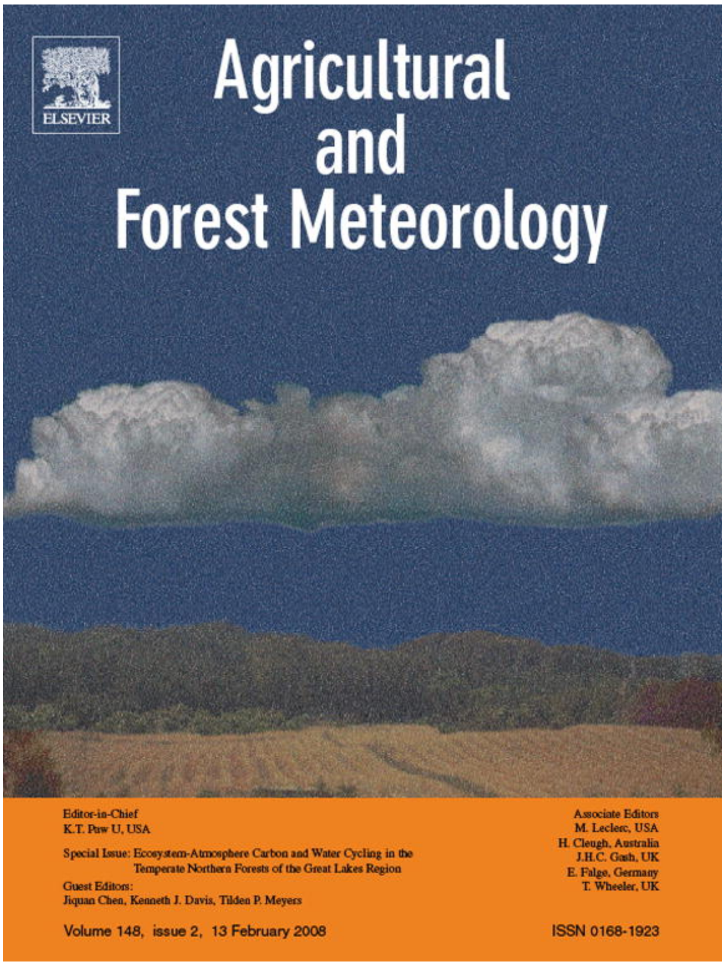
ELSEVIER
Agricultural
and
Forest Meteorology
Editor-in-Chief
K.T. Paw U, USA
Special Issue: Ecosystem-Atmosphere Carbon and Water Cycling in the Temperate Northern Forests of the Great Lakes Region
Guest Editors:
Jiquan Chen, Kenneth J. Davis, Tilden P. Meyers
Associate Editors
M. Leclerc, USA
H. Cleugh, Australia
J.H.C. Gash, UK
E. Falge, Germany
T. Wheeler, UK
Volume 148, issue 2, 13 February 2008
ISSN 0168-1923

AGRICULTURAL AND FOREST METEOROLOGY 148 (2008) 186–205

available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/agrformet

An assessment of observed vertical flux divergence in long-term eddy-covariance measurements over two Midwestern forest ecosystems

H.-B. Su[a,*], H.P. Schmid[b], C.S.B. Grimmond[b,c], C.S. Vogel[d], P.S. Curtis[e]

[a] *Department of Geography, East Carolina University, Greenville, NC 27858-4353, USA*
[b] *Department of Geography, Indiana University, Bloomington, IN 47405-7100, USA*
[c] *Department of Geography, King's College London, London WC2R 2LS, UK*
[d] *University of Michigan Biological Station, Pellston, MI 49769-9133, USA*
[e] *Department of Evolution, Ecology and Organismal Biology, The Ohio State University, Columbus, OH 43210-1293, USA*

ARTICLE INFO

Keywords:
Net ecosystem exchange (NEE)
Vertical flux divergence
Advection
Coordinate rotation
Averaging time period
Co-spectral correction

ABSTRACT

Vertical divergence of CO_2 fluxes is observed over two Midwestern AmeriFlux forest sites. The differences in ensemble averaged hourly CO_2 fluxes measured at two heights above canopy are relatively small (0.2–0.5 μmol m^{-2} s^{-1}), but they are the major contributors to differences (76–256 g C m^{-2} or 41.8–50.6%) in estimated annual net ecosystem exchange (NEE) in 2001. A friction velocity criterion is used in these estimates but mean flow advection is not accounted for. This study examines the effects of coordinate rotation, averaging time period, sampling frequency and co-spectral correction on CO_2 fluxes measured at a single height, and on vertical flux differences measured between two heights. Both the offset in measured vertical velocity and the downflow/upflow caused by supporting tower structures in upwind directions lead to systematic over- or under-estimates of fluxes measured at a single height. An offset of 1 cm s^{-1} and an upflow/downflow of 1° lead to 1% and 5.6% differences in momentum fluxes and nighttime sensible heat and CO_2 fluxes, respectively, but only 0.5% and 2.8% differences in daytime sensible heat and CO_2 fluxes. The sign and magnitude of both offset and upflow/downflow angle vary between sonic anemometers at two measurement heights. This introduces a systematic and large bias in vertical flux differences if these effects are not corrected in the coordinate rotation. A 1 h averaging time period is shown to be appropriate for the two sites. In the daytime, the absolute magnitudes of co-spectra decrease with height in the natural frequencies of 0.02–0.1 Hz but increase in the lower frequencies (<0.01 Hz). Thus, air motions in these two frequency ranges counteract each other in determining vertical flux differences, whose magnitude and sign vary with averaging time period. At night, co-spectral densities of CO_2 are more positive at the higher levels of both sites in the frequency range of 0.03–0.4 Hz and this vertical increase is also shown at most frequencies lower than 0.03 Hz. Differences in co-spectral corrections at the two heights lead to a positive shift in vertical CO_2 flux differences throughout the day at both sites. At night, the vertical CO_2 flux differences between two measurement heights are 20–30% and 40–60% of co-spectral corrected CO_2 fluxes measured at the lower levels of the two sites, respectively. Vertical differences of CO_2 flux are relatively small in the daytime.

* *Corresponding author*. Tel.: +1 252 328 1040; fax: +1 252 328 6054.
E-mail addresses: suh@ecu.edu (H.-B. Su), hschmid@indiana.edu (H.P. Schmid), Sue.Grimmond@kcl.ac.uk (C.S.B. Grimmond), csvogel@umich.edu (C.S. Vogel), curtis.7@osu.edu (P.S. Curtis).
0168-1923/$ – see front matter
doi:10.1016/j.agrformet.2007.08.009

Vertical differences in estimated mean vertical advection of CO_2 between the two measurement heights generally do not improve the closure of the 1D (vertical) CO_2 budget in the air layer between the two measurement heights. This may imply the significance of horizontal advection. However, a reliable assessment of mean advection contributions in annual NEE estimate at these two AmeriFlux sites is currently an unsolved problem.

1. Introduction

Carbon and energy fluxes measured at the University of Michigan Biological Station (UMBS) AmeriFlux site in the first 3 years (1999–2001) were published recently (Schmid et al., 2003). Annual net ecosystem exchange (NEE) estimates based on long-term eddy-covariance measurements are sensitive to criteria used in data quality control (e.g., friction velocity threshold) and gap-filling methods. In particular, annual NEE estimates based on measurements at a higher level (46–48.4 m, or 2.1h_c–2.2h_c, where h_c = 21.5 m is the mean canopy height) are consistently less negative (here a negative NEE value indicates that the forest ecosystem is a net sink of CO_2) by 50–90 g C m^{-2} than those observed at a lower level (34 m, or 1.5h_c) over each of the 3 years (Schmid et al., 2003). In these estimates, NEE is calculated as the sum of eddy-covariance flux and storage in the air layer from the ground to each flux measurement level. Hourly NEE rates in periods of measurement gaps and weak turbulent mixing (friction velocity $u_* < 0.35$ m s^{-1}) are estimated by parametric models of ecosystem respiration and gross photosynthetic uptake, and accounted for in the annual sums. These parametric models are based on measurements during periods when $u_* \geq 0.35$ m s^{-1}.

Eddy-covariance fluxes have also been measured at two heights (46 and 34 m, or 1.8h_c and 1.3h_c, h_c = 26 m) above canopy at the Morgan Monroe State Forest (MMSF) AmeriFlux site (Schmid et al., 2000). In the present work, a first step was taken to apply the same methods as in Schmid et al. (2003) to analyze the MMSF data. Annual NEE estimates were also less negative based on measurements at the higher level by 256 g C m^{-2} in 2001 at the MMSF site (Table 1).

Although the differences of 76–256 g C m^{-2} $year^{-1}$ in estimated annual NEE between the two measurement heights are relatively large (−41.8% to −50.6% relative to the lower level) at the UMBS and MMSF sites (Table 1), these differences are equivalent to hourly NEE rates of 0.201–0.676 μmol m^{-2} s^{-1}, which are relatively small compared to hourly eddy-covariance fluxes (especially in the growing season) at these two sites (Schmid et al., 2000, 2003). However, averaging over all hourly periods when measurements are available at both heights, differences in the eddy-covariance fluxes between the two heights are much greater contributors to the differences in the averaged hourly NEE rates than the storage in the air layer between the two measurement levels at both sites (Table 2).

In principle (Finnigan et al., 2003; Finnigan, 2004), the above estimates of NEE are incomplete since they do not account for mean advection and horizontal flux divergence in the air layer from the ground to each flux measurement height. However, only the mean advection and horizontal flux divergence in the air layer between the two measurement heights attribute to the differences in NEE estimates based on measurements at the two heights. Lee (1998) proposed a 1D framework to estimate the mean vertical velocity and advection when measurements of eddy-covariance flux at a single level above canopy and vertical profile of mean CO_2 concentration are only available on a single tower. Finnigan (1999) argued that the appropriate framework for scalar budget analysis in advective flows is unavoidably 2D or 3D, and it is generally incorrect to assume the vertical advection is everywhere much larger than the horizontal advection. Nonetheless, measurements are not available to directly estimate the mean horizontal advection and horizontal flux divergence at the UMBS and MMSF sites.

On the other hand, in conditions (e.g., Finnigan, 1999) when the horizontal flux divergence is small, advection by mean flows between measurement levels may be estimated using 1D (vertical) CO_2 budget analysis of eddy-covariance fluxes and storage measurements on a single tower (Yi et al., 2000; Davis et al., 2003). However, these earlier studies did not assess the effects of potential errors in flux measurements and calculations on the results they presented.

Table 1 – Annual NEE estimates based on eddy-covariance measurements at two heights above forests and vertical CO_2 concentration profiles measured from the ground to the flux measurement heights at the UMBS and the MMSF AmeriFlux sites in 2001

Site	Number of measured hourly NEE rates		Number of modeled hourly NEE rates		Total measured NEE (g C m^{-2})		Total modeled NEE (g C m^{-2})		Total annual NEE (g C m^{-2})		Difference in total annual NEE relative to the lower level
	Higher level	Lower level	Higher level	Lower level	Higher level	Lower level	Higher level	Lower level	Higher level	Lower level	
UMBS	3781	3628	4979	5132	−378	−436	272	254	−106	−182	−41.8%
MMSF	2562	2835	6198	5925	−344	−446	94	−61	−250	−506	−50.6%

Hourly NEE rates during measurement gaps and periods of weak turbulent mixing ($u_* < 0.35$ m s^{-1}) are estimated with parametric models (Schmid et al., 2003). The differences in total annual NEE values are defined as those at the higher level (46 m or 48.4 m) minus those at the lower level (34 m).

Table 2 – Ensemble average of measured hourly NEE rates and eddy-covariance fluxes at two heights above forests and storage in the air layer between the two measurement levels at the UMBS and the MMSF AmeriFlux sites in 2001

Site	Number of hourly measurement	NEE		Higher level NEE minus lower level NEE	Eddy-covariance flux		Higher level eddy-covariance flux minus lower level eddy-covariance flux	Storage in the air layer between the two measurement levels
		Higher level	Lower level		Higher level	Lower level		
UMBS	3033	−4.113	−4.544	0.431	−3.753	−4.269	0.516	−0.085
MMSF	2001	−3.108	−3.247	0.139	−2.876	−3.071	0.195	−0.056

Hourly NEE rates, eddy-covariance fluxes and storage are all in μmol m^{-2} s^{-1}. Only measurements available at both heights and during periods of $u_* \geq 0.35$ m s^{-1} are used.

In light of many recent discussions on the uncertainties and corrections in eddy-covariance measurements (e.g., Twine et al., 2000; Massman and Lee, 2002; Lee et al., 2004), the primary objective of this study is to assess the effects of different methods used in the basic procedures of eddy-covariance calculation and correction on fluxes measured at a single height, and particularly on the apparent vertical flux divergence observed at the UMBS and MMSF sites. These include coordinate rotation, averaging time period, sampling frequency, and co-spectral correction.

2. Materials and methods

2.1. Sites and instrumentations

Data used in this study were collected over two mixed hardwood forests in the Midwestern USA: UMBS in northern lower Michigan (45°35′N, 84°42′W), and MMSF in south-central Indiana (39°19′N, 86°25′W).

A detailed description of MMSF (topography, vegetation composition, vegetation area index or VAI, soil type, mean canopy height, flux tower structure, instrumentation, etc.) can be found in Schmid et al. (2000). A similar description of UMBS is given in Schmid et al. (2003). The MMSF site has a ridge/ravine topography with a relative relief of less than 60 m and an overall drop of 90 m in 4 km. At UMBS, the most significant topographic feature is the crest of an interlobate moraine approximately 1 km to the southwest of the flux tower with a relative elevation of about 30 m. Peak VAI was 3.5 at UMBS and 4.7 at MMSF. For the leafless periods, VAI was about 1 at UMBS and about 1.5 at MMSF, representing stem and branch area, and (in the case of UMBS) some evergreens in the understory. The mean tree height (h_c) was 21.5 m at UMBS and 26 m at MMSF.

