Ecosystem-atmosphere exchange of carbon dioxide over a mixed hardwood forest in northern lower Michigan

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[1] We report results from the first 3 years (1999–2001) of long-term measurements of net ecosystem exchange (NEE) at an AmeriFlux site over a mixed hardwood forest in northern lower Michigan. The primary measurement methodology uses eddy covariance systems with closed-path infrared gas analyzers at two heights (46 and 34 m) above the forest (canopy height is $\sim$22 m). One objective is to contribute to a more firmly established methodology of estimating annual net ecosystem production (NEP), by systematically examining the consequences of several variations of criteria to identify periods of unreliable measurements, and to fill gaps in the data. We compared two methods to fill data gaps (about 30% of time in 1999) due to missing observations or rejected data after quality control; one using short-term ensemble averages of the daily course and the other by semiempirical parametric models based on relationships between ecosystem respiration and soil temperature and between gross ecosystem photosynthetic uptake and photosynthetically active radiation. The modeled estimates were also used to replace eddy covariance fluxes during periods of weak and/or poorly developed turbulence when eddy covariance measurements cannot be expected to represent the ecosystem exchange. Examination of the fractions of eddy covariance fluxes and storage change relative to the expected ecosystem respiration suggested a friction velocity (u_*) of 0.35 m s^{-1} as the lower limit for the acceptance of micrometeorologically determined NEE for this site. The differences in estimated annual NEP due to different criteria of data acceptance, measurement height, or gap-filling strategies turned out to be at least as large as the interannual variations over the 3 years. After discussing various analysis strategies we conclude that the best estimate of annual NEP at our site is achieved by replacing data gaps and measurements in low-u_* conditions at all times with site and period-specific parametric models, using the upper measurement level (about 2.1 canopy heights). These "best estimates" of annual NEP for 1999–2001 amounted to 170 (1999), 160 (2000), and 80 (2001) g C m^{-2}. We also discuss some problems of assigning quantitative estimates of uncertainty for annual NEP.   *INDEX TERMS:* 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 0394 Atmospheric Composition and Structure: Instruments and techniques; 3307 Meteorology and Atmospheric Dynamics: Boundary layer processes; 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; *KEYWORDS:* AmeriFlux, forest-atmosphere exchange, eddy covariance, carbon sequestration, forest micrometeorology

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1. Introduction

[2] In this paper we present estimates of annual carbon exchange for the calendar years 1999–2001 over a northern hardwood ecosystem. The site for these measurements is part of the AmeriFlux and FLUXNET networks [*Baldocchi et al.*, 2001]. The estimates are largely based on hourly eddy

covariance measurements of net carbon dioxide flux (F_C) above the forest canopy, using a closed-path infrared gas analyzer (IRGA) in conjunction with a three-dimensional (3-D) sonic anemometer. Because the cumulative net ecosystem exchange (NEE) of carbon requires a complete time series of F_C, we present and discuss the consequences of different methodologies of data quality control for F_C, data rejection criteria, and strategies of filling data gaps by ensemble averages or modeled estimates of F_C. Although these methods and strategies have been applied to the entire data set for all 3 years, their details are discussed using the 1999 data as an example. A comparison of seasonal characteristics is also made between 1999 and 2000, the 2 years with the largest climatic contrast. Key results, such as seasonality of vegetation characteristics, parametric model parameters, and cumulative annual net ecosystem production (NEP) at both heights, are presented for all 3 years.

[3] Rates of net ecosystem exchange of carbon, based on long-term micrometeorological measurements, are considered to be among the best available estimates of carbon sequestration over terrestrial ecosystems [*Baldocchi et al.*, 2001]. This assessment rests on the notion that eddy covariance fluxes that are measured sufficiently high above a forest canopy respond to an ensemble of sources and sinks in the naturally inhomogeneous ecosystem, integrated over a flux footprint that is representative of the forest [*Schmid*, 1997]. The relatively large-scale spatial context of micrometeorological flux measurements provides a clear advantage over chamber flux measurement techniques and biomass-inventory-based estimates of carbon sequestration. However, when inferences about biosphere-atmosphere exchange are made from eddy covariance measurements at height over inhomogeneous areas, several potential sources of uncertainty or bias must be considered: variations of footprint size and orientation [*Schmid and Lloyd*, 1999]; drainage flows or mesoscale circulations generated by diabatic effects, and effects of temporal variations in the micrometeorological streamline coordinate system orientation, relative to the terrain [*Lee*, 1998; *Finnigan et al.*, 1999; *Baldocchi et al.*, 2000; *Paw U et al.*, 2000; *Su et al.*, 2000a]; inadvertent band-pass filtering by the sampling and processing technique [*Leuning and Judd*, 1996; *Massman*, 2000; *Cropley et al.*, 2000; *Su et al.*, 2000b, 2003]. The magnitude and consequences of these potential sources of bias for NEE are research questions that are not yet completely resolved. In this paper, we consider these potential sources of uncertainty and present our choice of strategy to deal with them. We formulate objective criteria to reject those eddy covariance measurements that are likely contaminated by biases and errors and replace them by estimates from a parametric model.

[4] Thus the first objective of this paper is to present the long-term forest-atmosphere exchange measurement program at our site, together with the results of cumulative annual NEP. However, an even more important goal is the systematic examination of the sensitivity of annual NEP estimates to various data quality control criteria, gap-filling methods, and measurement height.

2. Site and Instrumentation

[5] The measurement site lies on the land of the University of Michigan Biological Station (UMBS) (45°35′35.4″N,
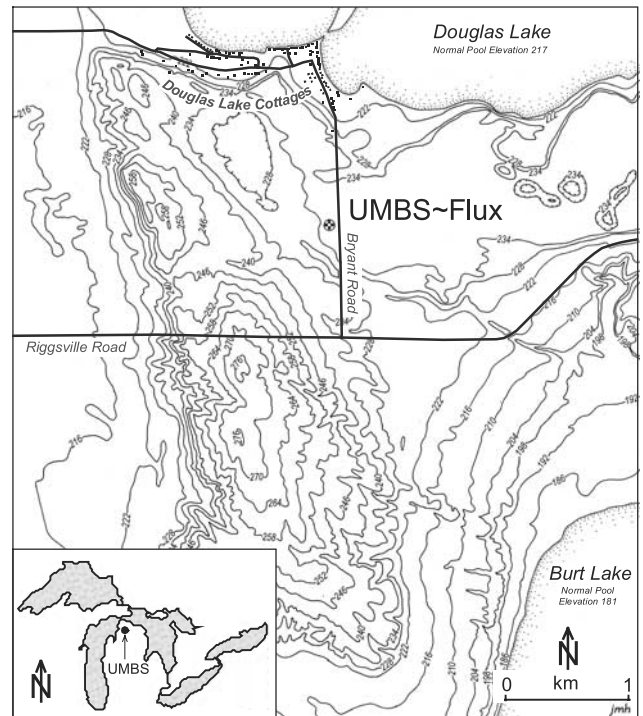

Figure 1. Map of the location of the University of Michigan Biological Station Flux (UMBS~Flux) site, in the north of Michigan's lower peninsula. The location of the tower is indicated by the checkered circle. The nearest town is Pellston, Michigan, about 7 km to the west. Access to the tower is from an unimproved driveway off Bryant Road. The cottage community on Douglas Lake is mostly seasonal-residential. Contours are in meters above sea level.

84°42′46.8″W), in the north of Michigan's lower peninsula (Figure 1). The site is in the transition zone between mixed hardwood and boreal forests on a level to gently sloping high-outwash plain derived from glacial drift. Soils are mostly excessively drained spodosols [*Pearsall*, 1995]. The presettlement white pine, red pine, hemlock forest was cut around 1880, and the area was disturbed repeatedly by fire until 1923.

[6] The majority of data for this study are gathered on a meteorological tower (the UMBS~Flux tower) in a secondary successional hardwood forest. The minimal forest fetch, to Douglas Lake in the north, is 1 km. The terrain gently drops (about 20 m over 1 km) to Douglas Lake and to Burt Lake (3.5 km to the southeast) but rises up for another 20 m over 1 km to the southwest, before dropping abruptly in a steep escarpment formed by an interlobate moraine. Access is provided through an unimproved driveway from Bryant Road (east of the site) to an atmospheric chemistry tower (the Program for Research on Oxidants: Photochemistry, Emissions, and Transport (PROPHET) tower with a height of 30 m) [*Carroll et al.*, 2001] about 100 m to the south of the UMBS~Flux tower. A footpath leads from the driveway to the UMBS~Flux tower itself.

[7] Bigtooth aspen (*Populus grandidentata*) and trembling aspen (*P. tremuloides*) dominate within a 1 km radius of the tower (Table 1) but with significant representation by maple (*Acer rubra*, *A. saccharum*), red oak (*Quercus*

Table 1. Biomass Distribution Estimates of Aboveground and Belowground Carbon of Trees Larger Than 3×10^{-2} m dbh Within a 10^3 m Radius of the University of Michigan Biological Station Flux (UMBS~Flux) Tower[a]

Species	Aboveground	Belowground	Total	Total %
Acer rubrum	9233 (1122)	1856 (204)	11,089 (1324)	13.7
A. saccharum	957 (463)	124 (58)	1081 (520)	1.3
Betula papyrifera	6997 (1128)	1006 (155)	8003 (1281)	9.9
Fagus grandifolia	2716 (943)	356 (117)	3072 (1059)	3.8
Pinus strobus	1324 (451)	462 (143)	1786 (592)	2.2
Populus grandidentata	27,369 (3400)	3986 (482)	31,355 (3880)	38.6
P. tremuloides	13482 (3124)	1723 (379)	15,205 (3501)	18.7
Quercus rubra	8277 (1676)	1103 (222)	9381 (1897)	11.5
Other	155 (47)	47 (13)	203 (59)	0.3
Total	70,509 (3031)	10,665 (384)	81,174 (3391)	100.0

[a]Estimates are in kg C ha^{-1}. Year is 2001. Data from 61 plots were used for all variables. Values are means, and standard deviations are in parentheses.

rubra), birch (*Betula papyrifera*), and beech (*Fagus grandifolia*) as well. In patches, there is a dense understory of young white pine (*Pinus strobus*), up to about 6 m high. The basal layer near the forest floor is dominated by bracken fern (*Pteridium aquilium*) and saplings of red maple, red oak, beech, and white pine.

[8] For the values in Table 1 we used allometric equations relating bole diameter at breast height (dbh) and tree height to aboveground biomass, obtained from previous work on forest productivity at UMBS [*Koerper and Richardson*, 1980; *Cooper*, 1981], to estimate the distribution of biomass among species and aboveground components. Belowground biomass was estimated using a generic (across species) equation relating dbh and tree height to biomass, following *Perala and Alban* [1994]. This analysis was done on all trees with more than 3×10^{-2} m dbh in 61 permanent plots. One of these (hereinafter referred to as the 60 m plot) covers the area within a 60 m radius from the tower. An additional 60 permanent plots of 16 m radius are distributed at 100 m

intervals along seven transect lines radiating out from the tower between 255° and 15° azimuth (through 0°), beginning at 100 m from the tower to a maximum distance of 1 km. The average total aboveground biomass of about 8×10^4 kg C^{-1} ha^{-1} (Table 1) is typical of stands on soils of intermediate fertility in northern lower Michigan.

