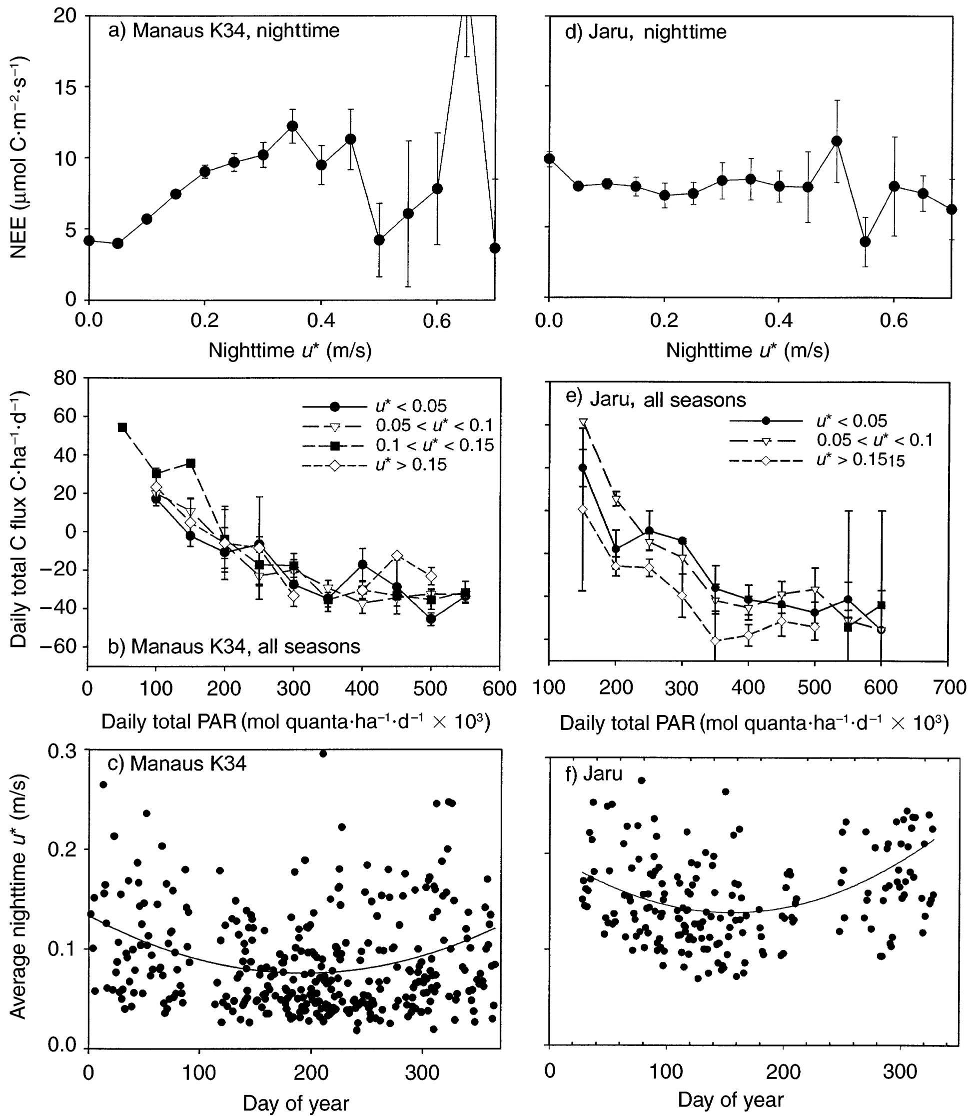

FIG. 9. Relationships between nighttime mixing (expressed as u^*) and carbon fluxes at Manaus K34 (left-hand panels) and Jarú (right-hand panels). In (a) and (d), NEE is storage corrected. In (b) and (e), u^* stands for average nighttime u^*.

this may explain why diurnal totals were higher with higher nighttime u^*. For K34, there may also be a weak seasonal variation in u^* with, on average, slightly enhanced nighttime turbulence during the wet season. This means that nighttime emission losses may occur during the dry season that may have been compensated for on a 24-h basis by reduced daytime uptake in that season. From Fig. 7 it can be seen, however, that at Manaus seasonal variation in average daily totals is less than 15 $kg \cdot ha^{-1} \cdot d^{-1}$, i.e., this could only partly compensate for the daily maximum nighttime loss at Manaus. The conclusion from this analysis must be that it does not support the assumption that net, long-term carbon emissions from these forests are underestimated as a result of a lack of mixing during calm nights, but it doesn't invalidate the assumption either. The overall picture emerging from the analysis of nighttime fluxes and turbulence is that as yet, the uncertainty in annual carbon uptake is of the same magnitude as the uptake itself at K34 and that at Jarú this uncertainty is small.