The main flux towers at both sites are about 46 m tall with identical structures, self-supporting with a triangular cross-section (Fig. 1), 5.1 m side length at the base and tapered to 1.8 m at 30.5 m, above which it is straight (Schmid et al., 2000). At each site, eddy-covariance systems, consisting of a Campbell Scientific, Inc. CSAT3 3D sonic anemometer-thermometer and a closed-path Licor-6262 infrared CO_2/H_2O gas analyzer (IRGA), are installed at two heights, 34 and 46 m. Thus, the two measurement heights are 1.5h_c and 2.1h_c at UMBS, and 1.3h_c and 1.8h_c at MMSF. However, on day 130, 2001, the 46-m level eddy-covariance system at UMBS was raised to 48.4 m (or 2.2h_c) fixed on a vertical cylindrical pipe extended from one of the three legs of the tower. At MMSF, both sonic anemometers and supporting booms pointed to 232°. The $UMBS_{34}$ sonic anemometer and boom remained pointing to 299°, but the top level sonic anemometer and boom varied in orientations: pointing to 299° from 1999 to Day 173, 2000, pointing to 240° from Day 173, 2000 to Day 128, 2001, and pointing to 300° from Day 130, 2001 to the present. Note that all the azimuth angles are in meteorological convention. It should also be pointed out that all sonic anemometers are placed away from the tower at a distance of about the side length (1.8 m) of the triangular cross-section (Fig. 1), except

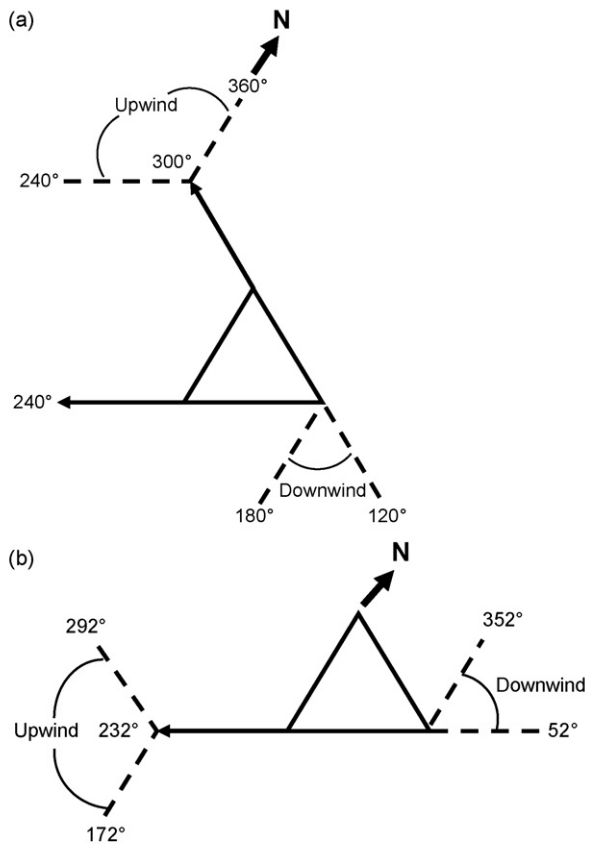

Fig. 1 – Schematic description of the orientation of the triangular cross-section of the top 15 m of the main flux towers, and the directional angles the sonic anemometers and supporting booms point to: (a) UMBS, (b) MMSF. Note that azimuths between the upwind and downwind directions are defined as crosswind directions.

for the sonic anemometer at 48.4 m at the UMBS site which is directly over the tower.

The IRGAs are kept in climate-controlled labs at the base of the towers and sample air is drawn from inlets close to the transducer array of each CSAT3 through long Teflon tubes (4.8×10^{-3} m inner diameter) with lengths of 52 and 40 m for $UMBS_{46/48.4,34}$, respectively, and similarly 56 and 46 m at MMSF. The flow rate at both heights is about 6.0 l min^{-1} (1.0×10^{-4} m^3 s^{-1}) at UMBS, and about 8.0 l min^{-1} (1.3×10^{-4} m^3 s^{-1}) at MMSF. All eddy-covariance measurements are sampled at 10 Hz and saved continuously, except for periods of instrument maintenance.

2.2. Data and quality analyses

For the present analyses, we use measurements in 2001 at both sites, a period with relatively fewer measurement gaps during the growing season. Quality analyses of the hourly raw 10 Hz data include the detection of "hard" and "soft" flags (Vickers and Mahrt, 1997; Schmid et al., 2000, 2003), and a simple block-average was used (i.e., no filtering such as linear-detrending or moving-average). Time lags due to tube delay are determined from maximum lagged correlations (Schmid et al., 2000, 2003). In co-spectral analyses, hourly data with continuous flags greater than 10 (1 s in time) and total flags more than 1.7% (1 min) are excluded (Su et al., 2004). This is a more conservative criterion than that used for direct eddy-covariance calculations, as commonly applied for spectral analysis, which led to smaller number of hourly fluxes when co-spectral corrections were applied.

To be consistent with Schmid et al. (2003), we excluded periods of weak turbulent mixing ($u_* < 0.35$ m s^{-1}) in the present study. This u_* criterion was also found suitable for the MMSF site.

In 2001, net carbon uptake based on the sign (negative) of measured daytime hourly NEE rates occurred from days 131 to 281 at UMBS (Schmid et al., 2003), and from days 114 to 292 at MMSF. Here we define these periods as growing seasons at both sites, which obviously differ from biological or ecological definitions.

2.3. Coordinate rotation

Both theoretical and operational aspects of coordinate systems for long-term flux measurements over non-flat terrain have been re-evaluated recently (Finnigan et al., 2003; Finnigan, 2004; Lee et al., 2004). In practice, two general methods are commonly used to transform measured statistics in the sonic anemometer's coordinate into a reference frame (Finnigan et al., 2003). The first involves three rotation angles determined from measured mean wind vector and Reynolds stress for each individual sample (e.g., 1 h) of data (Tanner and Thurtell, 1969; Wesely, 1970; McMillen, 1988; Kaimal and Finnigan, 1994). The first two rotations force the lateral and vertical mean velocities to zero, and the third rotation leads to the crosswind momentum flux to zero. In this case, the reference frame is the natural wind coordinate system (Lee et al., 2004). This method was used in Schmid et al. (2003) with a constraint on the second rotation angle proposed by McMillen (1988). Finnigan (2004) points out that the third rotation often leads to physically unrealistic results. Thus, in this study, we only use the first two rotations and denote this as ROT-1.

The second general approach defines the reference frame based on long-term measurements (Lee, 1998; Baldocchi et al., 2000; Paw U et al., 2000; Wilczak et al., 2001; Finnigan et al., 2003). In ROT-2, the first rotation is the same as in ROT-1, but long-term moving-bin-averaged second rotation angle (ϕ, denoted by the filled circles in Fig. 2) as a function of the azimuth (α) is used. This method has been used in the estimates of mean vertical velocity and advection (Baldocchi et al., 2000), in the discussions of coordinate rotation and averaging time period (Finnigan et al., 2003), and in the co-spectral analysis and correction (Su et al., 2004).

One potential problem in ROT-2 is that the effect of any offset in measured vertical velocity may be included in ϕ. The planar fit method (Paw U et al., 2000; Wilczak et al., 2001) applies a linear regression to long-term measurements: $U_z = b_0 + b_1 U_x + b_2 U_y$, where $\{U_x, U_y, U_z\}$ are measured mean velocity components in the sonic anemometer's x, y and z coordinate. The coefficients b_1 and b_2 are used to determine the pitch, roll and yaw angles (Wilczak et al., 2001), which are different from the rotation angles in the first general method using the natural wind coordinate system. The coefficient b_0 is a statistical measure of the offset in measured U_z. We applied the planar fit to long-term sets of measured hourly $\{U_x, U_y, U_z\}$ to estimate b_0 (Table 3), using measurements in the upwind directions (±60° from the direction each sonic anemometer points into, Fig. 1) to minimize the tower shadow effects. The only difference in ROT-3 (denoted by the open circles in Fig. 2) from ROT-2 is that the offset (b_0) is removed from the moving-bin averaged ϕ.

If the underlying surface is a plane with a uniform slope (the slope is zero for a level flat surface) and there is no flow distortion by the eddy-covariance instruments and supporting tower structures, the moving-bin averaged ϕ (with the offset removed) would be a sinusoidal function of the azimuth α: $\phi(\alpha) = \phi_t \sin(\alpha - \alpha_0)$, where ϕ_t is the tilt angle between sonic anemometer's x–y plane and local mean streamline plane, α_0 indicates the azimuth along which these two planes intersect. In this ideal situation, ROT-3 and the planar fit method would be equivalent.

In reality, flow distortions by supporting tower structures do exist, even in the upwind directions. Based on observations over relatively smooth surfaces on flat ground, upflows of 2.2° (Dyer, 1981) and 0.8° (Grant and Watkins, 1989) are reported for sonic anemometers fixed directly on top of short (4 m) masts. Dyer attributed the upflow to a horizontal arm (5 cm diameter) which was used to support other sensors in their experiment, whereas Grant and Watkins attributed the upflow primarily to the vertical mast (no horizontal supporting arm). The upflow may be quantified by fitting the bin-averaged ϕ (with the offset removed) as a function of α: $\phi(\alpha) = \phi_t \sin(\alpha - \alpha_0) + \phi_d$, where ϕ_d is the upflow angle. The open circles (ROT-3) in Fig. 2 fit this function quite well (Table 3) for all four sonic anemometers at the two sites in the 120° upwind azimuth range (±60° from the direction each sonic anemometer points into, Fig. 1). This may be expected at UMBS since the elevations change little (about 234 m above mean sea level) within 500 m radius from the flux tower in all directions (Schmid et al., 2003). At MMSF, the flux

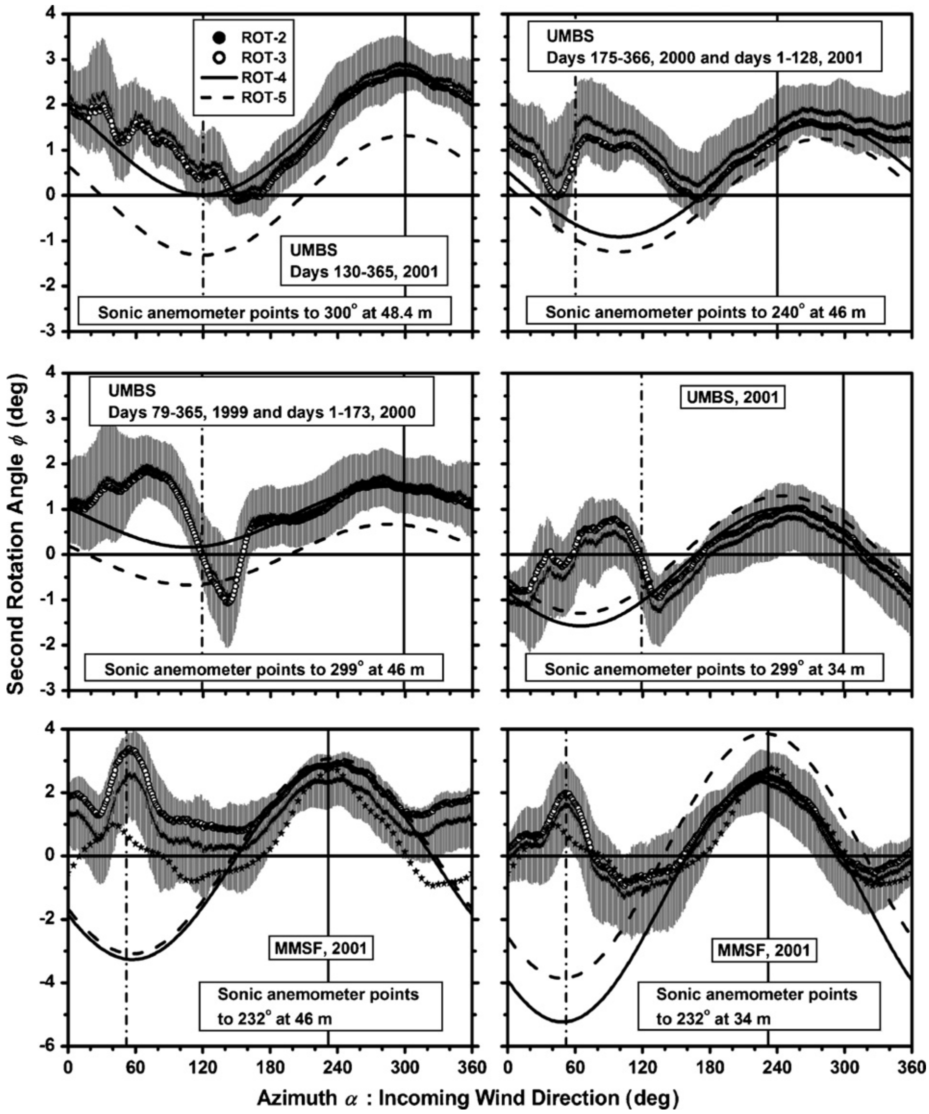

Fig. 2 – Comparison of the ensemble averaged second rotation angle ϕ as functions of azimuth α for coordinate rotation methods 2–5. The gray shaded areas indicate the standard deviations of the moving-bin averaged ϕ for a given α (ROT-2). The vertical solid line in each panel indicates the upwind direction each sonic anemometer points to and the vertical dash-dot line indicates the corresponding opposite direction. Elevation slope angles (reduced by a factor of 3) at 200 m radius from the MMSF main flux tower are given by stars in the lowest two panels.

tower is located on top of a ridge with the two sonic anemometers pointing to a direction ($\alpha = 232^{\circ}$) approximately perpendicular to the ridge axis (Schmid et al., 2000; Froelich et al., 2005). This may be seen as both the elevation slope angle and the moving-bin averaged ϕ have maximum values in this direction (Fig. 2). The planar fit and the sinusoidal fit may still be applicable to the upwind directions at MMSF if the streamline at the measurement height over this (upwind) side of the ridge is approximately a plane. It should be pointed out that the elevation slope angles (stars in Fig. 2) are derived at 200 m radius from the tower (10 and 25 times of the vertical distances from the canopy top to the higher and lower measurement heights, respectively, Finnigan, 2004), based on the topographic map (USGS Hindustan quadrangle 1:24,000 NAD27) and digital elevation model (Froelich et al., 2005). These elevation slope angles follow a similar pattern as a function of the azimuth (α) as the moving-bin averaged ϕ (Fig. 2). However, elevation slope angles derived at smaller (50 m) or greater (>300 m) radius from the tower do not show the same pattern.