[9] The mean canopy height (h) of the 60 m plot was estimated as about 22 m by visually inspecting the height of the crown layer from the tower, although a few large pine trees are as tall as 26 m. The forest architecture, with aspen dominating the overstory and young white pine in the understory, results in a bimodal vegetation area distribution profile (Figure 2a). This vegetation area profile and the total vegetation area index (VAI) were measured with leaf area index 2000 (LAI-2000) sensors (Li-Cor, Inc., Lincoln, Nebraska). The seasonal course of VAI and its comparison
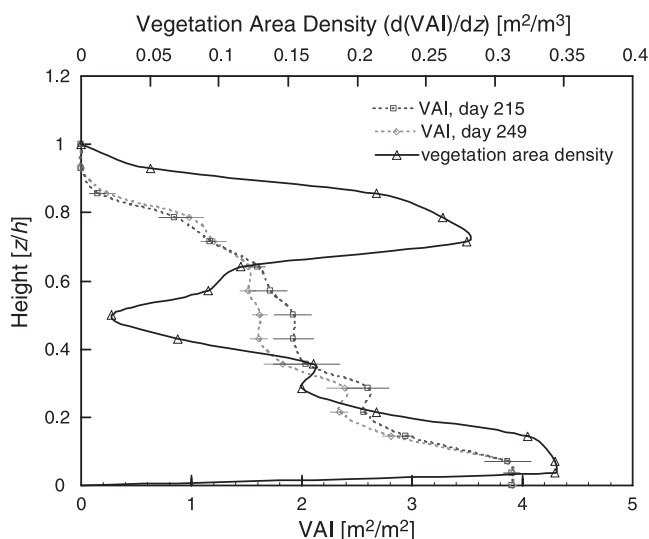
Figure 2a. Vegetation area density profile at UMBS~Flux, measured on the Canopy Tower in 1999. Dashed curves are measured cumulative vegetation area index (VAI) profiles, and the solid curve is the vegetation area density derived from their average. The horizontal bars indicate the standard deviation of nine measurements at the same height.
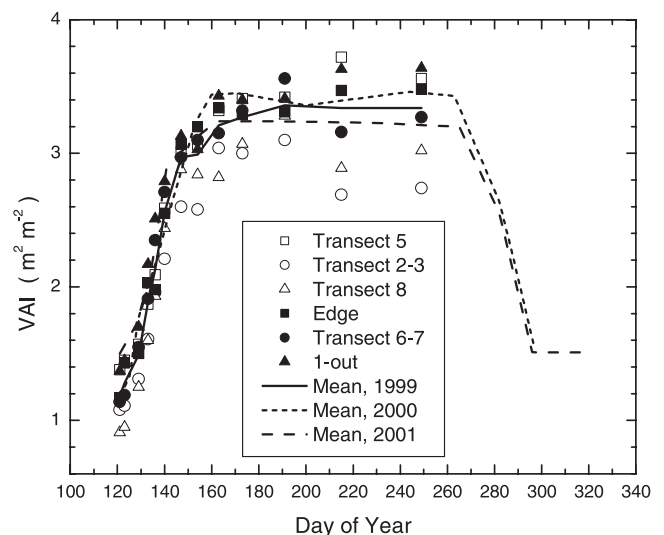
Figure 2b. Seasonal course of VAI for 1999 (symbols and solid curve) and for 2000 (short-dashed curve) and 2001 (long-dashed curve) in the 60 m main plot measured with a Li-Cor LAI-2000 Plant Canopy Analyzer. Each symbol represents leaf area index measured along a defined transect path in the main plot. The curves are the means of all transects. In 2000 and 2001, VAI measurements continued until after leaf fall, but only the means of all transects are shown.

Table 2. Micrometeorological Instrumentation at the UMBS~Flux Site

Instrument	Manufacturer	Model	Location[a]	Measurement
3-D sonic anemometer	Campbell Scientific	CSAT-3	46 m, 34 m	3-D turbulence, sonic temperature
Infrared gas analyzer	Li-Cor	LI-6262	46 m, 34 m	CO_2, H_2O, for eddy covariance
Infrared gas analyzer	Li-Cor	LI-6262	Canopy Tower	CO_2, H_2O, for mean profile
Mass flow controller	Aalborg	GFC-171	46 m, 34 m	IRGA flow rate
Datalogger	Campbell Scientific	CR23X	46 m, 34 m	data collection
Datalogger	Campbell Scientific	CR23X	lab	data collection and valve control
Datalogger	Campbell Scientific	CR10X	BC1	data collection
Multiplexer	Campbell Scientific	AM416	BC1	(CR10X)
Net radiometer	REBS	Q*7.1	46 m, 34 m	net radiation, $.25-60$ μm
Quantum sensor	Li-Cor	LI-190SZ	46 m, 34 m, BC1	PAR, $0.40-0.7$ μm, μmol m^{-2} s^{-1}
Quantum sensor profile	Li-Cor	LI-190SZ $\times$ 5	Canopy Tower	PAR, $0.40-0.7$ μm, μmol m^{-2} s^{-1}
Pyranometer	Li-Cor	LI-200SA	46 m, 34 m, BC1	short wave, $0.4-1.1$ μm, W m^{-2}
Relative humidity/ temperature probe	Rotronic	HPO-43	46 m, 34m, 21 m, 15 m, 3.5 m	RH/temp, aspirated shields
Rain gauge	Texas Electronics	TR-525-M	46 m, BC1	rain, mm; tipping bucket
Soil heat flux plate	REBS	HFT3 $\times$ 2	BC1	soil heat flux, W m^{-2}
Barometer	Vaisala	PTB101B	lab	atmospheric press, hPa
Cup anemometer and wind vane	Met One	034A-L Windset	48, 26, and 21 m	wind speed/direction
Soil temp profile		24 G type E Thermocouples	BC1 a,b,c	depths of 2, 7.5, 20, 50, and 100 cm
Tree stem temp		24 G type E Thermocouples	BC1	four trees, 1 cm depth
2 m air temp	Campbell Scientific	Campbell Thermistor and type t thermocouple	BC1	passive gill shield
Soil water profile	Vitel	type A probes	BC1	% H_2O volume, depths of 5, 10, 20, 51, and 102 cm

[a]Location codes are the following: 46 m, top of tower; 34 m, 34 m height on tower; BC1, below canopy station 1; Canopy Tower (CO_2/H_2O profile), 0.25, 0.6, 3.5, 7, 11, 14, 17, and 22 m; Canopy Tower (PAR profile), 1.5, 6.5, 11, 14, 17 m. IRGA locations refer to gas inlet; the IRGAs themselves are in the climatized lab.

to LAI (determined from leaf litter traps) is discussed below, in section 4.

[10] The main instrument tower is a 46 m high self-supporting structure of hot-dipped zinc galvanized steel with a triangular cross section. The tower has a base of 5.1 m side length and tapers to 1.8 m at 30.5 m. The top 15.3 m is vertical with uniform triangular cross sections. The tower is equipped with an interior ladder and six full steel grid work platforms every 6 m from the top. A climatized equipment shelter (5.5 $\times$ 2.5 m), with telephone (upgraded to a microwave data link in 2000) and power, close to the tower base houses the data acquisition equipment, the gas flow control system, and the Infrared Gas Analyzers (IRGAs) (Li-6262 from Li-Cor).

[11] The micrometeorological instrumentation is organized into two main observation levels for flux measurements on the tower (at 46 and 34 m, corresponding to $\sim$2.1 h and 1.5 h, respectively) (see Table 2 for a summary of all instrumentation). Measurements of 3-D turbulent velocity fluctuations and eddy covariance fluxes of momentum, sensible heat, water vapor, and CO_2 are conducted nearly continuously at these heights (except for short periods of maintenance). The fluxes of momentum and heat are evaluated directly from the 3-D sonic anemometers (CSAT-3, Campbell Scientific, Inc., Logan, Utah) (10 Hz sampling rate). Water vapor and CO_2 concentrations are measured by pumping sample air from near the sonic anemometer transducer arrays to individual closed-path IRGAs inside the shelter, through Teflon^{TM} tubes (4.8 mm inner diameter). The total line length for the tube from the 46 m measurement level amounts to 52 m (40 for 34 m level). Inline Teflon filters (Gelman, Inc.) (pore size 1 μm) near the gas intake prevent dust and dirt from entering the

tubing. Heating tape, applied to the tubing on both sides of the filters and to the filters themselves, prevents the pressure drop associated with filtration from causing condensation. Calibration of the gas analyzers against gas standards that are traceable to the National Institute of Standards is done at sampling pressure and flow rate to reduce the dependence upon the corrections applied using the IRGA's internal pressure transducer cell. A system of solenoid valves enables gas cylinders for IRGA calibration to be permanently connected so that the IRGA signals can be compared against the standards automatically and daily. Eddy covariance fluxes of CO_2 and water vapor are then obtained during postprocessing (section 3). Sensors for net radiation (R) (model Q*7, REBS, Inc., Seattle, Washington), incoming shortwave radiation ($K\downarrow$) (model Li-200SZ-50, Li-Cor, Inc.), and photosynthetically active photon flux density (PPFD) (model Li-190SZ-50, Li-Cor, Inc.) are also operated at the 46 and 34 m levels.

[12] Profiles of water vapor and CO_2 mixing ratio are obtained by cycling through eight levels of air intake tubes, using a computer-controlled solenoid valve manifold in conjunction with an IRGA. The intake tubes (up to canopy height) (Table 2) are fixed on an auxiliary mast (the Canopy Tower, 24 m, 0.35 m triangular section) $\sim$20 m from the main tower, within undisturbed canopy space. Air temperature and humidity profiles are provided by five levels of combined ventilated temperature and relative humidity (T/RH) probes (model HPO-43, Rotronic Instrument Corp., Huntington, New York) along one leg of the tower (Table 2).

[13] Other continuous and routine measurements within the 60 m plot include soil temperature (three locations, five depths: 2×10^{-2} m, 7.5×10^{-2} m, 0.2 m, 0.5 m, and 1 m),

soil heat flux (two locations), and bole temperature at 1×10^{-2} m depth (six trees). In addition, litter baskets (20 locations) serve to determine LAI, and periodic measurements of soil and bole respiration and soil water content are also carried out [*Curtis et al.*, 2002]. Precipitation is measured by tipping bucket gauges (model TE-525, Texas Electronics, Dallas, Texas) both at the tower top and near the forest floor.

3. Data Analysis

3.1. Eddy Covariance Measurements

[14] The eddy covariance systems at 34 and 46 m have been operational nearly continuously since 1999. The only large contiguous block of missing data occurred near the end of January and at the beginning of February 1999, due to changes in the Teflon tube plumbing system and frequent system testing. As discussed below, this is not considered a serious problem because this data gap fell within the snow covered period, where ecosystem fluxes, soil temperature, and other relevant environmental variables are nearly constant. Shorter data gaps are caused by periodic system maintenance events (e.g., replacement of inlet filters, change of reference nitrogen and CO$_2$ span calibration gas cylinders, manual IRGA calibration, etc.). If data gaps due to system maintenance exceeded 30 min within an hourly period, that hour was considered a missing observation. Over the entire year of 1999 a total of 7932 hourly values (91% of the year) of mean and turbulent quantities passed this initial data quality control and are used here. The further data quality control and analysis is outlined in sections 3.1.1–3.1.6.

[15] First, the 10 Hz raw voltage values of CO$_2$, H$_2$O, IRGA sample cell temperature, and pressure are used to calculate mixing ratios of CO$_2$ and H$_2$O in mole fractions relative to dry air, according to the procedures described in the manual of the Li-6262 instrument, and using calibration coefficients specific for each IRGA. This procedure is consistent with the density corrections proposed by *Webb et al.* [1980].

[16] Before a given hourly period of eddy covariance data was accepted for further analysis it had to pass several levels of data quality control. Gaps in the annual carbon flux time series, due to either missing or unacceptable data, were then filled by one of two alternative methods. These data quality control criteria and the gap-filling methods are outlined in section 3.1.6.

3.1.1. Despiking of 10 Hz Data

[17] The raw 10 Hz data from the CSAT-3 sonic anemometers (three orthogonal velocity components and sonic temperature) and from the IRGA (CO$_2$ and H$_2$O mixing ratio and IRGA cell temperature and pressure) were checked for two types of spikes (namely "hard" and "soft") before calculating eddy covariance fluxes, similar to the method described by *Schmid et al.* [2000a]. Following *Vickers and Mahrt* [1997] we defined "hard" spikes as caused by instrument (sensor and data sampling system) problems. For the CSAT-3 sonic anemometer outputs the hard spikes are indicated by the corresponding diagnostic values provided by the instrument (see CSAT-3 manual). For the IRGA output the hard spikes were defined as exceeding certain specified physical limits (e.g., CO$_2$ concentration

outside of the interval between 300 and 1000 ppm and H$_2$O higher than 100 mmol mol^{-1}).