CONCLUSIONS

Combined error analysis

It is useful to distinguish systematic and random errors, as the first type propagates linearly into long-term or multi-period averages, whereas the second type decreases over integration time (Goulden et al. 1996, Moncrieff et al. 1996). The distinction between systematic and random errors is not completely straight-

TABLE 4. Summary of systematic and random errors on CO_2 fluxes measured on towers over Amazon forest.

Error type	Systematic error	Random error on half-hourly F_c	Total one-sided error on annual totals for Amazon†
Spikes/noise	2%	11%	2%
Tube delay errors	⋯	3.5%	<0.1%
Rotation and averaging	10–25%‡	⋯	10% (Manaus) 25% (Jaru)‡
Frequency loss corrections, zero plane	0.27% × σ(*d*)	⋯	2.7%
Frequency loss corrections, flow rate	$1\% \times \sigma(f_t)/(f_t \times \sqrt{n_{cf}})$	⋯	<0.5%
Convert to area base		0.3%	<0.1%
Calibration uncertainty	(0–20% for 100 d)	⋯	0% (Jaru) 6% (Manaus)
General data gaps	Bias to daytime		
Similarity filter gaps	Bias to nighttime		
Missing data filling	⋯	$0.08–1$ kg C·ha^{-1}·h^{-1} or 30–50 kg C·ha^{-1}·d^{-1}/$\sqrt{n_{dfit}}$	0.25 Mg C·ha^{-1}·y^{-1}, 3% (Manaus) 1 Mg C·ha^{-1}·yr^{-1}, 20% (Jaru)
Total uncertainty			12.5% (Manaus) 32% (Jaru)
Nighttime losses	0–100+%	⋯	0% (Jaru) 100% (Manaus)

Notes: Relative systematic errors do not change over time, whereas relative random errors decrease with the inverse square-root of the number of independent observations. Key: σ(*d*) = uncertainty in zero-plane displacement; $\sigma(f_t)$ = uncertainty in tube flow rate f_t; n_{cf} = number of cycles in tube flow rate variation; n_{dfit} = number of days in gap-fill fit.

† Assuming the conditions at the Manaus K34 and Jarú towers as described in this paper, σ(*d*) = 10, $\sigma(f_t)/f_t = 0.5$, and $n_{cf} = 4$ yr^{-1}.

‡ Systematic errors appear to partly compensate between seasons, so average uncertainty may decrease over time.

forward, however, since often ‘‘systematic’’ errors, although strongly interdependent between periods over time, do vary randomly slowly or irregularly, with synoptic variation over seasons or even between years. Note, that the inherent stochastic uncertainty associated with turbulent flux measurements was not considered here. This error, recently reanalyzed by Finkelstein (2001) is by nature a random error and vanishes quickly over longer averaging times. An attempt to summarize all the errors is presented in Table 4. Although the table presents a rather ‘‘mixed bag’’ of effects (including a few that were not further discussed here), it is clear that the main uncertainties are associated with nighttime, gap filling, and rotation and averaging. The present analysis suggests the error resulting from gap filling is close to a simple function of the number of data days. Nighttime uncertainty is very large, and in Table 4, no effort was made to define a very precise uncertainty for this as from the present analysis two widely different interpretations represent an uncertainty range between 0% and >100%, and it is outside the scope of the present paper to decide on the most appropriate interpretation.