An upflow ($\phi_d > 0$) is found only for the top level sonic anemometer at UMBS whereas downflows ($\phi_d < 0$) are shown for the other three sonic anemometers (Table 3), even though the MMSF tower is located on top of a ridge. The values of $\phi_d = 1.3^{\circ}$ ($UMBS_{48.4}$) and -1.4° ($MMSF_{34}$) are equivalent to mean vertical velocities of 9 and -7 cm s^{-1} based on the long-term averaged hourly mean horizontal velocities of 4 or 3 m s^{-1} measured by the two sonic anemometers. These are much greater than the offsets ($b_0 = 1.0$ cm s^{-1} for $UMBS_{48.4}$ and -1.1 cm s^{-1} for $MMSF_{34}$). In addition, the upflow angle is

Table 3 – The offset (b_0) in measured vertical velocity is determined from the planar fit method

Sonic anemometer	Time period of measurements	Azimuth each sonic anemometer points to	Offset in vertical velocity b_0 (cm s^{-1})	ϕ_t	α_0	ϕ_d
UMBS, 48.4 m	Days 130–365, 2001	300°	1.0	1.3°	209.2°	1.3°
UMBS, 46 m	Days 1–128, 2001, Days 175–366, 2000	240°	1.6	1.2°	188.7°	0.3°
UMBS, 46 m	Days 1–173, 2000, Days 79–365, 1999	299°	0.6	0.7°	196.7°	0.8°
UMBS, 34 m	2001	299°	−1.1	1.3°	154.8°	−0.3°
MMSF, 46 m	2001	232°	−2.9	3.1°	147.3°	−0.2°
MMSF, 34 m	2001	232°	−1.1	3.9°	138.7°	−1.4°

The moving-bin-averaged second rotation angle ϕ with the offset removed (open circles in Fig. 2) is fit as a function of the azimuth α: $\phi(\alpha) = \phi_t \sin(\alpha - \alpha_0) + \phi_d$, where ϕ_t is the tilt angle between sonic anemometer's x–y plane and local mean streamline plane, α_0 is the azimuth along which these two planes intersect, ϕ_d is the upflow/downflow angle. The confidence level is 0.95.

greater ($\phi_d = 1.3°$) for the top level sonic anemometer at UMBS when it is elevated to 48.4 m but placed closer (directly over) to the tower than when it was at 46 m but further (1.8 m) away from the tower ($\phi_d = 0.3°$–$0.8°$).

However, whether a preferred direction of mean vertical motion exists at these two sites and if so, what their potential effects are on the offset and upflow/downflow estimated here, are currently unknown. This is because the long-term averaged coordinate system assumes the long-term averaged mean vertical velocity is zero (Lee, 1998; Lee et al., 2004).

A more serious type of flow distortion is the shadow effect in the downwind directions (Fig. 1) as measured mean wind

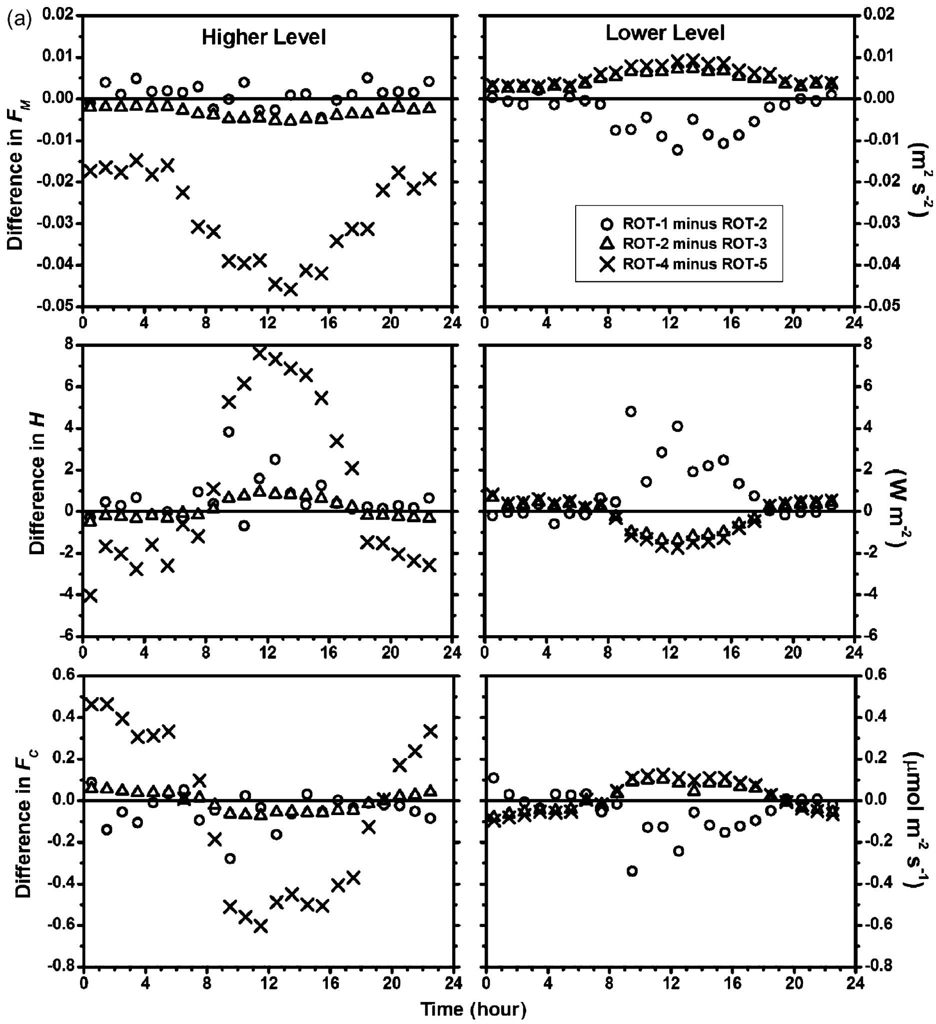

Fig. 3 – (a) Ensemble averaged diurnal pattern of differences in hourly vertical eddy-covariance fluxes of momentum (F_M), sensible heat (*H*) and CO_2 (F_c) among different coordinate rotation methods in the upwind directions during the growing season (days 131–281) at UMBS in 2001. The higher level is at 48.4 m and the lower level is at 34 m. The number of hourly fluxes is 909. (b) Similar to subpart (a) except at MMSF (days 114–292) in 2001. The higher level is at 46 m and the lower level is at 34 m. The number of hourly fluxes is 891.

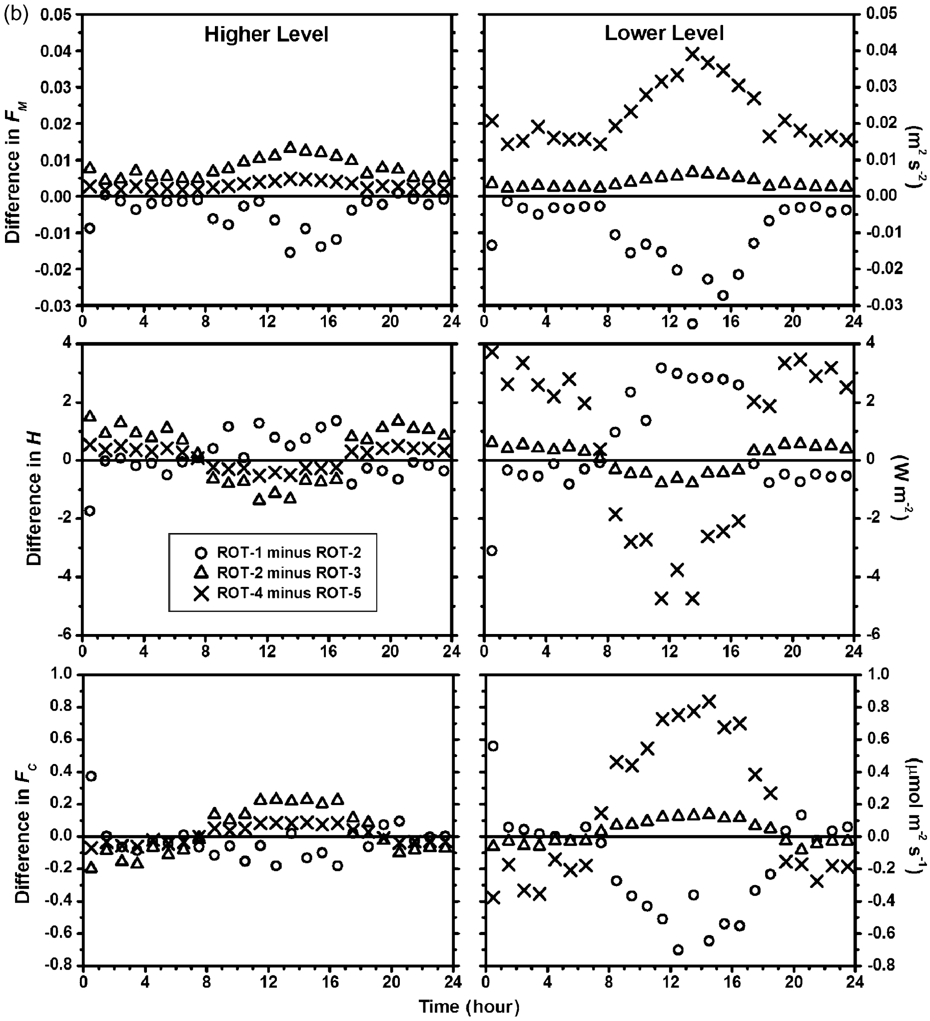

Fig. 3. (Continued).

speed, turbulent velocity and friction velocity are all greatly reduced (Su et al., 2000). It is shown as a sharp dip in the moving-bin averaged ϕ (Fig. 2). For $UMBS_{46,34}$, this dip is about 1–1.5° for α = 120–180° when both sonic anemometers point to 299°. It moves to α = 0–60° when the 46 m sonic anemometer points to 240° and the tower is on the opposite site of the sonic anemometer and supporting boom (Fig. 1). Both $MMSF_{46,34}$ sonic anemometers point to 232°, the relative position between the tower body and the sonic anemometers and supporting booms are similar to that for $UMBS_{46}$ sonic anemometer when it points to 240° (Fig. 1) and the dip (also about 1–1.5°) appears in a similar azimuth range of α = 0–52°. However, such a sharp dip is much reduced when the top level sonic anemometer at UMBS was raised to 48.4 m which is 2.4 m directly above the top of the tower, and the moving-bin averaged ϕ is much closer to a sinusoidal function of α (Fig. 2). Again, this may be due to relatively uniform elevations surrounding the UMBS flux tower. The top level sonic anemometer at MMSF had not been raised above the tower as was done at UMBS for the measurement periods used in this study.

In ROT-4, the second rotation angle is defined by the sinusoidal function $\phi(\alpha) = \phi_t \sin(\alpha - \alpha_0) + \phi_d$. Obviously, there is little difference between ROT-3 and ROT-4 in the upwind directions. This is not the case in the downwind and crosswind directions due to the tower shadow effects and the ridge/ravine topography at the MMSF sites.

In ROT-5, the second rotation angle is defined by $\phi(\alpha) = \phi_t \sin(\alpha - \alpha_0)$, which only corrects for the tilt but not the upflow/downflow. Thus, the difference between ROT-5 and ROT-4 may be used to compare the effects of tilt and upflow/downflow on fluxes in the upwind directions.

Finally, for the assessment of the differences among these five coordinate rotation methods, we use 1 h averaging time period and 10 Hz eddy-covariance data.

2.4. *Averaging time period and sampling frequency*

Determing an appropriate averaging time period is a classical issue in data analysis of atmospheric turbulence (Lumley and Panofsky, 1964; Wyngaard, 1973; Kaimal and Finnigan, 1994). Sakai et al. (2001) reported that flux contribution in lower frequencies is important in convective conditions. Finnigan et al. (2003) showed that an averaging time period up to 4 h is needed at some sites. Here we calculate fluxes with block averaging time periods of 5 min, 15 min, 30 min, 1 h, 2 h and

3 h using 10 Hz raw data. For an averaging time period less than 1 h, hourly 10 Hz data are evenly divided into non-overlap blocks with a length of the shorter averaging time period, and fluxes from all blocks are aggregated to an hourly value. Finnigan et al. (2003) showed that the difference between flux calculated using a shorter averaging time period (e.g., 5 min) and that using 1 h averaging time period is just the ensemble average of the (12) products of mean vertical velocity and mean scalar concentration calculated for each (5 min) block averaging time period. A moving window of 2 or 3 h width centered at each hour is used to calculate fluxes for comparison at that hour. The effect of sampling frequency is examined by a simple non-overlap block-average of 10 Hz raw data into 1 Hz with an averaging time of 1 h.

An alternative to find an appropriate averaging time period is to examine at what natural frequency the ogives reach an asymptote (Moncrief et al., 2004). The ogives are essentially integrations of the co-spectra, which are discussed next.

Finally, both ROT-3 and ROT-5 are used in assessing the effects of averaging time period and sampling frequency.