[18] The "soft" spikes were detected using a method similar to *Schmid et al.* [2000a], whose work is a modification of *Højstrup*'s [1993]. First, for each variable, hourly mean and standard deviations were calculated from the 10 Hz records, excluding the hard spikes. "Soft" spikes were then registered if instantaneous deviations from the hourly mean exceeded a given threshold. This process was repeated with an adjusted threshold until no more new soft spikes were identified. The threshold was defined as a multiple of the hourly standard deviation. The multiplier was set at 3.5 in the first iteration and increased by 0.1 in each subsequent iteration. The means and standard deviations were recalculated in each iteration, excluding both hard and soft spikes. We found that the maximum number of necessary iterations rarely reached or exceeded 4. *Schmid et al.* [2000a] ignored spikes with a duration of 4 or more consecutive flagged values, because these were interpreted as real turbulence events. However, this cutoff (corresponding to a persistence of >0.3 s for the 10 Hz sampling rate) is somewhat subjective and was not used in the current study. Alternately, such flagged intervals were examined in a second stage here. We calculated the mean and standard deviation of a local data window centered on the consecutive group of flagged values and extending by 10 times the width of the group on both sides. Only hard spikes were excluded in calculating the mean and standard deviations in this step. If the samples flagged in the first stage fell within 4 times the standard deviation from the mean in the local window, they were not considered soft spikes. We consider this alternate method to be more cognizant of the local data structure in the vicinity of a suspected spike. Hourly intervals, where the number of spikes (both hard and soft) of all variables (CSAT-3 and IRGA) exceeded 5% of the total 10 Hz records, were considered missing observations.

3.1.2. Coordinate Rotation

[19] Reynolds decomposition, based on hourly block averages, was used to calculate turbulent statistics and eddy covariance fluxes. Three rotation angles as defined in *Kaimal and Finnigan* [1994] were calculated for each hour. The first and the second rotations force the mean lateral and vertical velocities to zero, and the third rotation forces the lateral component of Reynolds stress to zero. Angles in the second and third rotations of more than 10° were interpreted as indicative of flow conditions that are either extremely calm or complex and not suitable for reliable eddy covariance measurements. Otherwise, all three rotations were performed, and turbulence statistics were determined on the rotated data.

3.1.3. Lagged Correlation Analysis

[20] Because our eddy covariance system uses sonic anemometers in conjunction with closed-path IRGAs in the field lab, the time lag between the sonic measurement and the IRGA measurement must be determined. On the basis of the observation that peak correlation between temperature and vertical velocity has no time lag [*Raupach et al.*, 1989; *Shaw and Zhang*, 1992], lagged correlation analysis was used to find the eddy covariance between CO$_2$ or H$_2$O and vertical velocity at a time lag that maximized the correlation [*Fan et al.*, 1990; *Goulden et al.*, 1996].

Continuous measurements of the flow rate through the sampling tubes showed little change (about 1×10^{-4} m^3 s^{-1}). Thus, if the time lag for peak correlation fell within 3 s (for the 46 m level) or 2 s (34 m level) of the most likely time lags estimated from the tube dimensions and the flow rate (about 8 s for 46 m and about 6 s for 34 m), that peak correlation and corresponding covariance were considered valid.

[21] A well-known feature of lagged correlation of turbulence quantities is that the correlation peak is well defined: The correlation generally decreases exponentially with increasing deviation from the optimum time lag. If the correlation peak was considerably less well defined for a given hourly period in this study, we excluded that period from further analysis if the absolute correlation was larger than 0.01. Thus even if the peak correlation was found in the valid range but the correlation did not change much (maximum difference <0.01) with time lag in the given range, we considered this as indicative of insufficiently developed turbulence or strong nonstationarity (trend) conditions, and the eddy covariance was considered invalid for that period. Periods where the correlation stayed smaller than 0.01 for all lags were not rejected but were determined as near-zero fluxes at a lag interpolated from those of periods before and after.

3.1.4. Additional Flux Selection Criteria

[22] To take advantage of the availability of eddy covariance measurements at two heights, we used additional quality assessment criteria by limiting the difference of eddy covariance fluxes between the 46 and 34 m levels. These include that sensible and latent heat fluxes and CO_2 flux must have the same sign at the two heights. When the criterion of u_* is set to >0.35 m s^{-1} as discussed later, the difference between these fluxes at the two levels should not exceed 100%, which is a very conservative requirement, allowing for some differences between the two levels due to potential variations in their footprint.

3.1.5. Frequency Response of CO_2 and H_2O Eddy Covariance

[23] The attenuation of high-frequency fluctuations of concentrations by long sample tubes in closed-path IRGA systems has been recognized and various methods have been proposed for corrections [Moore, 1986; Eugster and Senn, 1995; Leuning and Judd, 1996; Horst, 1997; Massman, 2000]. Some of these studies suggest that corrections to measured fluxes can be up to 30% or more. However, these methods were developed to adjust measured cospectra to those observed over smooth and uniform surfaces [Kaimal et al., 1972]. Recent studies [Sakai et al., 2001; Su et al., 2003] showed that spectra and cospectra in the roughness sublayer over forest canopies exhibit some different characteristics from those of Kaimal et al. [1972].

[24] A detailed study of flux losses due to damping by the long tubes in our closed-path IRGA systems is presented by Su et al. [2003]. For the growing season the cospectral corrections to CO_2 flux were found to be on average, about 3–4% in the daytime and 6–10% at night. Yet eddy covariance fluxes used in this study were not corrected using the cospectral method. The primary reason for this decision is that the spectral analysis as applied by Su et al. [2003] uses more restrictive data selection criteria than the present work and thus would lead to more data

gaps. However, as discussed below, annual NEP estimates are highly sensitive to the method for filling data gaps. In addition, cospectral corrections to CO_2 fluxes are partially cancelled out owing to their opposite signs in the day and at night during the growing season. Thus our results indicate that the percentage of correction due to tube damping is relatively small compared to the effects of gap-filling strategies and different measurement heights (see section 5.3).

3.1.6. Gap-Filling Methods

[25] Two methods were compared to fill missing observations of CO_2 fluxes. First, we used short-term ensemble averages of the diurnal course of hourly fluxes. The average periods were determined empirically to correspond to approximately uniform stages in the seasonal ecosystem development, according to the time series of soil and bole temperatures, VAI development, and the seasonality of measured CO_2 fluxes. Missing hours were then filled by the ensemble average for the same hour. We expect this method to work relatively well during leaf off periods, especially during the snow-covered period when ecosystem fluxes change little. The second method is using parametric models, consisting of a relationship between ecosystem respiration and soil temperature, and an equation relating gross ecosystem uptake to photosynthetically active radiation (PAR) during the growing/vegetative season. The details of these relations are given below (sections 4.3 and 4.4). We expect this method to work better in the vegetative season, because it accounts for some of the most important physical factors determining ecosystem carbon exchange. For example, many missing observations during the growing season were due to rain, when PAR was generally lower than clear sky conditions, and short-term ensemble averages are not representative of such conditions. However, this method requires that measurements of both soil temperature and PAR are available, which was often the case even when it was raining. For sensible and latent heat fluxes, only the short-term ensemble average method (corresponding to the same periods as for CO_2 fluxes) was used to fill missing hourly observations. These gap-filling methods are similar to those discussed in Falge et al. [2001a, 2001b].

3.2. CO_2 Storage Calculation

[26] In-canopy CO_2 profile measurements at eight levels started on day 80 in 1999. The quality analysis of these 1 Hz CO_2 concentration profile data included the checking of physical limits (i.e., the normal valid measurement range provided by the manufacturer), excluding system plumbing periods according to the field notes, and detecting and excluding IRGA zero and span calibration periods, which are similar to those for the 10 Hz IRGA data from the eddy covariance systems. In addition, in proper operation each height corresponds to a unique sample cell pressure value, which was also found very useful to detecting and excluding suspicious data. If more than half of the 1 Hz CO_2 concentration values were valid, the 30 s average concentration was calculated. The rate of change of CO_2 concentration with time for each hour at each of the eight heights was calculated as the average of the rate of change between two adjacent 30 s mean values in that hour. Hourly CO_2 storage was then obtained by integrating these hourly rates

with height to yield the hourly CO$_2$ storage within the canopy.

3.3. Radiation, Soil Temperature, and Soil Heat Fluxes

[27] Although periodical intercomparisons of radiation sensors at 46 and 34 m levels indicated no significant difference, occasional tower shadow effects were found on the 34 m radiation sensors when we compared the hourly values of net radiation, PAR, and downward shortwave radiation. Thus only the 46 m level radiation measurements were used in this study. Quality checking of these quantities was by physical limits only.

[28] The quality checking of soil temperature and soil heat flux also involved only physical limits. The limits on the difference between different sensor locations are also very relaxed with regard to the natural variability of soil temperature and soil heat flux. The averages of soil temperature measured at three locations, and of soil heat flux measured at two locations, were used in this study. The coverage of valid data was very good. For example, during the course of 1999, only 74 hourly radiation measurements and 83 hourly soil temperature and soil heat flux measurements were missing. Linear interpolation was used to fill these sporadic gaps.

4. Results

4.1. Seasonal Course of Ecosystem Characteristics

[29] VAI was measured periodically in the 60 m main plot along six transects, using Li-Cor LAI-2000 plant canopy analyzers, starting on 1 May 1999 (day 121), when leaf-bud-break was observed (Figure 2b). This was earlier than expected from phenological observations of previous years by about 2 weeks but was similar in 2000. In 1999 the VAI increased rapidly until May 26 (day 146), when the first full-sized leaves were observed and VAI was about 90% of its peak value. After that the increase in VAI became gradual, and the maximum VAI (3.34 ± 0.06) was reached near the end of June. The development in 2000 was very similar. Maximum LAI (leaves only) estimated from litter traps was 4.02 ± 0.12 (0.58 for pine needles and 3.44 from broad leaves) for 1999, somewhat higher than the value of 3.89 ± 0.15 in 2000. Because white pine has a total of 3 years' worth of needles on the tree at the end of a growing season and loses only the oldest set of needles in the fall, pine needle LAI was calculated as three times the surface area of pine needles collected in the litter traps. For the same reason, two thirds of the calculated pine needle LAI should be subtracted from the VAI measurements during the leaf off period to yield a rough estimate or stem area index of about 0.79. Subtracting this stem area estimate from the total VAI leads to a maximum LAI of 2.55 from the LAI-2000 measurements. This result is that only 63% of that measured by the litter traps and illustrates that leaf off stem area indexes and peak VAI from the vegetative season are not simply subtractive to yield LAI. Accurate LAI measurements are important to scale up leaf level measurements and for modeling of carbon exchange at the canopy scale. Thus the above discrepancy must be addressed in our future work. Nevertheless, the development of VAI shown in Figure 2b is very useful to indicate the seasonal course of the forest canopy and to divide it

into several stages of development for modeling and data analysis purposes.

[30] The snow cover periods (days 1–87 and 349–365 of 1999 and days 1–63, 72–78, and 320–366 of 2000) are clearly evident in the annual course of soil temperature and soil heat flux (G) (Figure 3a). In 2001, snow was on the ground between days 1–97 and 358–365. The snow cover caused the thermal regime of the soil to be nearly constant, with negligible daily amplitudes. As shown later, ecosystem respiration also was small and changed little during these periods. Thus, to parameterize ecosystem respiration, the days with snow cover may be treated as one characteristic regime.