In constructing an overall error estimate for the Manaus K34 and Jarú sites, we assumed that the various error sources are independent, normally distributed around the mean flux values. Especially the second assumption is questionable, of course, and therefore we cannot express errors as strict 95% confidence intervals, but rather we give a standard error. The overall error given was constructed as a geometrical sum of all the percentage errors of the individual sources, i.e., as the square root of the sum of squared errors. Clearly, any overall error is completely swamped by the 100% uncertainty in nighttime fluxes. Even at Jarú, where no nocturnal losses could be substantiated either way, we probably have to assume that the very high number for annual integral uptake implies that there is a large leak or missing source of carbon that we are not accounting for. Apart from the nighttime issues, we arrive at a fairly acceptable uncertainty of ∼12% for Manaus K34, amounting to ∼1.0 Mg·ha^{-1}·yr^{-1}. For Jarú, however, this error is much larger, about 32% or ∼2.0 Mg·ha^{-1}·yr^{-1}, as a result of higher sensitivity to rotation and averaging and less data coverage. Although the latter has recently been greatly improved upon, the former sensitivity is likely to be the result of terrain heterogeneity being more important than previously assumed. It is possible that a reduction in measurement height (presently almost two canopy heights with 62 m) may help in reducing this uncertainty at Jarú.

Having established uncertainty ranges for Manaus K34 and Jarú, the question now arises how general these results are for other Amazon forest tower sites or indeed for any eddy correlation data set. The present results hint at a relationship between uncertainty and terrain heterogeneity, associated with rotation and averaging. Similar analysis on other towers should be conducted to confirm this. Mahrt (1998) points out that errors on fluxes increase strongly with between-period non-stationarity, which agrees with our findings. Instead of calculating his non-stationarity index we adopted a more pragmatic approach. It is possible that effects in this study were exacerbated also by the large measurement heights, where the scale of surface-layer turbulence, with extensive footprints, is large and hard to distinguish from large-scale turbulence. Measurement height, or more precisely: turbulent length scale, parameterized as height above the zero-plane, is certainly one important factor determining the magnitude of other uncertainties studied here. High frequency loss corrections, for example, are small at this height but become more substantial at lower height. The reverse is true for the corrections for low frequency losses. The generally very weak wind speeds and large range of atmospheric stability conditions in the Amazon have a similar effect. Because of this, these errors cannot be simply applied to many of the much shorter towers over (shorter) temperate forests. On the other hand, the gap filling uncertainty appears fairly robust. In climates with more seasonality, a good regular data coverage including transition periods is likely to be even more important. But as long as system configurations, measurement heights, wind speeds and physical canopy properties are similar or comparable in the other sites, which they were in the sites studied here, it can be assumed that the present results are general for most Amazon forest eddy flux sites.

Most measurements of CO_2 fluxes over Amazon forest, including the ones studied here, before correction for apparent nighttime losses show a very high carbon uptake rate, of up to 8 $Mg \cdot ha^{-1} \cdot yr^{-1}$. These values are much higher than those predicted from ecological studies and models scaling up components of the ecosystem (soil, wood, leaf fluxes), or indeed atmospheric inversion studies, predicting (potential) uptake rates for Amazon forest in the order of only 1 $Mg \cdot ha^{-1} \cdot yr^{-1}$ or less (Chambers et al. 2001, Malhi and Grace 2001). This study indicates substantial uncertainties in eddy correlation, but, apart from the nighttime uncertainty none of them has the potential of bringing together these estimates. If flux losses at night are really as large as suggested by the plots of flux against u*, the majority of nighttime measurements needs to be discarded, which of course greatly reduces the usefulness of eddy correlation. If we accept the suggestion from this paper that perceived nighttime losses are not apparent in diurnal totals, of course the exact process behind this needs to be uncovered, and the predicted accumulating carbon should be accounted for.

It has been suggested (Keller et al. 2001) that perhaps eddy correlation results need to be tuned or constrained with the results from ecological components studies. This seems an unattractive option, as it takes away much of the power of independence in eddy correlation measurements. However, it is clear from for example the analysis on rotation and averaging in this paper that a flux measurement in one point above a complex forest lacks enough information to make very firm inference of the average flux from the surface. One improvement would be to develop spatial eddy correlation methods. Maybe a more realistic approach in the short term is to involve constraints as suggested above, not on the end result but rather on turbulent or physiological behavior, fitting parameters such as averaging time to known conserved properties of the exchange.

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APPENDIX

A description of the process of fitting an empirical function to CO_2 eddy flux data in ESA's Electronic Data Archive: *Ecological Archives* A014-024-A1.