2.5. *Co-spectral correction*

The co-spectral corrections presented in Su et al. (2004) are only for the higher measurement levels in June–August at the UMBS and MMSF sites. In this study, we extend the co-spectral corrections of CO_2 fluxes to both measurement heights during the entire growing season in 2001 at both sites. Details of the co-spectral models, forms of transfer functions, and correction methods can be found in Su et al. (2004). The characteristic time constant for tube attenuation of CO_2 for each of the four eddy-covariance systems are derived for each month. Hourly data with co-spectral corrections over 50% of uncorrected fluxes are discarded as the measurements are deemed unreliable. Su et al. (2004) only used data in the upwind directions in deriving the co-spectral models with a 1 h averaging time period. Thus, in this study, we apply co-spectral corrections only to measurements from the upwind directions with 1 h averaging time of 10 Hz data. Both ROT-3 and ROT-5 are used in calculating the co-spectra and ogives.

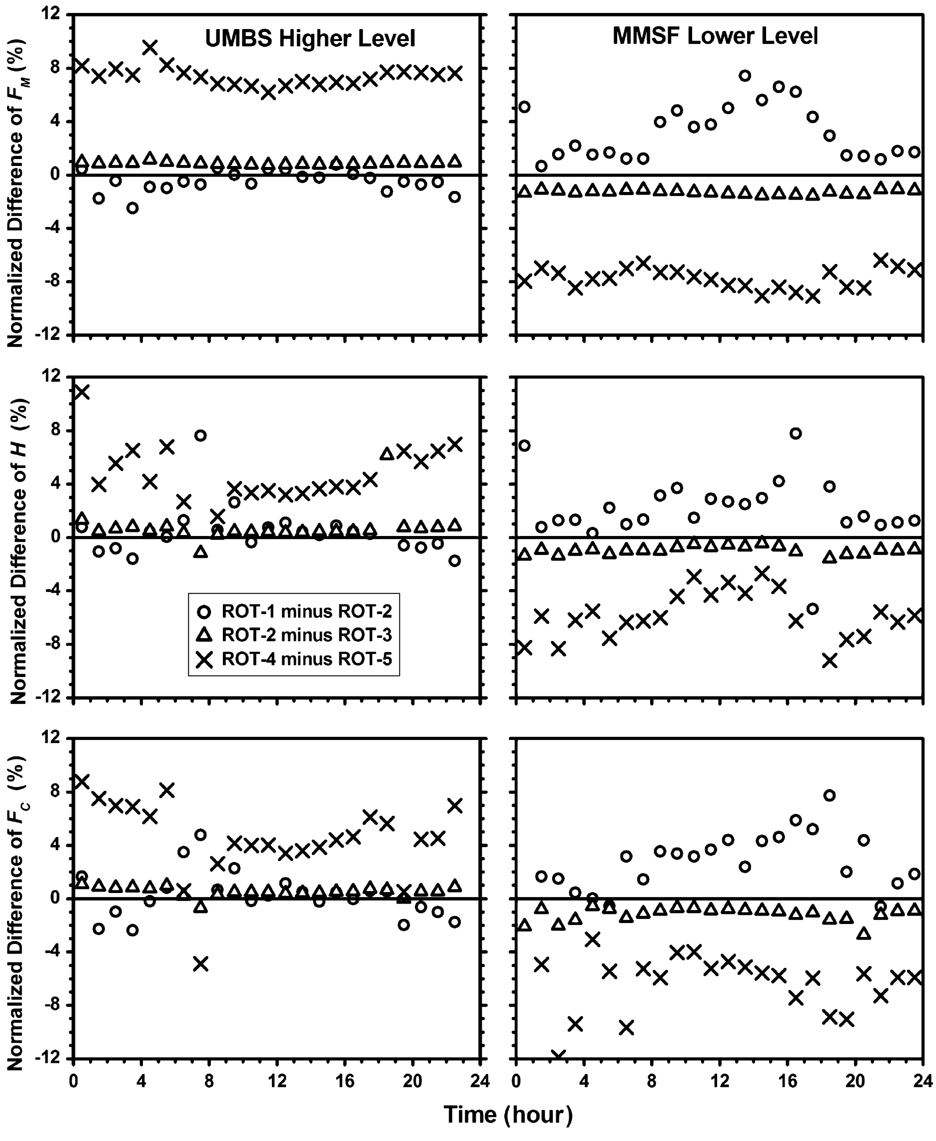

Fig. 4 – Flux differences among various rotation methods are normalized by fluxes calculated with ROT-3.

3. Results and discussions

3.1. Coordinate rotation

Obviously from Fig. 2, percentages of flux differences among ROT-2, ROT-3, ROT-4 and ROT-5 for each of the four eddy-covariance systems vary with wind directions. Here we focus our discussions on measurements in the upwind directions for several reasons. First, currently we do not have a well established method to properly correct the tower shadow effects on turbulent statistics in the downwind directions. As discussed earlier, these effects vary among the four eddy-covariance systems. Second, both the planar fit and the sinusoidal fit are applied only to measurements in the upwind directions. Third, co-spectral models are derived from measurements in the upwind directions. Finally, the upwind directions are the prevailing wind directions at both sites.

As described earlier (Fig. 1), the upwind directions are defined as ±60° from the direction each sonic anemometer points into (from 240° clockwise to 360° for $UMBS_{48.4}$, from 239° clockwise to 359° for $UMBS_{34}$, from 172° clockwise to 292° for $MMSF_{34,46}$). It should be pointed out that the long-term averaged differences in horizontal wind directions between the two measurement heights are small (1–2°) in the upwind directions at both sites. For the sake of brevity, we only present results from the growing season.

Differences between fluxes calculated with ROT-1 and ROT-2 are not consistent or systematic among the four eddy-covariance systems. At UMBS, ROT-1 under-estimates fluxes (relative to fluxes calculated with ROT-2) at the higher level at night, but over-estimates are shown at the lower level throughout the day (Fig. 3a). Whereas at MMSF, over-estimates are generally shown at both measurement heights during the daytime, and the over-estimates are greater at the lower level (Fig. 3b). This inconsistency may be an indication of the random or unpredictable nature of ROT-1, and that the natural wind coordinate system is not a good choice for a systematic evaluation of the vertical flux divergence.

On the other hand, flux differences between ROT-2 and ROT-3 (due to the offset b_0) and flux differences between ROT-4

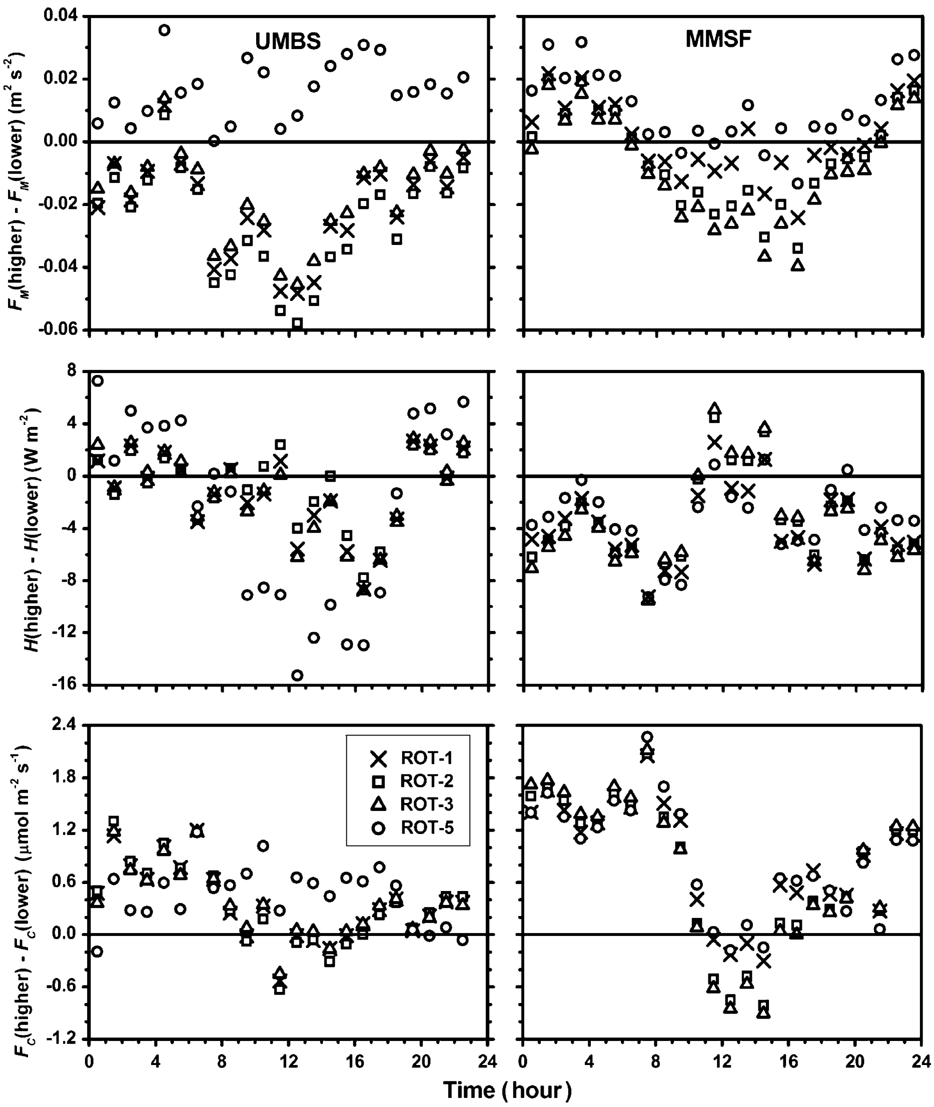

Fig. 5 – Ensemble averaged diurnal patterns of vertical differences (higher level minus lower level) of F_M, H and F_C, among four coordinate rotation methods in the upwind directions during the growing season in 2001.

and ROT-5 (due to the upflow/downflow ϕ_d) are systematic among the four eddy-covaraince systems. Positive ($UMBS_{48.4}$) and negative ($UMBS_{34}$ and $MMSF_{34,46}$) offsets (included in ROT-2) lead to over- and under-estimates of fluxes, respectively, relative to fluxes calculated with ROT-3 (offset removed from ϕ). On the other hand, the upflow ($UMBS_{48.4}$) and downflow ($UMBS_{34}$ and $MMSF_{34,46}$) which are not corrected in ROT-5 (only the tilt is corrected), lead to under- and over-estimates of fluxes, respectively, relative to fluxes calculated with ROT-4 (which corrects both tilt and upflow/downflow). It is well-known that momentum flux is more sensitive to flow distortion (Dyer, 1981) and tilt (Lee et al., 2004) than scalar fluxes. An offset (b_0) of 1 cm s^{-1} and an upflow or downflow angle (ϕ_d) of 1° lead to approximately 1% and 5.6% differences in momentum flux (F_M) throughout the day, respectively, but only half in sensible heat flux (H) and CO_2 flux (F_C) in the daytime (Fig. 4). However, the relative differences in H and F_C at night can be as large as those in F_M.

As expected, flux differences between ROT-3 and ROT-4 are negligible for each of the four eddy-covaraince systems since the second rotation angle used in ROT-4 is simply the sinusoidal fit of the moving-bin averaged ϕ (with the offset removed) used in ROT-3 in the upwind directions. Thus, we may consider that ROT-3 and ROT-4 are equivalent in the upwind directions, and only present results from ROT-3 in the rest of discussions.

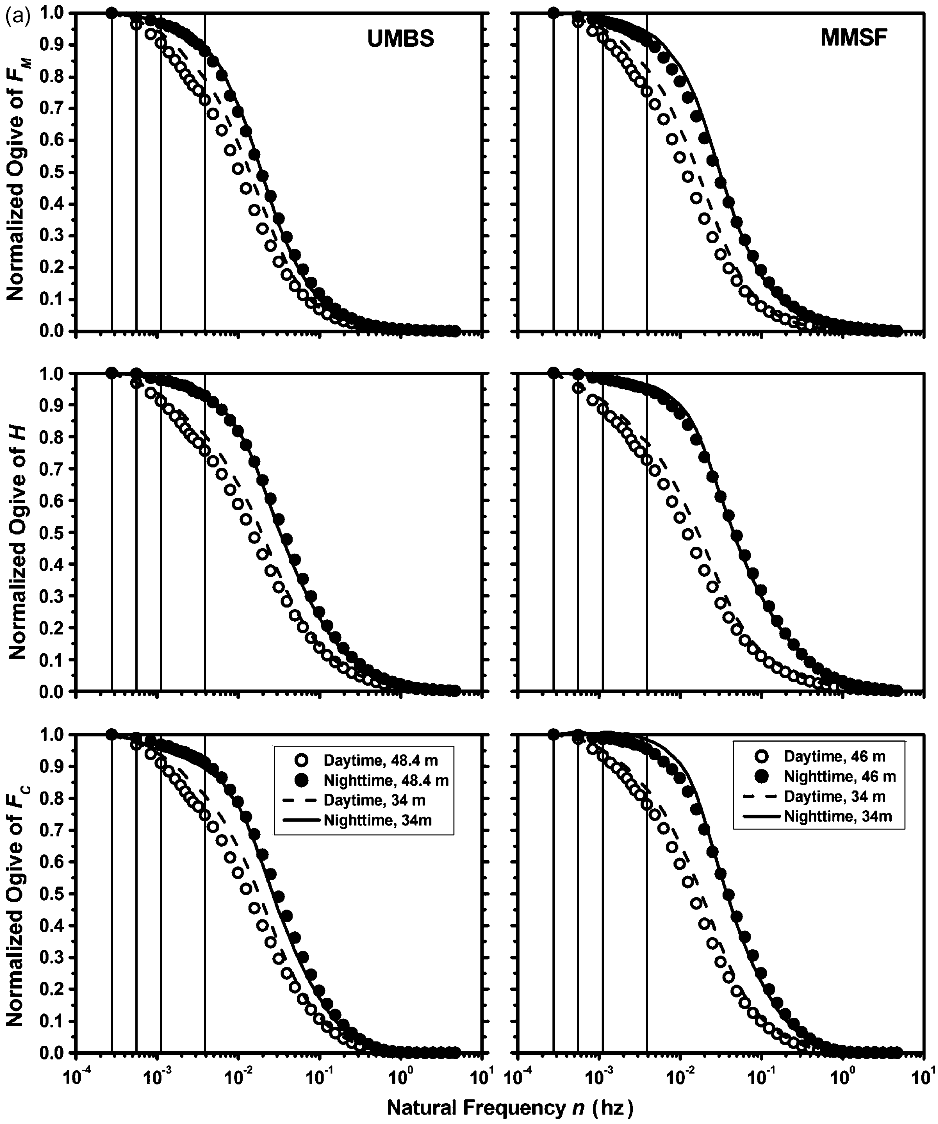

Fig. 6 – (a) Ensemble averages of normalized ogives for momentum, sensible heat and CO_2 in the upwind directions during the growing season in 2001. The four thin vertical lines in each panel, from left to right, correspond to time periods of 60, 30, 15 and 5 min, respectively. ROT-3 and 1 h averaging time are used with hourly records of 10 Hz raw data. The numbers of ogives are 381 (daytime, 10:00–16:00 LST) and 133 (nighttime, 22:00–04:00 LST) at UMBS, and 356 (daytime) and 203 (nighttime) at MMSF. (b) Effects of averaging time period and sampling frequency on ensemble averages of vertical fluxes of momentum, sensible heat and CO_2 normalized by fluxes calculated with 1 h averaging time period in the upwind directions during the growing season in 2001. ROT-3 is used with hourly records of 10 Hz data. The numbers of hourly fluxes are 355 (daytime) and 85 (nighttime) at UMBS, and 321 (daytime) and 188 (nighttime) at MMSF.