[31] Following a suggestion by Baldocchi (personal communication, 1999), *Schmid et al.* [2000a] discussed that the length of the vegetative season may be indicated by the soil temperature rising above a certain threshold. For the mixed hardwood ecosystem of the Morgan-Monroe State Forest site in Indiana, they determined 13°C as this threshold. At UMBS the daily maximum soil temperature at 2 cm and at 7.5 cm rose above 13°C on days 120 and 123 (1999), respectively, which was close to the date of bud break (day 121) for that year (see Figure 3a). The daily minimum soil temperature (T_S) fell below 13°C at 2 and 7.5 cm on days 258 and 259, respectively. In 2000 and 2001 the vegetative period determined by the 13°C threshold (for soil temperature, T_S at 2 cm) was between days 124 and 265 and days 120 and 257, respectively (Table 3). However, persistent (more than a few hours) downward daytime CO$_2$ fluxes were found from eddy covariance measurements at both 46 and 34 m between days 128 and 282 in 1999, similar to the equivalent periods in 2000 and 2001 (Table 3 and Figure 3a). Thus the period of net carbon assimilation was lagged and lasted longer than the vegetative season estimated by soil temperature by as much as 1 to 3 weeks. The length of the net carbon assimilation period was very similar in the 3 years (155, 158, and 151 days for 1999, 2000, and 2001, respectively) and will be used to define the vegetative period for the purpose of this study.

4.2. Seasonal Course of Energy Fluxes and CO$_2$ Exchange

[32] Here we compare the seasonal courses of key variables governing the energy balance and CO$_2$ exchange for 1999 and 2000 (Figures 3a and 3b). We also compare in more detail the average daily courses in July for the same 2 years (Figure 4).

[33] The seasonal course of net radiation (R_N) was very similar between the 2 years (Figure 3b), with largest and smallest daily means around the solstices (days 172/173 and 355/356 for the 2 years). The daily maxima appeared to be more strongly variable in 2000 than in 1999, but the mean values did not seem to be significantly affected. Also, the mean daily courses of net radiation in July showed no significant differences between the 2 years (Figure 4). Similarly, Figure 3b shows hardly a difference in the general course of sensible heat flux (H) between 2000 and 1999, although the daily maxima in July were significantly higher in 2000 than in 1999 (Figure 4). On the annual course the maximal sensible heat flux was reached just before leaf emergence (around day 110–120 for both years), with a
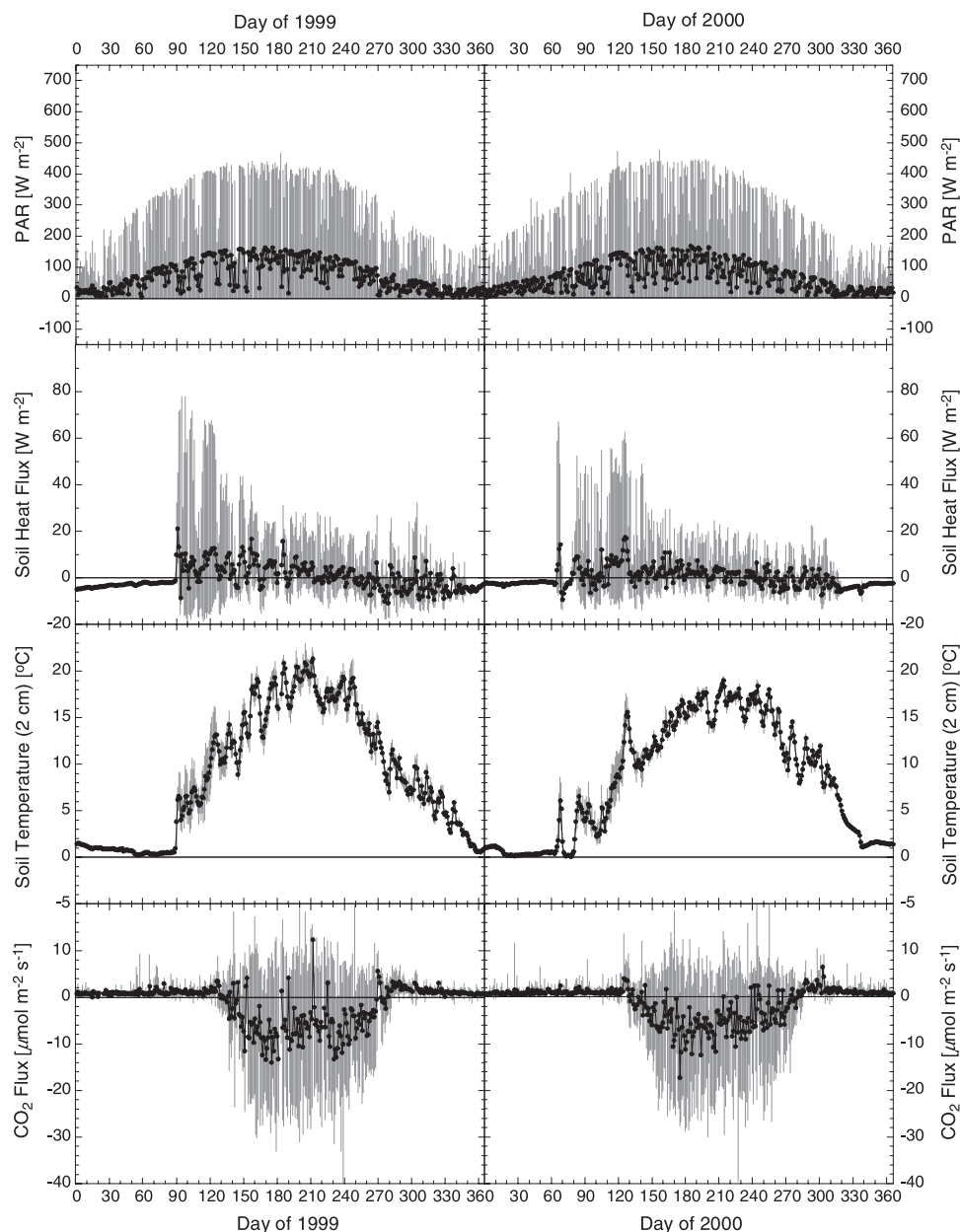
Figure 3a. Seasonal variation of photosynthetically active radiation (PAR), soil heat flux, soil temperature (at 2×10^{-2} m), and CO_2 fluxes for 1999 and 2000. Solid circles are daily averages, and shaded bars indicate the daily range of values (max/min).

marked reduction between days 150 and 180. On the other hand, the latent heat fluxes (*LE*, evapotranspiration) appeared to be significantly less in the summer of 2000 than in 1999 (by about 50 W m^{-2} in the daily averages between days 150 and 240). Figure 4 shows that the maximum of the ensemble average daily course of latent heat flux in July was about 150 W m^{-2} larger than that of 2000. Figure 3b includes a panel showing the energy partitioning factor, $\varepsilon = LE/(H + LE)$, as the portion of daytime available convective energy used for evapotranspiration. The graph for 2000 shows much more variability than its equivalent for 1999, with large maxima particularly on days with small average net radiation. However, the average ε values in the first part of summer 2000 are visible as a dip in the graph and

are considerably lower than in 1999. In July 2000 (days 183–213), only about 65% of the available convective energy was used for evapotranspiration, while that portion was typically above 75% in July 1999. In soil heat flux, no significant difference was observed between the 2 years (Figures 3a and 4). Soil temperature at the 2×10^{-2} m depth (as well as air temperature; not shown) was consistently lower in July 2000 than July 1999 by about $2°–3°C$, which was also often the case throughout most of the year (except for the snow cover period). All this evidence points to a cooler and dryer summer in 2000 compared to 1999. It should be pointed out that the lower Midwest and the eastern part of the United States experienced a significant drought in the summer of 1999, but this evidently did not reach the
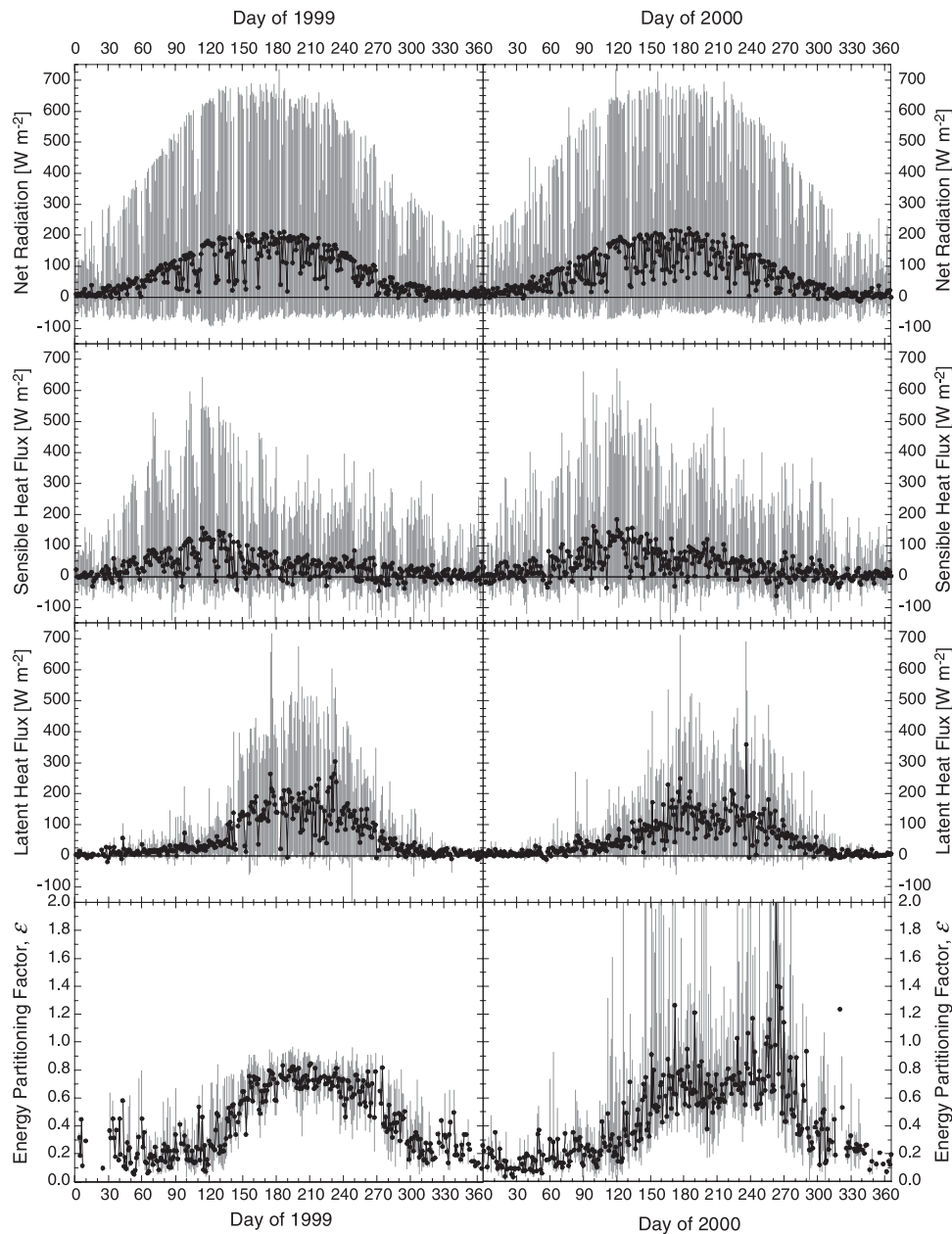
Figure 3b. Seasonal variation of energy balance components for 1999 and 2000: net radiation, sensible heat flux, latent heat flux, and the daytime energy partitioning factor, $\varepsilon = LE/(H + LE)$. Solid circles are daily averages, and shaded bars indicate the daily range of values (max/min).

more northern location of UMBS. The above-canopy precipitation measurements at UMBS (not shown) corroborate this notion: While the annual total precipitation in 2000 was higher than in 1999 (652 and 548 mm, respectively), most of this water fell after July. By June 30, the accumulated precipitation was just 187 mm in 2000, compared to almost twice that amount (318 mm) in 1999. The July increment was 94 mm in 1999 but only 20 mm in 2000.