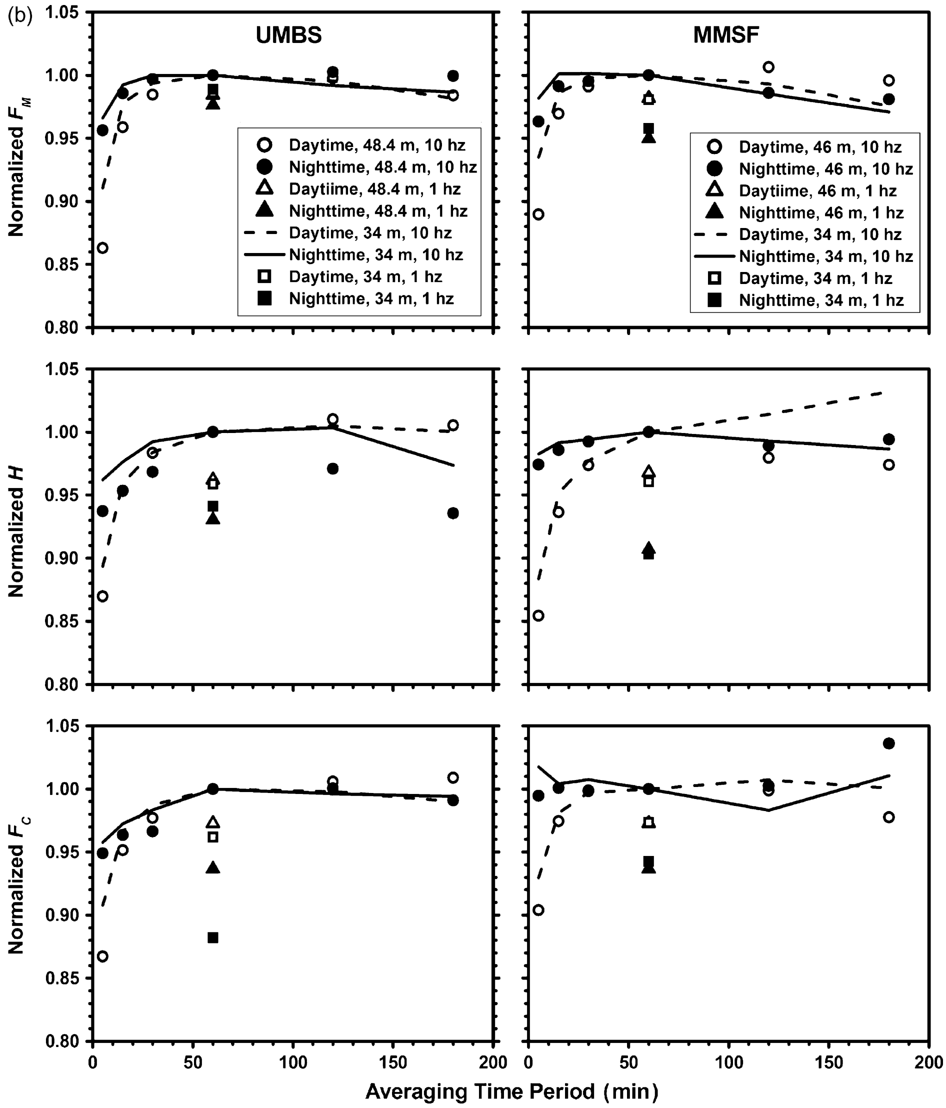

Fig. 6. (Continued).

The magnitude and even the sign of vertical flux difference (higher level minus lower level) vary among the four rotation methods (Fig. 5). This may be expected since flux differences among the four rotation methods differ between eddy-covariance systems at the two measurement heights of both sites. For example, at UMBS, the positive and negative offsets (b_0) in ROT-2 over- and under-estimate fluxes at the higher and lower levels, respectively, relative to fluxes calculated with ROT-3 (Fig. 3a). In addition, during the growing season, it is typical although not shown here for the sake of brevity, all four eddy-covariance systems observed that the ensemble averaged diurnal patterns of hourly momentum fluxes are negative throughout the day, sensible heat and CO_2 fluxes are positive and negative during the daytime, respectively, but reverse sign at night. Therefore, the opposite effects of the offsets at the two measurement levels at UMBS introduce a negative bias in the vertical differences of momentum fluxes calculated using ROT-2 compared to those using ROT-3 throughout the day (Fig. 5). This negative bias is also shown in the vertical differences of sensible heat fluxes at night and CO_2 fluxes in the daytime, whereas a positive bias is shown in the vertical differences of daytime sensible heat fluxes and nighttime CO_2 fluxes. At MMSF, the offsets (b_0) are negative at both measurement heights but much greater at the higher level (Table 3), which leads to greater under-estimates of fluxes at the higher level (Fig. 3b). Consequently, there is a positive bias in the vertical differences of momentum fluxes calculated with ROT-2 compared to those calculated with ROT-3 (Fig. 5). This positive bias is also shown in the vertical differences of nighttime sensible heat fluxes and daytime CO_2 fluxes, whereas a negative bias is shown in the vertical differences of daytime sensible heat fluxes and nighttime CO_2 fluxes.

Similarly, the under- and over-estimates of fluxes using ROT-5 (only corrects tilt but not upflow/downflow) compared to fluxes calculated with ROT-3 (equivalent to ROT-4 in the upwind directions which corrects both tilt and upflow/downflow), differ between eddy-covariance systems at the two measurement heights of both sites and thus have different effects on vertical flux differences. At UMBS, the opposite sign of ϕ_d between the two measurement levels leads to a positive bias in the vertical differences of momentum fluxes calculated using ROT-5 compared to those using ROT-3 throughout the day (Fig. 5). This positive bias is also shown in the vertical differences of nighttime sensible heat fluxes and daytime CO_2 fluxes, whereas a negative bias is shown in the vertical differences of daytime sensible heat fluxes and nighttime CO_2 fluxes. At MMSF, ϕ_d is negative at both measurement heights but much greater at the lower level (Table 3), which leads to greater over-estimates of fluxes using ROT-5 relative to ROT-3 at the lower level (Fig. 3b). Therefore, there is also a positive bias in the vertical differences of momentum fluxes calculated with ROT-5 compared to those calculated with ROT-3 (Fig. 5). This positive bias is shown in the vertical differences of nighttime sensible heat fluxes and daytime CO_2 fluxes, whereas a negative bias is shown in the vertical differences of daytime sensible heat fluxes and nighttime CO_2 fluxes.

As expected, the bias in vertical flux differences due to differences of upflow/downflow angles between the eddy-covaraince systems at two heights, has a greater magnitude than the bias in vertical flux differences due to the differences of offsets between the eddy-covaraince systems at two heights (Fig. 5).

With regard to our main objective on the vertical differences of CO_2 fluxes, it is clear (Fig. 5) that integrating over the diurnal course, all four rotation methods yielded positive vertical differences of ensemble averaged CO_2 fluxes at both sites.

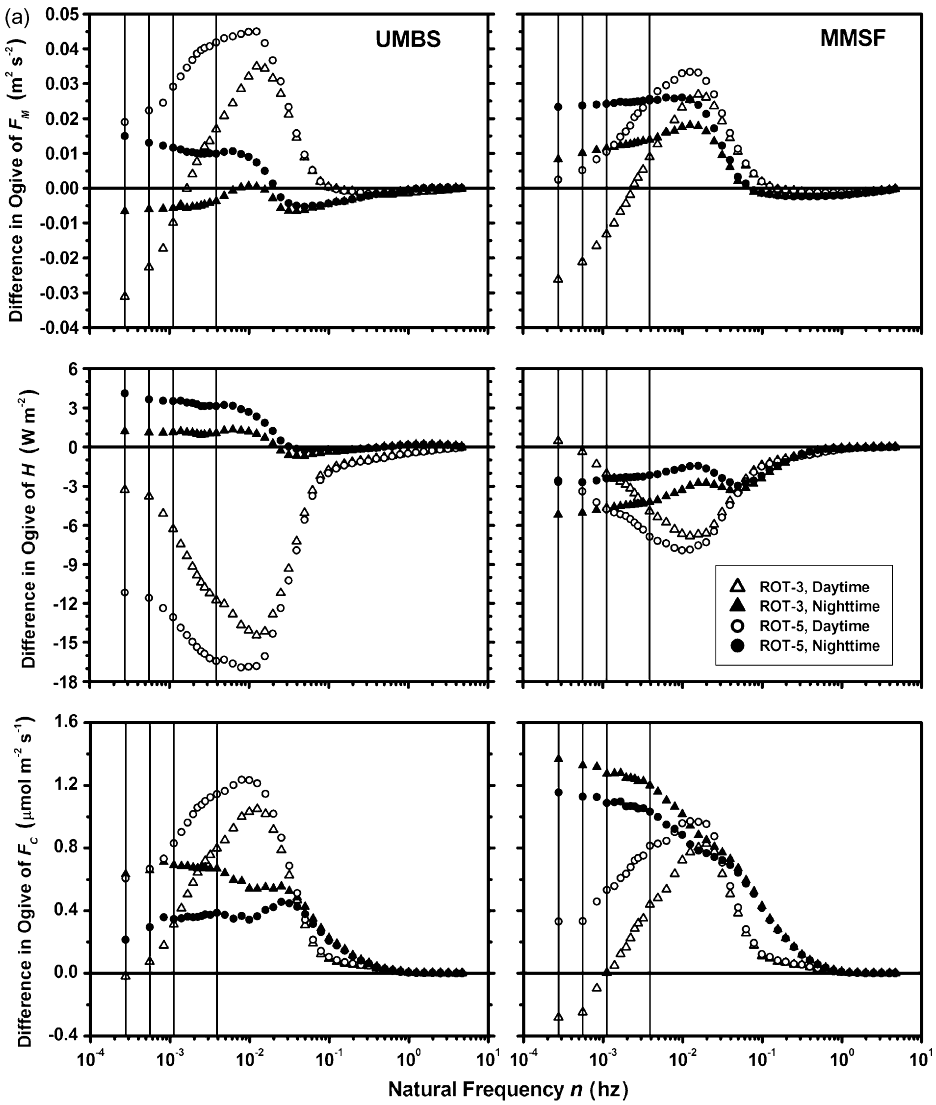

Fig. 7 – (a) Vertical differences (higher level minus lower level) in ensemble averaged ogives of momentum, sensible heat and CO_2 in the upwind directions during the growing season in 2001. The four vertical lines are the same as in Fig. 6a, so are the numbers of ogives. (b) Effects of averaging time period and sampling frequency on ensemble averages of vertical differences (higher level minus lower level) of momentum, sensible heat and CO_2 fluxes in the upwind directions during the growing season in 2001. The numbers of hourly fluxes are the same as in Fig. 6b. (c) Vertical differences (higher level minus lower level) in ensemble averages of $nCo_{F_M}(n)$, $nCo_H(n)$ and $nCo_{F_C}(n)$ in the upwind directions during the growing season in 2001. The vertical line corresponds to a time period of 5 min. The numbers of co-spectra are the same as those of the ogives in Fig. 6a and subpart (a) of the figure.

3.2. *Averaging time period and sampling frequency*

As expected, the effects of different averaging time period and sampling frequency on measured eddy-covariance fluxes differ between daytime and nighttime. Measurements from all four eddy-covaraince systems show that the normalized ogives increase with decreasing natural frequency (n) much faster at night than in the daytime (Fig. 6a). This increase is also generally faster at the lower measurement levels of both sites, particularly in the daytime. Most of these features are also shown as relatively greater percentages of flux underestimates using shorter (than 1 h) block averaging time periods in the daytime and at the higher measurement level (Fig. 6b). It is noted that the normalized fluxes (Fig. 6b) for a given short block averaging time period (e.g., 5 min) are greater than the normalized ogives at corresponding natural frequency (Fig. 6a). It should be pointed out that for each hourly sample of 10 Hz data, the integration of co-spectra over all frequencies is equal to eddy-covariance directly calculated using 1 h block-averaging, which are used to normalize the ogive (Fig. 6a) and flux (Fig. 6b), respectively. However, the eddy-covaraince calculated using a given short block averaging time period (e.g., 5 min) is not identical as the ogive at corresponding natural frequency. First, the Fourier transform used to calculate the co-spectrum decomposes the time series of 10 Hz data into a set of sine and cosine functions, and the co-spectrum at a given frequency is determined from the coefficients of these functions at the same frequency. But the sine and cosine functions do not represent the characteristics of turbulent time series observed in the roughness sublayer over forest canopies very well. For example, ramp signatures are often observed in time series of temperature and other scalar concentrations (Gao et al., 1989). Second, the co-spectrum (and thus ogive) at a given frequency may be influenced by many factors (leakage, red, white and blue noises, etc.) as discussed in Stull (1988). Third, turbulent fluctuations are defined as departures from block-averages over the short (e.g., 5 min) time period but as departures from the 1 h averages in calculating the co-spectra and ogives.

Nevertheless, both the ogive plots (Fig. 6a) and the eddy-covaraince fluxes calculated using block-averaging (Fig. 6b)

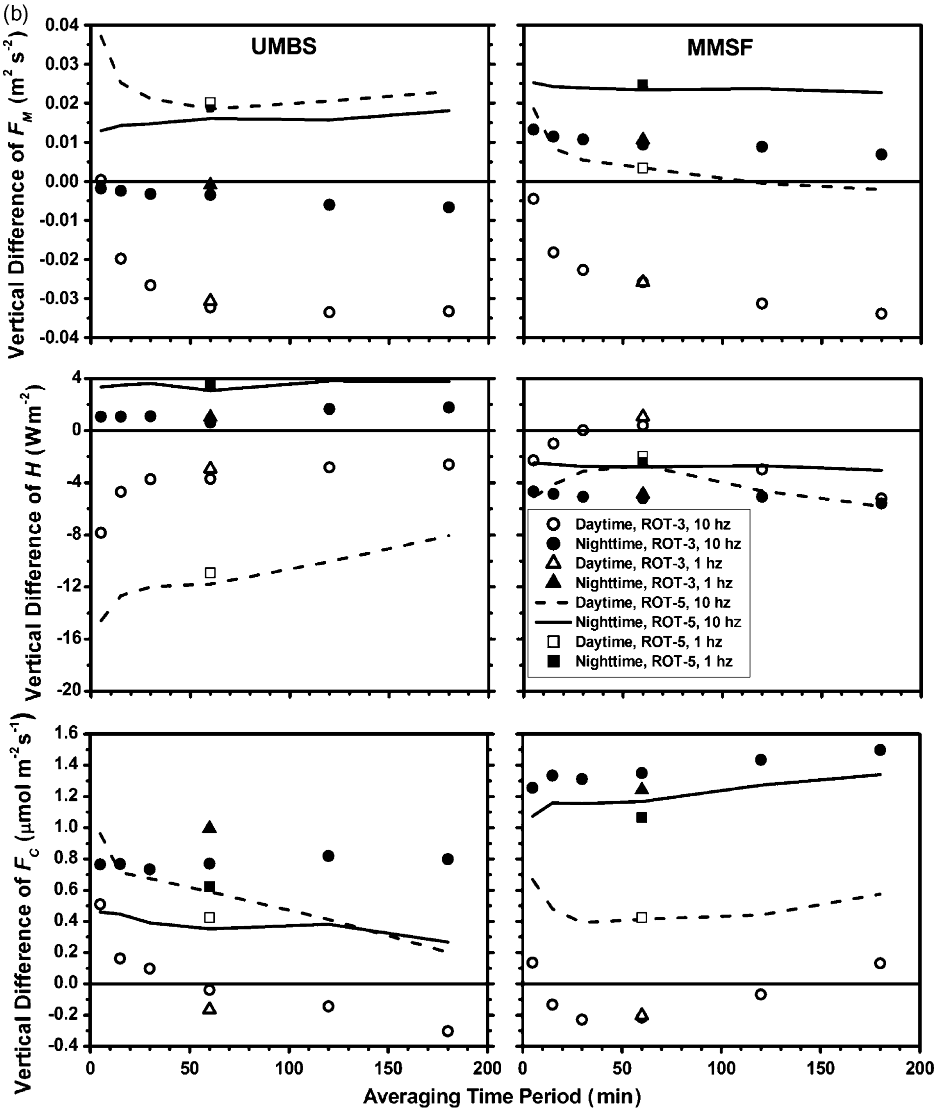

Fig. 7. (Continued)

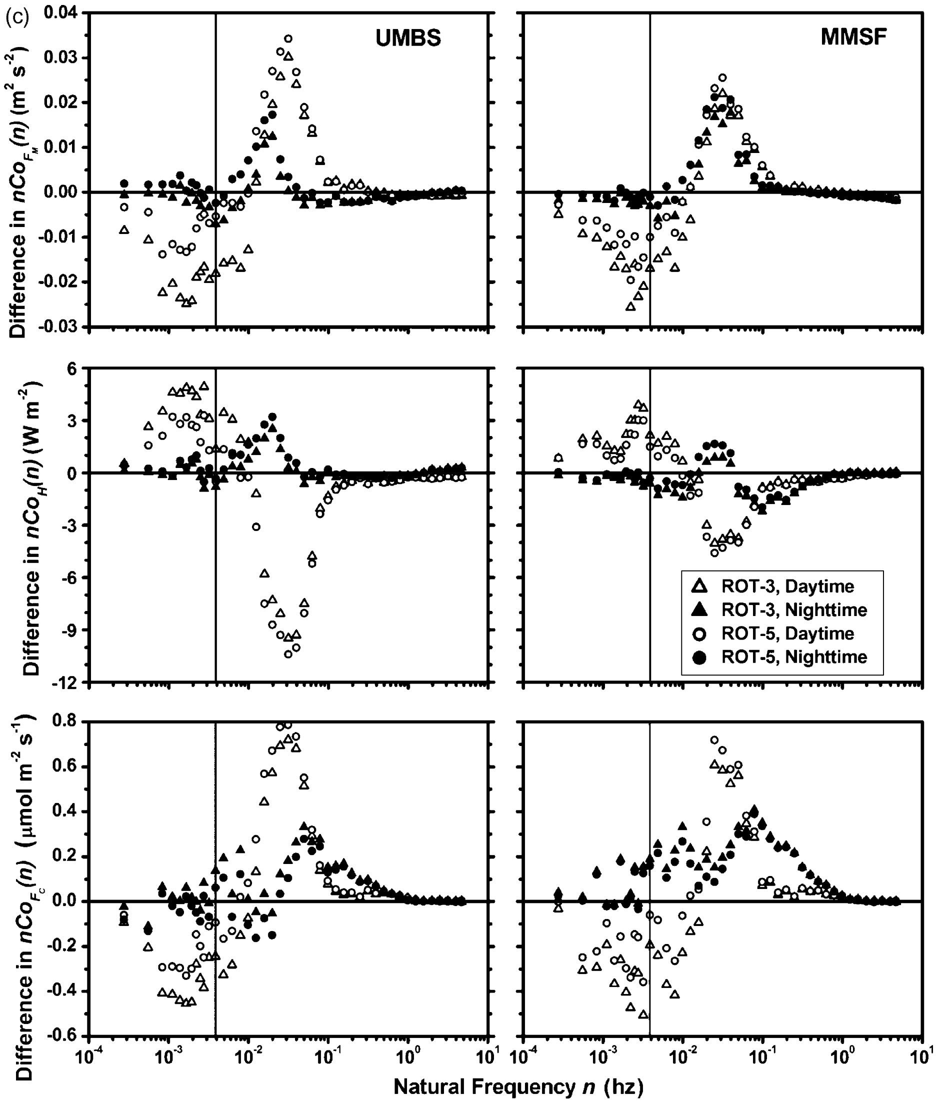

Fig. 7. (Continued).

illustrate that a 30 min averaging time period captures 95% or more of fluxes calculated with a 1 h averaging time period both in the daytime and at night and at both measurement heights of UMBS and MMSF. Especially at MMSF, ensemble averaged CO_2 fluxes at night calculated with a 5 min averaging time period are only 0.6% (or 0.026 μmol m^{-2} s^{-1}) less and even 1.7% (or 0.061 μmol m^{-2} s^{-1}) greater than those calculated with a 1 h averaging time period at the higher and lower levels, respectively.

Longer (than 1 h) averaging time periods do not always lead to increases in ensemble averaged fluxes during the daytime (Fig. 6b). At UMBS, the increases in sensible heat and CO_2 fluxes at the higher level are insignificant (<1%). At the lower level, there are essentially no changes in sensible heat fluxes and very small (<1%) decreases in CO_2 fluxes. At MMSF, there are up to 2–3% decreases in sensible heat and CO_2 fluxes at the higher level. And at the lower level, there are essentially no changes in CO_2 fluxes and up to 3% increases in sensible heat fluxes. Even though longer (than 1 h) averaging time periods are usually not used in calculating nighttime fluxes, it is shown (Fig. 6b) that they generally lead to decreases in fluxes, except for CO_2 fluxes at MMSF (1% and 3.6% increases at the lower and higher levels, respectively). These results indicate that a 1 h averaging time period is appropriate for both the UMBS and the MMSF sites.

Also as expected, higher (than 1 Hz) frequencies have relatively greater flux contributions at night than in the daytime (Fig. 6b). These contributions are also greater for sensible heat and CO_2 fluxes than for momentum flux.

For the same rotation method (ROT-3 or ROT-5), the magnitude and sign of the vertical differences of ogives (Fig. 7a) or eddy-covaraince fluxes calculated with block-averaging (Fig. 7b) vary with the natural frequency or averaging time period. This variation is generally greater in the daytime than at night.

In addition, the negative or positive bias in vertical flux differences calculated with ROT-3 compared to ROT-5 using a 1 h averaging time period (discussed in Section 3.1) generally decreases with increasingly shorter (than 1 h) averaging time period (Fig. 7b). This is also shown as the same bias in vertical differences of ogives decreases with increasing natural frequency (Fig. 7a). However, this negative or positive bias in vertical flux differences changes little when longer (than 1 h) averaging time periods are used (Fig. 7b).

By plotting vertical differences (higher level minus lower level) of $n\mathrm{Co}_{xy}(n)$ in linear scale and n in logarithmic scale (n is the natural frequency in Hz, and $\mathrm{Co}_{xy}(n)$ is the co-spectral density between x and y in an unit of the covariance per unit frequency), the area under or above the curve of the vertical differences of $n\mathrm{Co}_{xy}(n)$ is proportional to the vertical flux difference.

In the daytime, the absolute magnitudes of ensemble averaged $n\mathrm{Co}_{F_M}(n)$, $n\mathrm{Co}_H(n)$ and $n\mathrm{Co}_{F_C}(n)$ for n = 0.02–0.1 Hz are all smaller (i.e., less negative $n\mathrm{Co}_{F_M}(n)$ and $n\mathrm{Co}_{F_C}(n)$ but less positive $n\mathrm{Co}_H(n)$) at the higher measurement level at both sites. However, the opposite is true for $n < 0.01$ Hz. Thus, air motions in these two frequency ranges counteract each other in determining the vertical flux differences. These features are shown whether ROT-3 or ROT-5 is used, except that ROT-3 leads to smaller vertical decreases but greater vertical increases in the absolute values of $n\mathrm{Co}_{F_M}(n)$, $n\mathrm{Co}_H(n)$ and $n\mathrm{Co}_{F_C}(n)$ in the two frequency ranges of n = 0.02–0.1 Hz and $n < 0.01$ Hz, respectively. Consequently, the absolute magnitudes of the vertical differences of ogives increase from 0.1 to 0.02 Hz, reach peak values at a frequency between 0.02 and 0.01 Hz, and then decrease for $n < 0.01$ Hz (Fig. 7a). The increase is slower and the decrease is faster using ROT-3 than ROT-5.

At night, the positive vertical differences of $n\mathrm{Co}_{F_M}(n)$ in n = 0.02–0.1 Hz at MMSF have similar magnitude as those in the daytime, which are the most dominant contributors to the vertical differences of momentum fluxes. At UMBS, the positive vertical differences of $n\mathrm{Co}_{F_M}(n)$ are in a narrower frequency range (n = 0.01–0.03 Hz) with smaller magnitudes than those in the daytime. The vertical differences of $n\mathrm{Co}_{F_M}(n)$ in n = 0.04–0.4 Hz and $n < 0.01$ Hz are also important in