[34] The cooler and dryer conditions in July 2000 led to reduced soil respiration in 2000, as seen in the nighttime CO$_2$ fluxes in Figure 4. However, daytime net ecosystem uptake of CO$_2$ was also significantly smaller in July 2000 than in July 1999, regardless of whether gaps and weak turbulent mixing periods were replaced by parametric

models (see sections 4.4 and 4.5). The daily average CO$_2$ flux plot of Figure 3a indicates that slightly lower daytime carbon uptake in 2000 was typical over much of the growing season. Since no significant difference was observed in PAR

Table 3. Estimates of Vegetative Season Length at UMBS~Flux for the Years 1999 and 2000

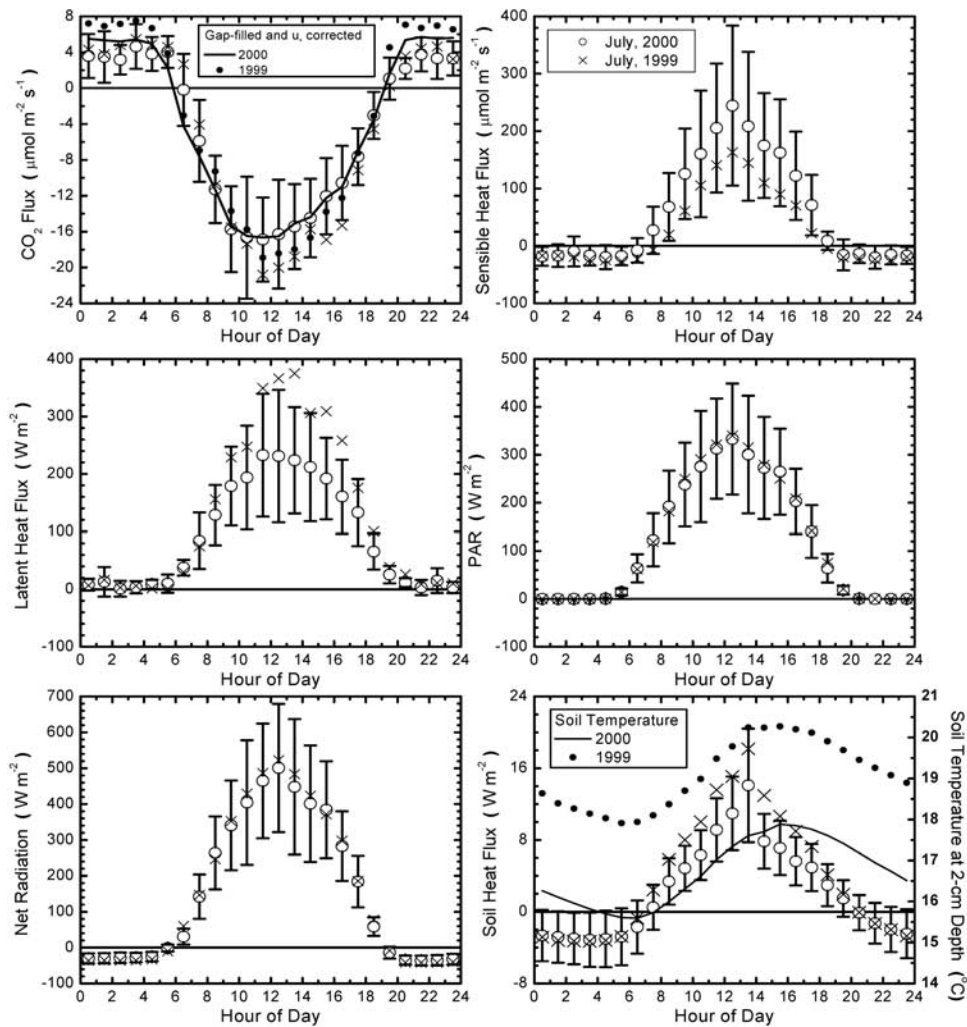|	1999	2000	2001
Carbon assimilation period, year days	128–282	128–285	131–281
Duration, days	155	158	151
Period with $T_s > 13°C$, year days,	120–271	124–265	120–257
Duration, days	152	142	138
Leaf-bud break, year day	121	125	121

Figure 4. Ensemble average daily course of CO$_2$, sensible and latent heat fluxes, net radiation, PAR, soil heat flux, and soil temperature at 2 cm depth in July 1999 and 2000. Crosses are values for 1999, and open circles for 2000 are shown with standard deviation bars indicating the range of daily variations. The panel for CO$_2$ flux also shows the mean daily course of the gap-filled fluxes, using the friction velocity u_* criterion described in section 4.3.

over these 2 years, it seems to indicate that the lower temperatures of 2000 also reduced photosynthesis. Cooler conditions in the first half of the growing season of 2000 appear to have been somewhat offset by rather warmer temperatures in fall (after about day 250; see Figure 3a), and a slightly longer period of net carbon uptake in 2000 (Table 3).

4.3. Nighttime CO$_2$ Fluxes

[35] It is widely recognized that eddy covariance measurements often become unreliable during calm nights, indicated by a systematic underscoring of expected ecosystem respiration estimates, as determined by ecophysiological indicators. The precise mechanisms responsible for this effect are still under debate. If turbulence is weak, vertical mixing between the forest floor and the level of the eddy covariance measurements is effectively suppressed. In flat and horizontally homogeneous conditions, CO$_2$ emitted from the forest floor or the canopy will then contribute to CO$_2$ storage change rather than the eddy covariance flux. Thus

measurements of the CO$_2$ storage change are expected to serve as valid corrections to the eddy covariance flux measurements in such conditions. In sloping and horizontally inhomogeneous terrain, horizontal flow divergence can remove material emitted from the forest floor laterally [*Lee*, 1998; *Finnigan et al.*, 1999]. In this case, measurements from a single tower cannot properly account for this loss.

[36] To determine the conditions conducive to this effect, *Goulden et al.* [1996] used a friction velocity criterion of 0.17 m s^{-1}, while *Black et al.* [1996] used mean wind speed >3.9 m s^{-1} at the height of their eddy covariance system as a threshold to accept storage-corrected eddy covariance flux measurements. By examining the relationship between measured nighttime eddy covariance fluxes and storage in the canopy layer over the entire vegetative season (days 128–282 in 1999) (Figure 5), we found 0.35 m s^{-1} to be a better choice of the u_* criterion for this site [*Schmid et al.*, 2000b]. This criterion actually agrees with that indicated by the data for Harvard Forest shown by *Goulden et al.* [1996].
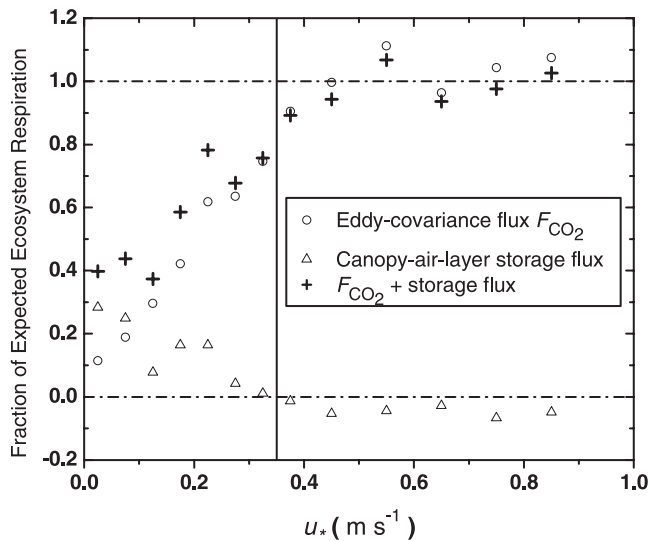
Figure 5. Fraction of nighttime expected ecosystem respiration accounted for by measured eddy covariance flux of CO$_2$ and storage change contributions versus friction velocity. The expected ecosystem respiration is modeled by equation (1). Binned values from hourly nighttime measurements in the growing season of 1999 (days 128–282) are shown.

While their data indicate that storage change at their site becomes small only when u_* is greater than about 0.35 m s^{-1}, they chose to be less restrictive with a 0.17 m s^{-1} threshold. Figure 5 also illustrates that, overall, the storage correction does improve the measured ecosystem respiration closer to the expected value (as estimated by the parametric model described in the next section). However, it cannot explain all the unaccounted flux when u_* is small, especially below 0.2 m s^{-1}. Thus we included the storage correction with the eddy covariance fluxes in the following regardless of the magnitudes of u_*. However, the criterion of $u_* > 0.35$ m s^{-1} was used to select hourly values of eddy covariance flux and corresponding measured soil temperature and PAR to obtain the empirical coefficients used in the parametric models which were applied to interpolate for missing observations or to replace unreliable eddy covariance measurements during calm nights and transitional turbulence conditions. Consequences of this choice are discussed in section 5.2.

4.4. Ecosystem Respiration

[37] A simple exponential form has often been used to model soil respiration R_S [e.g., *Davidson et al.*, 1998] or ecosystem respiration R_E (including soil, stems, and leaves)

as a function of soil temperature T_S [*Wofsy et al.*, 1993; *Goulden et al.*, 1996; *Black et al.*, 1996], while other researchers used air temperature instead [*Valentini et al.*, 1996].

$$R_E = a \exp(bT_S), \qquad (1)$$

[38] In this study, soil temperature at 2 cm depth was used. The coefficients a and b (and the corresponding ratio of the respiration at a given temperature to that at a temperature 10°C lower, $Q_{10} = \exp \times b10$) were obtained from nonlinear regressions using nighttime eddy covariance fluxes (46 or 34 m) and canopy layer storage change (Tables 4a–4c and Figure 6). The regression for the entire year tends to overestimate respiration at the higher temperatures (e.g., for the vegetative season) and underestimate respiration at lower soil temperature (e.g., days 283–365, after leaf fall). In 1999 the coefficient Q_{10} was determined at 3.25 for the ecosystem respiration over the entire year. This value is essentially the same in 2000, but in 2001 a lower value, $Q_{10} = 2.6$, was found. These estimates fall between the values of 5.4 reported by *Black et al.* [1996] over a boreal aspen forest and 2.1 reported by *Wofsy et al.* [1993] for the Harvard Forest (deciduous). Seasonally, Q_{10} was seen to vary between 2.44 for the vegetative season, 4.53 (46 m), and 5.00 (34 m) before buds break and 6.05 (46 m) and 5.64 (34 m) after leaf fall, in 1999. Note also that we obtained the same coefficients Q_{10} and b from the eddy covariance fluxes at the two heights (for the vegetative season or for the entire year), but the parameter a was smaller at 34 than at 46 m. The effects of differences in a and b, due to variations in regression procedures, on the cumulative annual ecosystem respiration are discussed later, in section 5.

4.5. Gross Ecosystem Carbon Uptake

[39] During the growing season (e.g., in 1999, days 128–282), net ecosystem CO$_2$ exchange as measured by the eddy covariance method (F_C) may be considered as the sum of gross ecosystem photosynthetic assimilation (A_C) and total ecosystem respiration (leaf, stem, and soil) (R_E). A rectangular hyperbola equation (Michaelis-Menten-type function) [*Jones*, 1992] has often been used to describe the relation-

Table 4b. Same as Table 4a, but for 2000

Days, 2000	Number of Hours	46 m				34 m			
		a	b	Q_{10}	R^2	a	b	Q_{10}	R^2
1–366	1173	0.769	0.119	3.287	0.699	0.672	0.122	3.387	0.626
1–127	369	0.661	0.137	3.935	0.661	0.573	0.145	4.263	0.654
128–285	384	1.229	0.091	2.484	0.253	1.064	0.094	2.560	0.187
286–366	420	0.663	0.127	3.561	0.614	0.587	0.128	3.597	0.638

Table 4a. Coefficients of a and b for the Ecosystem Respiration Versus Soil Temperature Relationship Used in Equation (1), for 1999

Days, 1999	Number of Hours	46 m				34 m			
		a	b	Q_{10}	R^2	a	b	Q_{10}	R^2
1–365	1178	0.807	0.118	3.254	0.672	0.771	0.118	3.254	0.695
1–127	385	0.571	0.151	4.527	0.565	0.510	0.161	5.003	0.683
128–282	291	1.346	0.089	2.435	0.337	1.274	0.089	2.435	0.363
283–365	502	0.485	0.180	6.050	0.546	0.492	0.173	5.641	0.555

Table 4c. Same as Table 4a, but for 2001

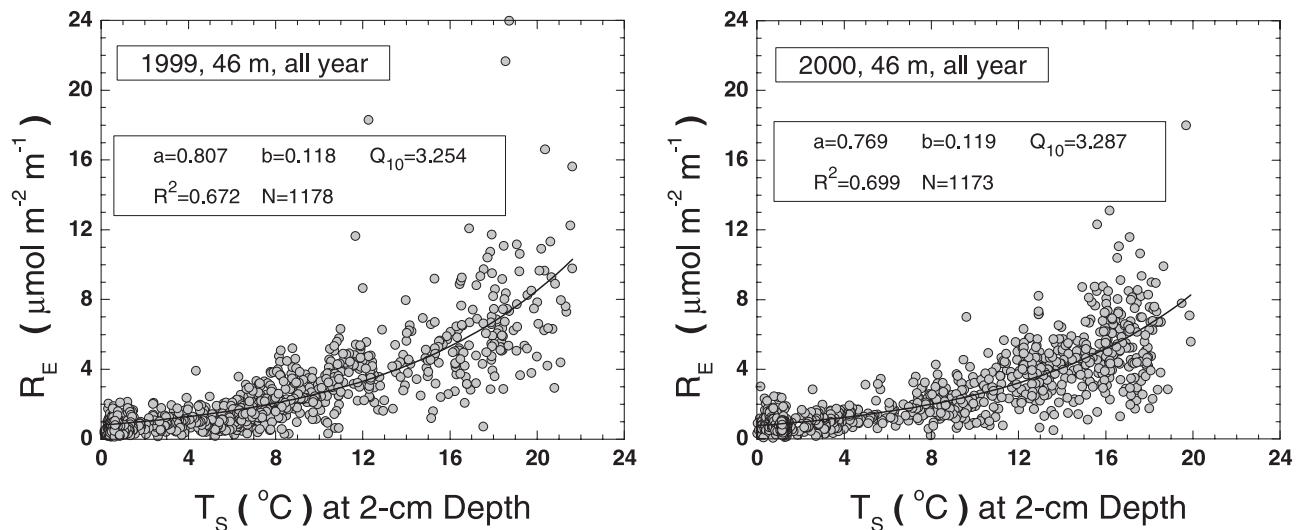| Days, 2001	Number of Hours	46 m				34 m			
		a	b	Q_{10}	R^2	a	b	Q_{10}	R^2
1–365	848	1.054	0.095	2.586	0.611	0.945	0.094	2.560	0.583
1–130	368	0.707	0.140	4.055	0.660	0.609	0.137	3.935	0.637
131–281	269	2.167	0.054	1.716	0.140	2.051	0.050	1.649	0.108
282–365	211	0.542	0.166	5.259	0.606	0.517	0.163	5.104	0.588

Figure 6. Ecosystem respiration (nighttime eddy flux measured at 46 m plus storage change) and soil temperature (2 cm depth) relationship for the entire year shown for (left) 1999 and (right) 2000. Ecosystem respiration is determined from eddy flux measured at 46 m plus storage change in well-ventilated ($u_* > 0.35$ m s^{-1}) and photosynthetically nonactive periods. The regression parameters a and b refer to equation (1); see Tables 4a and 4b.

ship between A_C and photosynthetically active photon flux density (*PPFD*)

$$F_C = -A_C + R_E = -\frac{\alpha A_{C,Sat} PPFD}{A_{C,Sat} + \alpha PPFD} + R_E. \qquad (2)$$

Here α is the quantum yield efficiency, describing the initial slope of the light response curve, and $A_{C,Sat}$ is the saturated (potential) rate of ecosystem uptake. It should be noted that both these parameters represent the whole ecosystem and may differ from those used at the leaf level. They could be influenced by many environmental factors, such as leaf temperature, air temperature and humidity, seasonality of leaf physiology, water availability, and those leading to variability in eddy covariance measurement of F_C (atmospheric turbulence, stability and footprint, etc.). Here we follow *Goulden et al.* [1996] to assume that the parametric respiration model (equation (1)) of R_E based on nighttime measurement during the growing season is a reasonable representation of ecosystem respiration during daytime. Thus we can obtain the coefficients α and $A_{C,Sat}$ using nonlinear regression over a range of $F_C - R_E$ and *PPFD* for a given period of the growing season.

[40] The shape of the A_C versus *PPFD* relationship (for the entire growing season of 1999 and 2000) is illustrated in Figure 7, and the seasonality of α and $A_{C,Sat}$ (for all 3 years) is evident from Tables 5a–5c. The potential uptake rate increases at the beginning and decreases at the end of the vegetative season, which is likely related to the seasonal development of foliage density (Figure 2b). As an example, in 1999 the average value of $A_{C,Sat}$ during days 151–244 (June–August) was about 37 (46 m) or 36 (34 m) μmol m^{-2} s^{-1}, and the average value of α was about 0.55 (46 m) or 0.59 (34 m), which was similar to those reported in the Harvard Forest [*Goulden et al.*, 1996]. For the main part of the growing season (days 151–244), regression over shorter time periods (1–2 weeks) showed some variations

of α (0.44–0.80) and $A_{C,Sat}$ (30.86–48.00 μmol m^{-2} s^{-1}) (Table 5a). However, they lead to little difference in modeled annual gross ecosystem photosynthetic carbon uptake using measured PAR values.

5. Annual Carbon Balance and a Discussion of Uncertainty

5.1. Uncertainty in Long-Term Accumulations of Net Ecosystem Exchange

[41] To establish annual totals of carbon exchange, all chemical forms of carbon entering and leaving the ecosystem would strictly need to be taken into account. Yet it is common to assume that the exchange of chemical species other than CO$_2$ contribute to <1% of the annual carbon exchange. However, the aspen, oak, and birch (Table 1) in the forest at our site constitute a significant source of isoprene (C$_5$H$_8$), which is recognized as the dominant hydrocarbon emitted by deciduous vegetation [*Guenther et al.*, 1995]. *Westberg et al.* [2001] report on an ongoing program to measure isoprene fluxes from the UMBS~Flux tower. Over 44 days in 2000 (2 July–14 August) the carbon in the total measured emitted isoprene amounted to about 1.34 g C m^{-2}. During the same period, net CO$_2$ uptake was estimated at 223 g C m^{-2}, giving a ratio of isoprene emission to net CO$_2$ uptake of about 0.6%. Even considering that this ratio was determined during the time when carbon assimilation was at its most efficient, we conclude that the contribution of isoprene to NEP is small at our site. In the face of the potential systematic uncertainties discussed below, the omission of non-CO$_2$ carbon sources and sinks for NEP estimation is thus negligible.

[42] The assignment of quantitative estimates of the uncertainty associated with long-term carbon exchange measurements is an unsolved problem. Comparisons between different sensor systems at the same site (e.g., using the AmeriFlux "roaming" system; R. Evans, personal
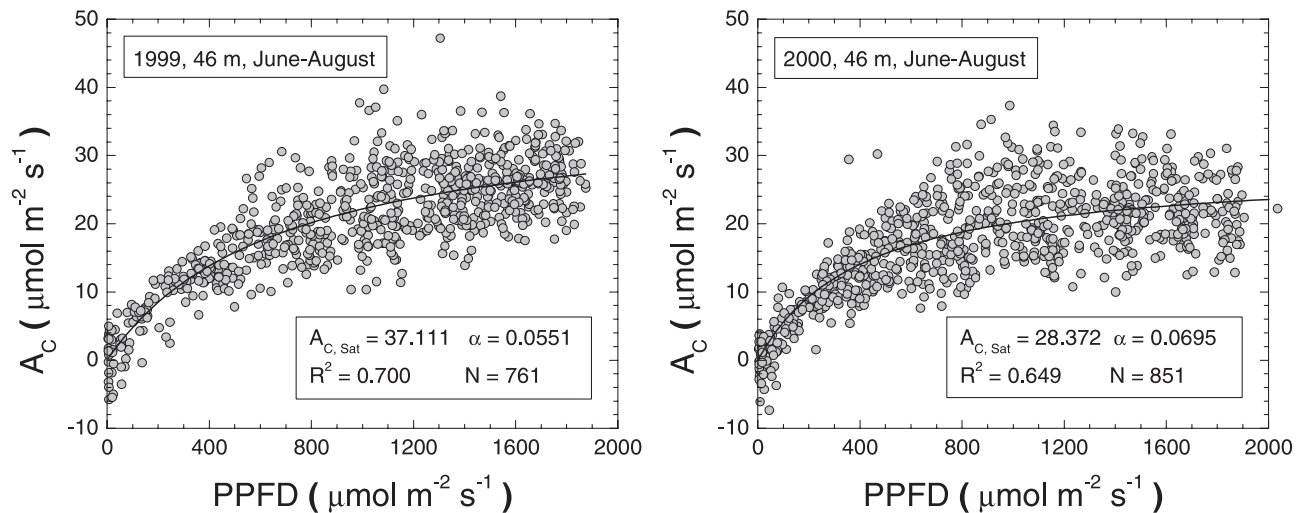
Figure 7. Gross ecosystem photosynthetic uptake (A_C) and photosynthetically active photon flux density relationship (light response) during the fully developed vegetative season for (left) 1999 (days 151–244) and (right) 2000 (days 152–245). Gross ecosystem photosynthetic uptake was determined from daytime-measured CO$_2$ fluxes at 46 m and ecosystem respiration (Figure 6) as $A_C = R_E - F_{CO2}$. The regression parameters $A_{C,sat}$ and α refer to equation (2); see Tables 5a and 5b.

communication, 2002) indicate that typical differences of hourly or half-hourly flux measurements typically amount to a few percent. *Moncrieff et al.* [1996] discussed the propagation of errors for long-term mean fluxes and argued that even with a random error of 20% in the hourly fluxes, cancellation in the annual average over $N = 8760$ hours reduces the compounded random error to $1/\sqrt{N}$, or roughly 0.2% of the root mean square hourly flux of the year. It should be noted that, for their analysis, *Moncrieff et al.* [1996] implicitly assume that the flux time series consists of statistically independent samples from a stationary population, with no autocovariance at any lag. However, in the face of clear diel and seasonal patterns in the fluxes these assumptions seem questionable (see also below). Moreover, they do not mention the compounded error in the long-term sum of carbon exchange. Indeed, with the same assumptions for the measurement uncertainty as *Moncrieff et al.* [1996] the integral random error would grow with $\sqrt{N}$, because for independent measurements the variance of the sum is equal to the sum of the variances [e.g., *Box et al.*, 1978]. Thus it would appear that the random uncertainty of the annual sum could result in a value of a multiple of the annual NEP. However, as mentioned, this analysis dwells on the assumption of no autocorrelation in the data, but the consistency in

annual NEP results between sites and years reported by *Baldocchi et al.* [2001] indicates that this type of random error model does not adequately reflect reality. With pronounced annual trends, seasonal and diel cycles, and persistent weather-related episodes in the flux data (e.g., Figures 3 and 4), it appears that neither independence nor stationarity are particularly well-founded assumptions. Alternately, *Goulden et al.* [1996] used a Monte Carlo approach to simulate the propagation of random errors in the annual sum and concluded that the accumulated random error amounted to <15% of an annual NEP of 210 g C m^{-2}. The measurement system at UMBS∼Flux is sufficiently similar to that used by *Goulden et al.* [1996] that we expect the random uncertainty of the annual NEP at UMBS∼Flux to be of a similarly small magnitude. An ad hoc Monte Carlo simulation based on the CO$_2$ flux measurements of 2000 supported this notion.