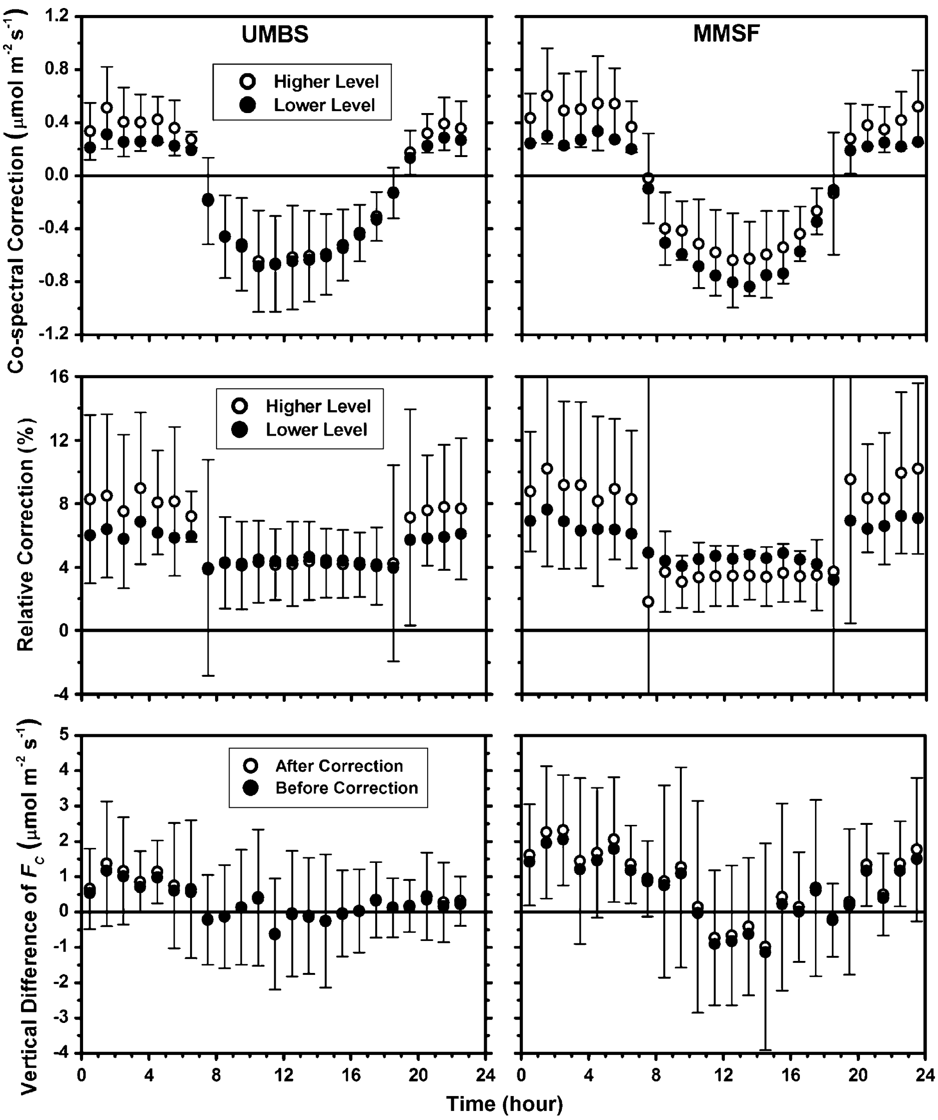

Fig. 8 – Ensemble averaged diurnal pattern of co-spectral corrections of F_C calculated with 1 h averaging time period in the upwind directions during the growing season in 2001. ROT-3 is used with hourly records of 10 Hz data. The numbers of hourly F_C are 652 at UMBS and 542 at MMSF.

determining the magnitude and sign of vertical differences of momentum fluxes. Similarly, the vertical differences of $nCo_H(n)$ in $n = 0.01 - 0.03$ Hz are most significant in determining the vertical differences of sensible heat fluxes at UMBS. But at MMSF, the vertical differences of $nCo_H(n)$ have similar magnitudes but different signs in three frequency ranges ($n < 0.02$ Hz, $n = 0.02 - 0.04$ Hz, $n = 0.04$–0.4 Hz) and make comparable contributions to vertical differences of sensible heat fluxes. At both UMBS and MMSF, $nCo_{F_C}(n)$ are significantly more positive at the higher level in $n = 0.03$–0.4 Hz. These vertical increases are also shown at most frequencies lower than 0.03 Hz, except when ROT-5 is used at UMBS. Thus, nighttime fluxes and ogives of CO_2 are more positive at the higher measurement levels of both sites, and ROT-3 yielded greater vertical increases than ROT-5 (Figs. 5 and 7a and b).

Finally, vertical differences of ensemble averaged $nCo_{F_M}(n)$, $nCo_H(n)$ and $nCo_{F_C}(n)$ are all very small at the two sites for $n > 1$ Hz both in the daytime and at night (Fig. 7a and c). But 1–10 Hz frequencies appears to have relatively more significant contributions to eddy-covariance fluxes calculated with a 1 h block averaging time period (Fig. 7b). As discussed earlier, this could be in part due to the differences between co-spectra calculated using the Fourier transform and covariances calculated using block-averaging.

3.3. *Co-spectral correction*

During the growing season, on average, co-spectral corrections of CO_2 fluxes are smaller by 0.1–0.2 μmol m^{-2} s^{-1} at night but greater by -0.03 to -0.3 μmol m^{-2} s^{-1} in the daytime at the lower measurement levels of both sites (Fig. 8). The relative corrections at the same measurement height are 3–4% during the daytime and 6–10% at night. These results are similar between ROT-3 and ROT-5, although only results using ROT-3 are shown for the sake of brevity.

The differences in co-spectral corrections at the two measurement levels generally lead to a positive shift in the vertical differences of CO_2 fluxes throughout the day at both sites (lowest two panels in Fig. 8). Therefore, the co-spectral corrections enhance the positive vertical differences of daily cumulative CO_2 fluxes.

3.4. *1D CO_2 budget in the air layer between two measurement heights*

Since there are no sources or sinks of CO_2 in the air layer between the two measurement heights above the forests, we may define an imbalance as the negative of the sum of the storage flux in this layer and the vertical difference (high level minus lower level) of eddy-covaraince fluxes (Fig. 9). In

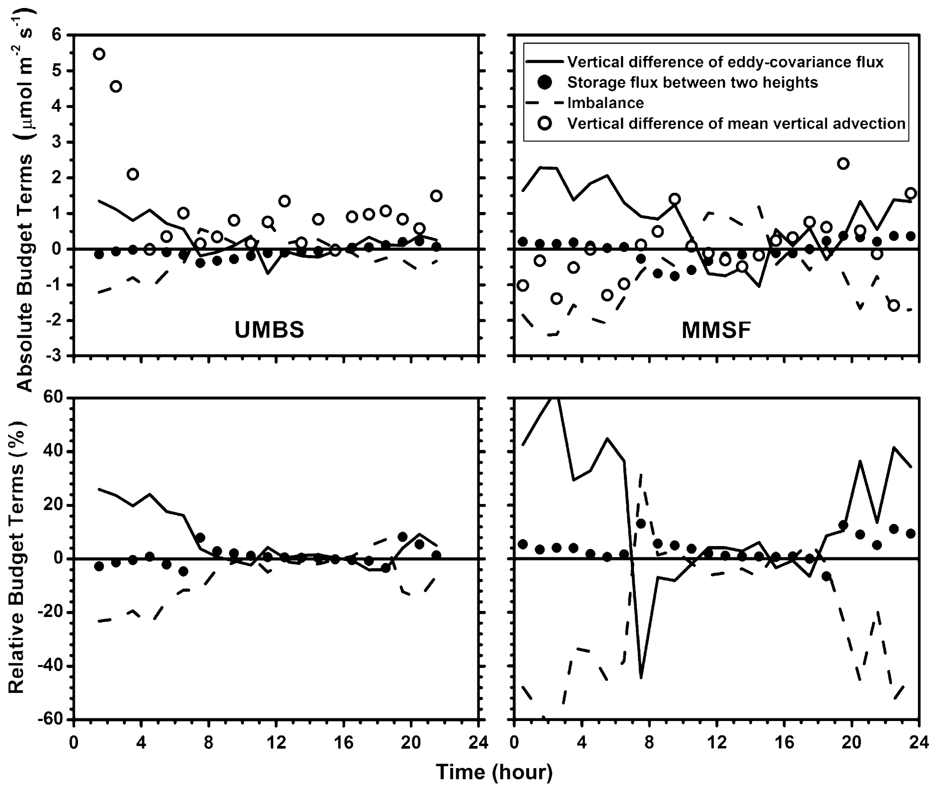

Fig. 9 – Ensemble averages of 1D CO_2 budget in the air layer between two measurement heights in the upwind directions during the growing season in 2001. The numbers of hourly samples are 645 at UMBS and 535 at MMSF. A vertical difference is calculated as higher level minus lower level. The imbalance is the negative of the sum of vertical difference of eddy-covariance flux and storage flux in the air layer. ROT-3 and 1 h averaging time period are used with hourly records of 10 Hz data. Co-spectral corrections are included. Eddy-covariance flux at the lower level is used to normalize budget terms in the lower panels. The vertical differences of mean vertical advection of CO_2 are for $u_* \geq 0.35$ m s^{-1} and only shown in the top panels.

theory, this imbalance reflects the net result of both horizontal and vertical mean advection as well as horizontal flux divergence. Obviously, the imbalance could also include any errors associated with the measurements and calculations of the storage and eddy-covariance fluxes. For the sake of brevity, we only show results calculated with ROT-3.

Except for the transitional periods after sunrise and sunset when the storage is relatively more significant, vertical flux difference is the greater term in the 1D CO_2 budget (Fig. 9). Thus, the imbalance is generally of an opposite sign to that of the vertical flux difference. Since mean advection are usually associated with large-scale motions and source/sink heterogeneity, it is perhaps no coincidence that turbulent motions in the lower frequencies ($n < 0.01$ Hz) counteract the most energetic turbulent eddies ($n = 0.02$–0.1 Hz) in the daytime to determine the vertical flux divergence as discussed in Section 3.2 (Fig. 7c).

Both the vertical flux difference and the imbalance are relatively (normalized by co-spectral corrected eddy-covariance flux measured at the lower level) smaller (<5% at UMBS and <7% at MMSF) in the daytime than at night (20–30% at UMBS and 40–60% at MMSF). The greater vertical differences of CO_2 fluxes or the imbalance during the night at MMSF could be due to more complex topography and/or greater horizontal heterogeneity and thus potentially greater advection of CO_2 at this site.

The need to estimate mean vertical velocity and mean vertical advection is one of the original motives leading to the discussions on long-term averaged coordinate systems (Lee, 1998). Since measurements are only available on a single tower at both UMBS and MMSF, we followed Lee (1998) and calculated the mean vertical advection of CO_2 at a single measurement level above the two forests as $W\delta C$, where W and C are hourly mean vertical velocity and CO_2 concentration at this level, $\delta C = C - \langle C \rangle$, and $\langle C \rangle$ is the average CO_2

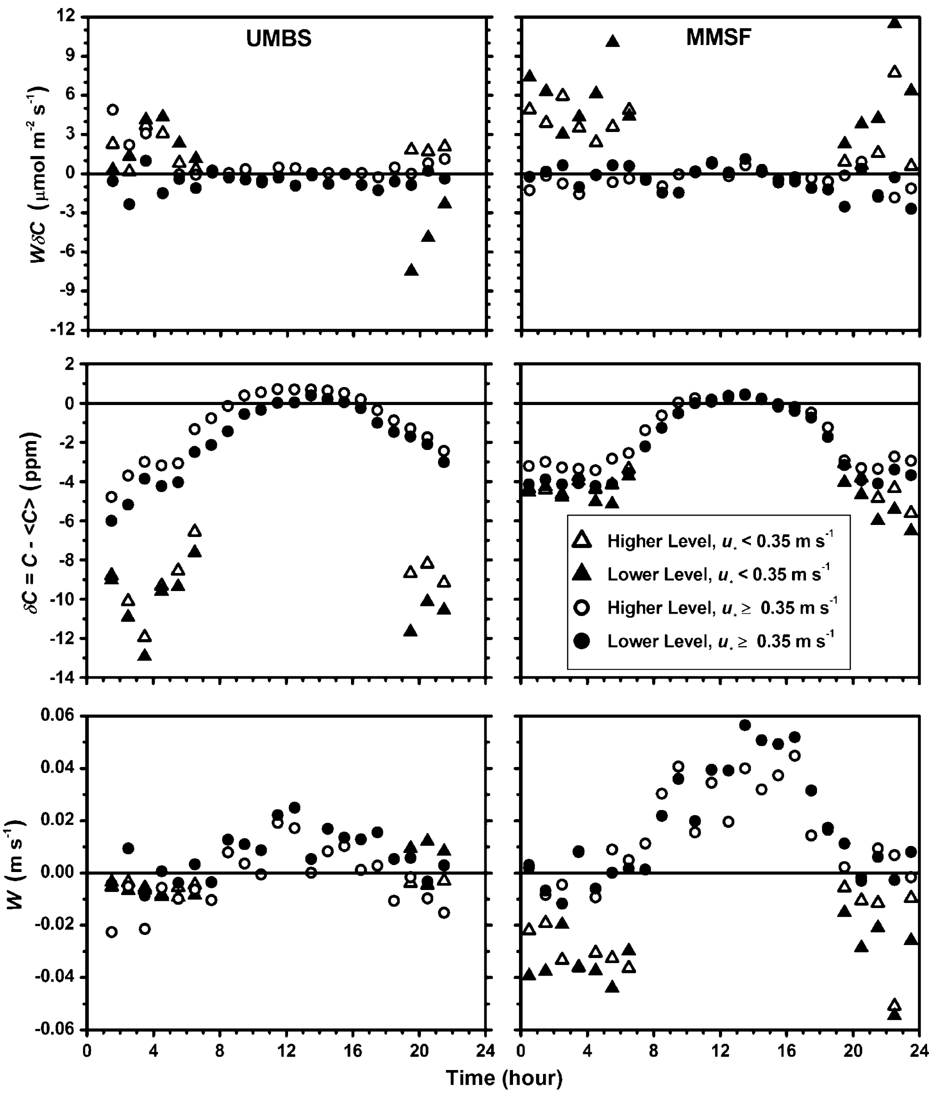

Fig. 10 – Ensemble averages of mean vertical advection of CO_2 (top panels), mean vertical difference of CO_2 concentration (middle panels) and mean vertical velocity (bottom panels) in the upwind directions during the growing season in 2001. ROT-3 and 1 h averaging time period are used with hourly records of 10 Hz data. The numbers of hourly measurements are the same as in Fig. 9.

concentration between this level and the ground. Discussions on the theory, assumptions and limitations of this method, as well as measurement requirements in practice for such estimates, are detailed in Lee (1998, 1999), Finnigan (1999) and Lee et al. (2004).

Similar to Lee (1998), at both UMBS and MMSF, the magnitude of ensemble averaged δC is very small in the daytime and much greater at night when $u_* \geq 0.35$ m s^{-1}, and even greater when $u_* < 0.35$ m s^{-1} at night (Fig. 10).