[43] Although the estimation of random errors in annual flux sums is difficult, the evidence suggests that the uncertainty problem of long-term exchange accumulations is more likely dominated by the presence of systematic errors. Various sources for such biases in closed-path eddy covariance measurements must be expected to play a role, but their determination is often hampered by the lack of an absolute reference (see *Moncrieff et al.* [1996] or *Leuning and Judd* [1996] for an overview and the more recent

Table 5a. Coefficients α and $A_{C,Sat}$ for Ecosystem Photosynthetic Uptake and Photosynthetic Photon Flux Density Relationship, 1999

Days, 1999	Number of Hours	46 m			34 m		
		α	$A_{C,Sat}$	R^2	α	$A_{C,Sat}$	R^2
128−136	83	0.0299	7.028	0.624	0.0265	7.253	0.662
137−150	114	0.0408	19.968	0.729	0.0418	19.322	0.750
151−244	761	0.0551	37.111	0.700	0.0590	35.777	0.712
245−269	207	0.0743	22.500	0.597	0.0734	22.280	0.610
270−282	64	0.0334	14.083	0.620	0.0324	15.188	0.620

Table 5b. Same as Table 5a, but for 2000

Days, 2000	Number of Hours	46 m			34 m		
		α	$A_{C,Sat}$	R^2	α	$A_{C,Sat}$	R^2
128−136	78	0.0250	10.859	0.855	0.0218	11.259	0.862
137−151	136	0.0260	16.270	0.450	0.0252	15.572	0.457
152−245	848	0.0695	28.372	0.649	0.0651	27.653	0.677
246−271	213	0.0591	26.629	0.740	0.0536	25.866	0.784
272−285	107	0.0255	13.583	0.497	0.0245	13.150	0.525

Table 5c. Same as Table 5a, but for 2001

Days, 2001	Number of Hours	46 m			34 m		
		α	$A_{C,Sat}$	R^2	α	$A_{C,Sat}$	R^2
131−136	61	0.0256	9.681	0.656	0.0346	9.096	0.607
137−151	153	0.0445	17.908	0.626	0.0460	17.465	0.601
152−243	826	0.0650	30.792	0.597	0.0633	28.900	0.637
244−273	200	0.0657	23.690	0.614	0.0700	24.395	0.681
274−281	52	0.0238	12.665	0.452	0.0289	12.895	0.466

discussions of *Lee* [1998], *Finnigan et al.* [1999], and *Massman* [2000]). If the accuracy of commonly used flux systems is estimated at 0.5 μmol m^{-2} s^{-1}, a sustained bias of this magnitude accumulates to an annual systematic error in NEP of ±190 g C m^{-2}, a value that is much larger than the estimated random error of *Goulden et al.* [1996] and of the same magnitude as many published estimates of annual NEP for midlatitude deciduous forests [*Baldocchi et al.*, 2001; *Curtis et al.*, 2002]. Fortunately, it is unlikely that the net bias of all sources combined is of the same sign and magnitude throughout the year, and the accumulated systematic errors can be expected to be smaller than that.

[44] Some authors advocate the use of energy balance closure in assessing the quality of eddy covariance measurements (including *Wilson et al.* [2002]). However, there are reasons to argue that the degree of energy balance closure found with a particular measurement system does not directly assess NEE and thus is not a useful indicator of the F_C measurement quality. Although, in our case, the sonic anemometer and the IRGA are common to both latent heat flux (*LE*) and NEE, the system characteristics are found to be quite different for CO$_2$ and for H$_2$O, as is well known. In our case, as reported by *Su et al.* [2003], tube attenuation of *LE* by our closed-path system (10−20%) is much greater than that of F_C (3−7%). In addition, as previously reported by *Leuning and Judd* [1996], attenuation of *LE* increases with tube aging, but such an increase is absent for F_C. In addition, the causes for energy imbalance are not generally known, and it is by no means certain whether the error is entirely in the eddy covariance measurements.

[45] The assessment of the different components of the energy balance in a tall forest environment is a focus of ongoing work pursued in our group. This includes calculations of storage flux in various components of the forest biomass and the soil layer above the soil heat plates, etc. Preliminary results [*Ciasto et al.*, 2002] indicate that the hourly heat storage in the biomass can be very large compared to sensible heat flux (*H*) and *LE* during the daily transition periods (sunrise/sunset), especially during the foliated season, and its estimate is often subject to great uncertainty. Thus the consequences on the hourly energy balance closure can be considerable. However, there is no equivalent biomass storage contributing to F_C over such short timescales (only for the canopy air space, which we account for). These findings are another reason why it seems inappropriate to use energy closure to assess the quality of NEE, at least for the daily transition periods. Nevertheless, *Su et al.* [2003] show that before cospectral correction (daytime, growing season, outside of the transition periods when biomass storage is large) the slope of linear regression (forced through the origin) of hourly values of (*H* + *LE*) versus ($R_N − G$) is about 0.97 (1999),

0.94 (2000), and 0.96 (2001) for the 46 m level, where *G* is not corrected for soil layer storage (2.5 cm depth). This degree of energy balance closure is very good, compared to the mean imbalance of 20% reported by *Wilson et al.* [2002] for FLUXNET sites.

[46] Thus the high degree of energy balance closure found for our flux measurements indicates the general soundness of our system and our methods of analysis. However, for the reasons mentioned above, good energy balance closure should not be adopted as an endorsement of the absolute values of our F_C measurements.

[47] The foregoing illustrates the evident difficulties to track the progression of systematic and random errors for annual NEP estimates in a consistent fashion. In the present stage of this important research problem we feel that there is insufficient knowledge to assign a quantitative value of measurement uncertainty to our annual NEP estimates. An additional source of uncertainty in NEP estimates is the treatment and analysis of the measured data. In section 5.2 we offer a discussion about the quantitative consequences of variations in data analysis strategy, involving a progression of criteria for data rejection and gap filling. The difference in NEP due to a change in the analysis strategy indicates the sensitivity of long-term flux accumulations to small systematic adjustments that are asymmetrically applied to positive and negative fluxes. The results of this analysis are summarized in Table 6, using the 1999 flux observations at the 46 and 34 m levels.

5.2. Estimates of Annual Ecosystem Exchanges: The Influence of Analysis Criteria

[48] Flux observations can be missing for a variety of reasons, including sensor or transmission errors, maintenance and calibration periods, or system failure. To obtain annual estimates of NEP, the data gaps need to be filled. Here we discuss the sensitivity of the resulting annual exchange values to choices and criteria of quality control and the gap-filling strategy, using the 1999 data as an example.

[49] When missing CO$_2$ flux observations were filled by short-period ensemble averages of diurnal patterns, we obtained an annual NEP of 290 (46 m) or 330 (34 m) g C m^{-2} with a difference of 40 g C m^{-2}.

[50] Using the parametric relation of equation (1) with measured soil temperatures, modeled annual ecosystem respiration R_E is 1190 (46 m) or 1140 (34 m) g C m^{-2} when the model regression was done for the entire year. Individual regressions over three shorter periods (days 1−127, 128−282 and 283−365) yielded 1170 (46 m) or 1110 (34 m) g C m^{-2}. The difference for the same height using the two different regression strategies is 20 (46 m) or 30 (34 m) g C m^{-2}, considerably less than the corresponding difference between the two heights, 50 or 60 g C m^{-2}. The cause of this difference is not entirely known, but some discussion is offered in section 5.3.

[51] Relation (2) was used to determine the modeled total ecosystem photosynthetic uptake or assimilation, A_C, during the vegetative season (days 128−282; see Table 3). A_C is 1350 g C m^{-2}, with negligible difference between the measurement heights, when the model regression was performed over five periods (days 128−136, 137−150, 151−244, 245−269, and 270−282). Dividing the period

Table 6. Estimates of Ecosystem Exchange Using Different Analysis Criteria[a]

UMBS~Flux, 1999–2001	46 m	34 m
1999 Net Ecosystem Production, annual (NEP) [g C m^{-2}]		
Gaps: ensemble averages	290	330
Gaps: modeled, no u_*-criteria	250	300
Gaps: modeled, $u_* < 0.35$, condition	140	200
Gaps: modeled, $u_* < 0.2$, cond.	160	230
Gaps: modeled, $u_* < 0.35$, all	**170**	**220**
Gaps: modeled, $u_* < 0.2$, all	170	230
Modeled	180	250
1999 Gross Ecosystem Production, annual (GEP) [g C m^{-2}]		
Modeled, 5 periods	1350	1350
Modeled, 14 periods	1350	1360
1999 Net Ecosystem Respiration, annual (R$_E$) [g C m^{-2}]		
Modeled, all year	1190	1140
Modeled, 3 periods	1170	1110
2000 Net Ecosystem Production, annual (NEP) [g C m^{-2}]		
Gaps: modeled, $u_* < 0.35$, all	**160**	**210**
2001 Net Ecosystem Production, annual (NEP) [g C m^{-2}]		
Gaps: modeled, $u_* < 0.35$, all	**80**	**170**

[a]Bold values represent the "best estimates" of NEP described in the text. The values are rounded to the nearest 10 g C m^{-2}. Equivalent units: 100 g C m^{-2} = 0.1 kg C m^{-2} = 10^3 kg C ha^{-1} = 1 ton C ha^{-1} = 1 Mg C ha^{-1}.

151–244 further into 10 shorter periods for regression yielded 1350 (46 m) or 1360 (34 m) g C m^{-2} of ecosystem assimilation. The corresponding difference of 10 g C m^{-2} for the 34 m level is on the same order as the difference between the two heights, noting that cumulative uptake using the 46 m level results in a smaller number. The difference is small compared to that for R_E, but the 34 m level again shows the larger magnitude. See also section 5.3.

[52] Thus if only the modeled R_E and A_C based on regressions over several short periods were used, the modeled annual NEP is 180 (46 m) and 250 (34 m) g C m^{-2}, with a difference of 70 g C m^{-2} (about 39%) that is largely attributable to the difference in R_E. Alternately, when only missing observations were filled by corresponding modeled values, we obtained an annual NEP of 250 (46 m) or 300 (34 m) g C m^{-2} with a difference of 50 g C m^{-2}. This result is 40 g C m^{-2} (46 m) or 30 g C m^{-2} (34 m) smaller than that using the ensemble average gap-filling method. However, following *Falge et al.* [2001a], we place more confidence in the gap-filling method by parametric models, because it is based on physical processes that reflect the conditions at the time of the missing values. Because most missing observations were due to rain, and thus occurred in relatively low PAR conditions, ensemble averages of existing observations are biased toward high PAR conditions and thus tend to overestimate photosynthetic uptake. Furthermore, when eddy fluxes during periods when u_* was smaller than 0.35 m s^{-1} (except daytime for the vegetative season) were also replaced by modeled values, we obtained 140 (46 m) or 200 (34 m) g C m^{-2} with a difference of 60 g C m^{-2}. When the u_* criterion was relaxed to $u_* < 0.2$ m s^{-1}, the estimated annual NEP increased to 160 (46 m) or 230 (34 m) g C m^{-2} with a difference of 70 g C m^{-2}. The change between the two u_* criteria lead to a difference of about 15% in annual NEP. As shown in section 4.3, nighttime eddy covariance fluxes (even with storage change correction) systematically underestimate the expected ecosystem respiration. Thus the less restrictive u_* criterion ($u_* < 0.2$ m s^{-1} in this case) leads to an overestimation of annual NEP.

[53] Finally, if eddy fluxes during periods when $u_* < 0.35$ m s^{-1} were replaced by modeled values at all times (not only at night), the annual NEP was determined as 170 (46 m) or 220 (34 m) g C m^{-2} with a difference of about 50 g C m^{-2}. Again, if $u_* < 0.2$ m s^{-1} was used instead, we obtained 170 (46 m) or 230 (34 m) g C m^{-2}. Compared to the nighttime-only case, the change in NEP due to the same difference in the u_* criterion becomes smaller (<2%). The rationale for the common practice of concentrating on nighttime low-u_* conditions for replacement of measured fluxes with the parametric model assumes that, during the day, natural convection assures efficient mixing throughout the canopy layer, so that drainage and advective effects below canopy become unimportant. However, positive vertical potential temperature gradients and negative sensible heat fluxes below canopy in the morning and late afternoon transitional periods, when above-canopy conditions are clearly lapse [*Villani et al.*, 2003], indicate that this assumption is not always warranted. It is thus likely that small amounts of net carbon uptake during such episodes are not properly captured by the eddy covariance system, with the effect that NEP is underestimated by including those measured values. The increase of the NEP estimate by replacing also daytime low-u_* values from roughly 140 to 170 g C m^{-2} (using the 46 m data) supports this argumentation. Thus we consider this last version of analysis to be the best estimate of NEP for the UMBS~Flux site. The application of this $u_* > 0.35$ ms^{-1} criterion resulted in the rejection of 35% of data, a similar magnitude to that reported by other sites [e.g., *Schmid et al.*, 2000a]. This fraction did not change considerably over the 3 years reported here. The majority of data rejections occurred at night (about two thirds of the total), when calm conditions and low u_* are more frequent.

5.3. Some Considerations of Variability, Real and Apparent

[54] Table 6 also shows the annual NEP results for the years 2000 and 2001, and the cumulative NEE curves for all 3 years (and both heights) are plotted in Figure 8. These
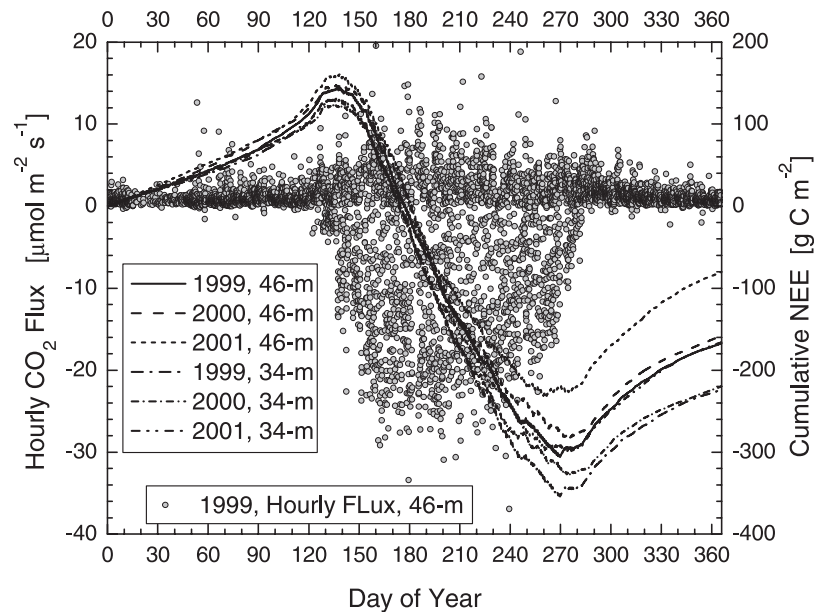
Figure 8. Annual net ecosystem exchange (NEE) estimates at UMBS∼Flux for the years 1999–2001. The curves represent the "best estimates" of cumulative NEE based on the two measurement heights, where data gaps and measurements in low u_* conditions were replaced by parametric model values at all times. The dots are measured hourly CO$_2$ fluxes for the year 1999.

results are obtained by the same criteria as the best estimate of NEP for 1999, where data gaps and the measurements of all periods with $u_* < 0.35$ m s^{-2} were replaced by parametric models. Despite the signs of reduced water availability in the summer of 2000 (Figures 3b and 4), the NEP difference to 1999 is small. The difference between the NEP estimates based on the two measurement levels is much larger than the difference between these 2 years. As pointed out in section 4.2, the cooler and dryer conditions in July 2000 reduced both ecosystem respiration and carbon uptake, with partial cancellation of their effect in the net exchange. However, while the reduction in carbon uptake in 2000 cannot be seen to carry over to the following year, the consequence of reduced ecosystem respiration in 2000 may be an increase in organic soil carbon and leaf litter available for respiration in 2001. This effect may partially contribute to the drastically reduced annual NEP estimates for 2001 (Table 6), although such interpretations of interannual variations require careful scrutiny that will be the focus of other work.

[55] At present, we do not have conclusive indications what the relatively large and consistent differences between the NEP estimates of the two measurement levels are attributable to, nor which of the two levels comes closer to the "true" ecosystem exchange. The data for 1999, summarized in Table 6, suggest that the difference arises primarily in the ecosystem respiration component, based on leaf off and nighttime measurements. To elucidate this phenomenon, we examined the seasonal and diurnal distribution and characteristics of NEE differences between the 46 and 34 m measurements. Using the year 2000 as an example, the annual NEP difference is 62 g C m^{-2} (larger for the 46 m level). About 58% of this difference derives from the leaf off period (due to consistently larger positive F_C at 46 m throughout the day), and only 42% of the bias

was accumulated over the growing season (mainly more positive nighttime F_C at 46 m, with partial cancellation by more negative F_C during the day).

[56] To shed further light on these differences, we used all hourly values that passed quality control, to compare F_C and H between the two heights, by linear regressions of the 46 m values against the 34 m values for the leaf off period and the growing season. The results are summarized in Table 7. The average offsets for F_C and for H for both seasons are smaller than the commonly expected absolute accuracy of such measurement systems. This result demonstrates that small biases can build up to sizable differences (such as the 62 g C m^{-2}, reported above), when they are accumulated over a long period of time. The relative offsets show that the bias is much more serious for F_C than for H, particularly in the leaf off period when F_C fluxes are usually small. As mentioned, the 46 m F_C values exhibit a larger magnitude than their 34 m counterparts both for positive and negative values, so there is partial cancellation between daytime and nighttime biases. Interestingly, this partial cancellation is not present (or at least is much reduced) in the biases for H.

[57] At present we can only speculate about the causes for this small but fairly persistent bias that is expressed more strongly in F_C than in H. Differences due to flux footprint variations (which are strongly height dependent), are not likely an important factor, because with changes in wind direction the consistent bias pattern seen here cannot be supported by this effect. In addition, effects of fetch, owing to horizontal variations in vegetation and land cover, are expected to exhibit their signature also in energy partitioning and thus sensible heat flux, and not only in carbon exchange. However, the relative differences in H between the measurement levels are much smaller and less consistent (i.e., more randomly distributed) than those of

Table 7. Linear Regression Statistics of Hourly Values of F_C and H From the 46 m Against the 34 m Measurement Level[a]

	Leaf Off Period		Growing Season, Days 128–285	
	F_C	H	F_C	H
Offset	+0.15, μmol m^{-2}s^{-1}	−0.93, W m^{-2}	+0.17, μmol m^{-2}s^{-1}	−1.2, W m^{-2}
Relative offset	16%	0.9%	1.9%	0.9%
Slope	1.022	0.98	1.025	0.98
R^2	0.77	0.98	0.96	0.98
N	1874	1874	1824	1824

[a]For the leaf off and the growing seasons of the year 2000. The offset is the expected value at the 46 m level when the 34 m value is zero. The relative offset is the offset divided by the standard deviation (range indicator) of the 46 m values. A slope larger than unity indicates that the 46 m values grow faster than the 34 m values. R^2 is the coefficient of determination, and N is the number of values in the regression.

F_C (not shown). A simple instrumentation error is also unlikely to be the determinating factor, because the IRGAs are regularly calibrated to the same gas standards, and a systematic difference in the sonic velocities should affect H to the same extent as F_C. Tube attenuation effects are expected to reduce the flux amplitudes of the 46 m level more than those of the 34 m level, in contrast to the present findings. Thus potential causes include insufficient high-frequency sampling resolution (which may be more important at 34 m than at 46 m) and the potentially larger aerodynamic disturbance of the 34 m eddy covariance measurements by the tower structure. The importance and the consequences of either of these possibilities on measured scalar fluxes are largely unknown. For these reasons we tend to place more confidence in the NEP values based on the 46 m measurement level. The small but persistent bias points to the way the flux is measured, rather than a real physical process, as the cause for the reported differences. Thus the height dependence of NEP is likely only apparent. We are hoping that cospectral analysis at both measurement levels (work in preparation) and detailed instrument comparisons will provide some clarification about this issue. However, it is important to note that most long-term flux sites conduct measurements at only one height that is closer to our lower level, in relation to the canopy height. Naturally, such sites do not have any information about a potential height variation of their results, apparent or real. Thus our discussion here can serve as a warning flag, even if we cannot offer conclusive explanations.

6. Conclusions

[58] Our results from 3 years of measurements of forest-atmosphere exchange at the AmeriFlux site of the University of Michigan Biological Station (UMBS~Flux) illustrate that long-term estimates of NEP, based on fixed tower eddy covariance measurements, have come of age. Much knowledge of the ecosystem-atmosphere exchange processes and dynamics has been accumulated over the last few years. Yet a number of research questions and fundamental operational issues remain unresolved. For example, our discussion of uncertainty issues led us to recognize that commonly applied statistical estimates of random measurement uncertainty do not hold up to scrutiny for the annual sum of a large number of hourly fluxes of ecosystem exchange. Instead of assigning error bars with no well-based level of confidence, we thus propose to assess the quantitative consequences of a systematic progression of data analysis criteria as a qualitative expression of the confidence associated with individual NEP estimates. Other key results are the following:

[59] (1) Cumulative NEE based on measured fluxes at two heights above canopy show marked differences, although the IRGAs involved are regularly calibrated to the same gas standards. We found that the differences derive from small but persistent biases that affect CO$_2$ fluxes more than sensible heat fluxes. Because our lower level is likely to suffer more high-frequency loss and more aerodynamic disturbance than the 46 m level, we guardedly put more confidence on the results from the upper level. Because we are not aware of other long-term flux sites to have reported NEE from two levels above canopy, we do not know whether similar phenomena are in effect at other locations.

[60] (2) In agreement with other studies we find that net ecosystem exchange values, based on eddy covariance measurements in conditions of poorly developed turbulence above the forest, in combination with measured storage change in the canopy air volume, systematically underestimate the respiration magnitude indicated by parametric models. As suggested by other studies, this bias appears to be strongly correlated with friction velocity. At UMBS~ Flux a threshold of $u_* > 0.35$ m s^{-1} was found to be suitable for the acceptance of eddy covariance measurements at all times (not just at night, as commonly applied).

[61] (3) The choice of criteria and strategies of data quality control and gap filling can affect the outcome of annual accumulations of NEE by a factor of 2. However, we found that biophysical arguments and constraints can be used to invest more or less confidence in a given method. In our case, such arguments led us to conclude that replacement of both data gaps and low-u_* conditions (see above) by parametric models, based on short-period regressions, represents the "best estimate" strategy. This result may well be site-specific and dependent on the distribution and causes for the occurrence of data gaps.

[62] (4) Persistent cooler and dryer conditions at the height of the growing season (as was the case in July 2000 at UMBS) can significantly reduce both respiration and carbon uptake, even if the entire year is not classified as dry. During the year of a midsummer drought, the response of respiration and carbon uptake appear to largely cancel each other. Some indications that reduced respiration in 1 year may translate to increased respiration in the following year, due to a surplus of available soil carbon and litter, need to be further examined.

[63] (5) The forest ecosystem of UMBS~Flux has been acting as a persistent carbon sink of moderate magnitude over the last 3 years. Our best estimates (see above) of

annual NEP at this site for the 3 available years of measurement amounted to 170 (1999), 160 (2000), and 80 (2001) g C m^{-2}, adding up to 410 g C m^{-2} over the 3 years. The variation exhibited by these 3 years underlines the importance of obtaining long-term observations of ecosystem exchange over several years, to cover at least some of the climatic and ecophysiological timescales involved.

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