In the daytime ($u_* \geq 0.35$ m s^{-1}), ensemble averaged W is generally positive at both measurement heights of the two sites with greater magnitudes at the lower levels of both sites and at the MMSF site. Nevertheless, the ensemble average of WδC is ±1 μmol m^{-2} s^{-1} or less (due to very small δC), which is an order of magnitude smaller than the ensemble averaged daytime eddy-covaraince flux F_C (−14 μmol m^{-2} s^{-1} at UMBS, −16 μmol m^{-2} s^{-1} at MMSF).

At night, ensemble averaged W is negative at both measurement heights of MMSF when $u_* < 0.35$ m s^{-1} but can be either positive or negative when $u_* \geq 0.35$ m s^{-1}. The magnitude of ensemble averaged W is also greater when $u_* < 0.35$ m s^{-1} and at the lower level, so is the ensemble averaged δC. Consequently, the ensemble average of WδC is much greater when $u_* < 0.35$ m s^{-1} and at the lower level, with values comparable to the ensemble averages of nighttime eddy-covaraince fluxes F_C (3–6 μmol m^{-2} s^{-1}) when $u_* \geq 0.35$ m s^{-1} at this site. At UMBS, nighttime ensemble averaged W and WδC do not show the same variations with the friction velocity at the two measurement heights as at MMSF. At the higher level, ensemble averaged W is more negative when $u_* \geq 0.35$ m s^{-1} but ensemble averaged δC is more negative when $u_* < 0.35$ m s^{-1}, so the ensemble average of WδC has comparable positive values in this two ranges of u_*. At the lower level, the ensemble averages of W and WδC can be either positive or negative in both ranges of u_*.

Relevant to the 1D CO_2 budget (Fig. 9) are the vertical differences of mean vertical advection of CO_2 between the two measurement heights when $u_* \geq 0.35$ m s^{-1}. It is shown that these verticle differences often have very different magnitude and/or opposite sign as the imbalance. This could indicate the significance of horizontal advection of CO_2 in the air layer between the two measurement heights as discussed by Finnigan (1999), if the estimates of all budget terms, including the mean vertical advection of CO_2, are valid.

4. Conclusions

It is shown that vertical divergence of CO_2 fluxes are apparently observed at both the UMBS and the MMSF AmeriFlux sites. Although the differences in ensemble averaged CO_2 fluxes measured at two heights above the forests are small (0.2–0.5 μmol m^{-2} s^{-1}) relative to fluxes measured at a singe height, they are the major contributors to differences in annual NEE estimates between the two heights. In 2001, annual NEE estimates based on measurements at the higher levels are 76–256 g C m^{-2} less negative (−41.8% to −50.6%) than those at the lower levels.

In principle, the observed vertical flux divergence could be in part due to mean flow advection which is not accounted for in current estimates of annual NEE. However, measurements are not available to fully assess mean advection contributions (particularly the horizontal component) to annual NEE. In this study, our focus is to investigate how the observed flux divergence may be influenced by different methods used in basic procedures of eddy-covariance flux calculations (coordinate rotation, averaging time period, sampling frequency and co-spectral correction). Due to the lack of a well established method to correct the tower shadow effects, our discussions are mainly based on measurements in the upwind directions. The main findings are summarized in the following.

- A positive or negative offset in measured vertical velocities (estimated using the planar fit method) leads to a systematic over- or under-estimate of fluxes measured at a single height, if it is not removed from the ensemble averaged second rotation angle. An offset (b_0) of 1 cm s^{-1} leads to about 1% differences in momentum fluxes and 0.5–1% differences in sensible heat and CO_2 fluxes. The values of b_0 vary from −2.9 to 1.6 cm s^{-1} among the four sonic anemometers.
- The upflow or downflow (estimated by fitting the bin-averaged second rotation angle with the offset removed as a sinusoidal function of the azimuth) leads to a systematic under- or over-estimate of fluxes measured at a single level, if it is not corrected. An upflow or downflow angle (ϕ_d) of 1° leads to about 5.6% differences in momentum fluxes and 2.8–5.6% differences in sensible heat and CO_2 fluxes. The values of ϕ_d vary from −1.4° to 1.3° among the four sonic anemometers.
- The magnitude and/or sign of both b_0 and ϕ_d vary between sonic anemometers at the two measurement heights of both UMBS and MMSF. Thus, if the offset is not removed and the upflow/downflow is not corrected, a large positive or negative bias exists in the vertical flux differences.
- A 1 h averaging time period is shown to be appropriate for both the UMBS and MMSF sites. Shorter (than 1 h) averaging time periods lead to greater under-estimates of fluxes in the daytime than at night. However, we find no clear evidence that longer (than 1 h) averaging time periods lead to further increases of fluxes in the daytime. Higher (than 1 Hz) frequencies have relatively greater contributions to sensible heat and CO_2 fluxes than to momentum flux. These contributions are also relatively greater at night than in the daytime.
- During the daytime, the absolute magnitudes of ensemble averaged co-spectral densities decrease with increasing height in the natural frequency range of n = 0.02–0.1 Hz but increase in the lower frequencies ($n < 0.01$ Hz). This indicates that air motions in these two frequency ranges counteract each other in determining vertical flux differences. The magnitude and the sign of vertical flux differences also vary with averaging time periods since the natural frequency corresponding to the shortest averaging time period used in this study is less than 0.01 Hz. At night, co-spectral densities of CO_2 are more positive at the higher measurement levels of both sites in the frequency range of n = 0.03–0.4 Hz. These vertical increases are also shown at most frequencies lower than 0.03 Hz.

- The magnitude of the systematic positive or negative bias in vertical flux differences (due to upflow/downflow) is also smaller using shorter (than 1 h) averaging time periods, but changes little when longer (than 1 h) averaging time periods are used.
- At both sites, differences in co-spectral corrections at the two measurement heights generally lead to a positive shift in vertical differences of ensemble averaged hourly CO_2 fluxes throughout the day.
- At night, the positive vertical differences of ensemble averaged CO_2 fluxes are about 20–30% and 40–60% of co-spectral corrected ensemble averaged hourly CO_2 fluxes measured at the lower levels of UMBS and MMSF, respectively. The vertical differences of mean vertical advection of CO_2 (estimated using Lee's, 1998 method) between the two measurement heights often have very different magnitudes and even opposite sign as the imbalance (the negative of the sum of vertical differences of eddy-covaraice fluxes and storage). This may imply the significance of horizontal advection in the air layer between the two measurement heights above canopy at both sites. However, given the theoretical limitations of the Lee's (1998) method and the practical difficulties to measure the mean vertical advection accurately, a full assessement of mean advection is currently unsolved problem at both sites.

Acknowledgements

Funding for this research was provided by the US Department of Energy through its National Institute of Global Environmental Change. We would like to acknowledge the important contributions by James Teeri and Brian Bovard in the establishment of UMBS, and by Brian Offerle, Ford Cropley, Steve Scott and Andrew Oliphant for MMSF. Numerous graduate and undergraduate students also contributed to the field and lab research at both sites. We thank Dr. Kyaw Tha Paw U for his detailed suggestions for improving the manuscript.

REFERENCES

Baldocchi, D.D., Finnigan, J.J., Wilson, K.B., Paw U, K.T., Falge, E., 2000. On measuring net ecosystem carbon exchange over tall vegetation on complex terrain. Boundary-Layer Meteorol. 96, 257–291.

Davis, K.J., Bakwin, P.S., Yi, C., Berger, B.W., Zhao, C., Teclaw, R.M., Isebrands, J.G., 2003. The annual cycles of CO_2 and H_2O exchange over a northern mixed forest as observed from a very tall tower. Glob. Change Biol. 9, 1278–1293.

Dyer, A.J., 1981. Flow distortion by supporting structures. Boundary-Layer Meteorol. 20, 243–251.

Finnigan, J.J., 1999. A comment on the paper by Lee (1998): on micrometeorological observations of surface-air exchange over tall vegetation. Agric. For. Meteorol. 97, 55–64.

Finnigan, J.J., Clements, R., Malhi, Y., Leuning, R., Cleugh, H.A., 2003. A re-evaluation of long-term flux measurement techniques part I: averaging and coordinate rotation. Boundary-Layer Meteorol. 107, 1–48.

Finnigan, J.J., 2004. A re-evaluation of long-term flux measurement techniques part II: coordinate systems. Boundary-Layer Meteorol. 113, 1–41.

Froelich, N.J., Schmid, H.P., Grimmond, C.S.B., Su, H.-B., Oliphant, A.J., 2005. Flow divergence and density flows above and below a deciduous forest, Part I: non-zero mean vertical wind above canopy. Agric. For. Meteorol. 133, 140–152.

Gao, W., Shaw, R.H., Paw U, K.T., 1989. Observation of organized structure in turbulent flow within and above a forest canopy. Boundary-Layer Meteorol. 47, 349–377.

Grant, A.L.M., Watkins, R.D., 1989. Errors in turbulence measurements with a sonic anemometer. Boundary-Layer Meteorol. 46, 181–194.

Kaimal, J.C., Finnigan, J.J., 1994. Atmospheric Boundary Layer Flows: Their Structure and Measurement. Oxford University Press, Oxford, U.K., 289 pp.

Lee, X., 1998. On micrometeorological observations of surface-air exchange over tall vegetation. Agric. For. Meteorol. 91, 39–49.

Lee, X., 1999. Reply to comment by Finnigan on On micrometeorological observations of surface-air exchange over tall vegetation. Agric. For. Meteorol. 97, 65–67.

Lee, X., Finnigan, J., Paw U, K.T., 2004. Coordiate systems and flux bias error. In: Lee, X., Massman, W.J., Law, B. (Eds.), Handbook of Micrometeorology—A Guide for Surface Flux Measurement and Analysis. Kluwer Academic Publishers, 250 pp., pp. 33–66.

Lumley, J.L., Panofsky, H.A., 1964. The Structure of Atmospheric Turbulence. Interscience-Wiley, New York, 239 pp.

Massman, W.J., Lee, X., 2002. Eddy covariance flux corrections and uncertainties in long-term studies of carbon and energy exchanges. Agric. For. Meteorol. 113, 121–144.

McMillen, R.T., 1988. An eddy correlation technique with extended applicability to non-simple terrain. Boundary-Layer Meteorol. 43, 231–245.

Moncrief, J., Clement, R., Finnigan, J., Meyers, T., 2004. Averaging, detrending, and filtering of eddy covariance time series. In: Lee, X., Massman, W.J., Law, B. (Eds.), Handbook of Micrometeorology—A Guide for Surface Flux Measurement and Analysis. Kluwer Academic Publishers, 250 pp., pp. 7–31.

Paw U, K.T., Baldocchi, D.D., Meyers, T.P., Wilson, K.B., 2000. Correction of eddy-covariance measurements incorporating both advective effects and density fluxes. Boundary-Layer Meteorol. 97, 487–511.

Sakai, R.K., Fitzjarrald, D.R., Moore, K.E., 2001. Importance of low-frequency contributions to eddy fluxes observed over rough surfaces. J. Appl. Meteorol. 40, 2178–2192.

Schmid, H.P., Grimmond, C.S.B., Offerle, B., Cropley, F.D., Su, H.-B., 2000. Measurements of CO_2 and energy fluxes over a mixed hardwood forest in the Midwestern United States. Agric. For. Meteorol. 103, 355–373.

Schmid, H.P., Su, H.-B., Vogel, C.S., Curtis, P.S., 2003. Ecosystem-atmosphere exchange of carbon dioxide over a mixed deciduous forest in northern lower Michigan. J. Geophys. Res. 108 (D14), 4417 doi:10.1029/2002JD003011.

Stull, R.B., 1988. An Introduction to Boundary Layer Meteorology. Kluwer Academic Publishers, The Netherlands, 666 pp.

Su, H.-B., Schmid, H.P., Grimmond, C.S.B., Vogel, C.S., Curtis, P.S., 2000. Temporal and spatial variability of mean flow and turbulence characteristics over a deciduous forest. In: Proceedings of the 14th Symposium on Boundary Layers and Turbulence, American Meteorological Society, Aspen, CO, pp. 318–321.

Su, H.-B., Schmid, H.P., Grimmond, C.S.B., Vogel, C.S., Oliphant, A.J., 2004. Spectral characteristics and correction of long-term eddy-covariance measurements over two mixed hardwood forests in non-flat terrain. Boundary-Layer Meteorol. 110, 213–253.

Tanner, C.B., Thurtell, G.W., 1969. Anemoclinometer Measurements of Reynolds Stress and Heat Transport in the Atmospheric Surface Layer. Dept. of Soil Science, Univ. of

Wisconsin, Madison, WI, Research and Development Technical Report ECOM 66-G22-F to the US Army Electronics Command.

Twine, T.E., Kustas, W.P., Norman, J.M., Cook, D.R., Houser, P.R., Meyers, T.P., Prueger, J.H., Starks, P.J., Wesley, M.L., 2000. Correcting eddy-covariance flux underestimates over a grassland. Agric. For. Meteorol. 103, 279–300.

Vickers, D., Mahrt, L., 1997. Quality control and flux sampling problems for tower and aircraft data. J. Atmos. Ocean Tech. 14, 512–526.

Wesely, M.L., 1970. Eddy correlation measurements in the atmospheric surface layer over agricultural crops. Ph.D. Thesis. Univ. of Wisconsin, Madison, Wis. (Diss. Abstr. No. 70-24, 828), 102 pp.

Wilczak, J.M., Oncley, S.P., Stage, S.A., 2001. Sonic anemometer tilt correction algorithms. Boundary-Layer Meteorol. 99, 127–150.

Wyngaard, J.C., 1973. On surface layer turbulence. In: Haugen, D.A. (Ed.), Workshop on Micrometeorology. American Meteorological Society, Boston, 392 pp.

Yi, C., Davis, K.J., Bakwin, P.S., Berger, B.W., Marr, L.C., 2000. Influence of advection on measurements of the net ecosystem-atmosphere exchange of CO_2 from a very tall tower. J. Geophys. Res. 105 (D8), 9991–9999.