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**SPECTRAL ANALYSES OF LONG-TERM MEASUREMENTS OF  
 TURBULENT EXCHANGE OVER MIXED HARDWOOD FORESTS**

Hong-Bing Su<sup>\*1</sup>, Hans Peter Schmid<sup>1</sup>, C. S. B. Grimmond<sup>1</sup>, Christoph S. Vogel<sup>2</sup> and Andrew J. Oliphant<sup>1</sup>  
<sup>1</sup>Indiana University, Bloomington, IN; <sup>2</sup>University of Michigan Biological Station, Pellston, MI

**1. INTRODUCTION**

It is well recognized that losses in measured eddy-covariance fluxes can be caused by path/line averaging, sensor separation, inadequate sensor frequency response, damping through tubes in closed-path gas analyzers, data processing, etc., (Moore, 1986). Previous studies using spectral methods have shown that corrections to measured fluxes range from a few to over 30% (Eugster & Senn 1995, Leuning & Judd 1996, Horst 1997, Massman 2000). The magnitudes of such flux losses in the higher frequency range could be on the same order as unaccounted lower frequency fluxes due to inadequate averaging time (Rimann & Tetzlaff 1994, Sakai et al. 2001, Finnigan et al. 2002).

Spectral methods used to correct the flux losses often require knowledge of the true spectra and cospectra, as well as the transfer functions (Moore, 1986; Massman, 2000). The most used spectral and cospectral models are those of Kaimal et al. (1972) and Wyngaard and Cot (1972) derived from observations over smooth surfaces and flat terrain. Sakai et al. (2001) indicated that the normalized cospectra of momentum and sensible heat in the roughness sublayer over forest canopies have nearly identical form in convective conditions.

Here we examine spectra and cospectra characteristics to determine appropriate similarity forms of spectral and cospectral for subsequent applications. Then, we focus on the frequency loss of CO<sub>2</sub> and water vapor fluxes due to damping through the long tubes, assuming this to be the major cause of frequency losses. Variations in the coefficients of damping function and the magnitudes of flux correction are also discussed.

Data used here were collected at the UMBS (University of Michigan Biological Station in lower northern Michigan) AmeriFlux site. Eddy-covariance systems (CSAT-3 sonic anemometers and a LiCor-6262 closed path infrared gas analyzers) were installed at 34 m and 46 m. The mean tree height is 22 m and peak LAI is 3.5. Results are derived from over 2,400 hourly spectra and cospectra during June-August of 1999 and 2000 at 46 m. Similar analyses are to be performed for the MMSF (Morgan-Monroe State Forest in south central Indiana) site.

**2. METHOD**

The true vertical eddy-covariance fluxes of a scalar (s) can be expressed as the integral of its true cospectrum over frequency n,

$$\overline{w's'} = \int_0^\infty Co_{ws}(n)dn$$

where w' and s' are fluctuations of vertical velocity and scalar concentration, and the overbar indicates ensemble average. In practice, the integration is limited by the sampling rate and averaging time.

Similarly, the measured flux and co-spectrum, denoted by the superscript m, are written as:

$$\overline{w's'^m} = \int_0^\infty Co_{ws}^m(n)dn = \int_0^\infty H_s(n)Co_{ws}(n)dn$$

where H<sub>s</sub>(n) is a net transfer function or the product of a set of transfer functions characteristic of a particular eddy-covariance system and the scalar s.

The flux correction factor is defined as:

$$\alpha = \frac{\overline{w's'^m}}{\overline{w's'}} = \int_0^\infty H_s(n) \frac{Co_{ws}(n)}{w's'} dn = \int_0^\infty H_s(n) \frac{Co_{ws}(n)}{w'\theta'} dn$$

where θ is potential temperature, and it is assumed that the true normalized co-spectra of all scalars have the same form. Thus, knowledge of both H<sub>s</sub>(n) and the normalized cospectra are needed.

**3. SOME RESULTS AND DISCUSSIONS**

For the normalized power spectra of the vertical velocity, the stability dependence and orderly progression of the spectral peak and roll-off with decreasing frequency, are similar to Kaimal et al. (1972) (Figure 1). But different stability functions and constants were used to normalize the spectra.

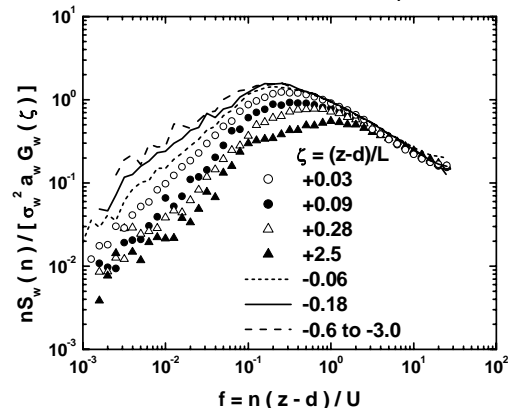


Figure 1 Normalized power spectra ( $S_w$ ) of vertical velocity (w),  $a_w$  and  $G_w(\zeta)$  are spectral constant and stability ( $\zeta$ ) function for w, z height above ground, d displacement height, L Monin-Obukhov length, n and f are natural and normalized frequencies, U mean wind speed at z.

In stable conditions, the cospectra of momentum (Figure 2) and sensible heat (Figure 3) are also similar to Kaimal et al. (1972). For momentum, the progressive increases in cospectral density in the lower frequencies extend to weak unstable condition ( $\zeta > -0.2$ ) (Figure 2). This extension is absent for the sensible heat (Figure 3). As in Kaimal et al. (1972),

\* Corresponding author: Department of Geography, Indiana University, 120 Student Building, Bloomington, IN 47405-7100. Email: hsu@indiana.edu

the  $-4/3$  line starts at a higher frequency for sensible heat than for the momentum, indicating smaller eddies are more efficient in the vertical transport of heat than momentum.

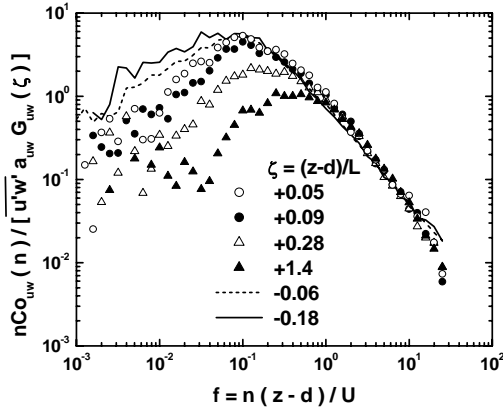


Figure 2 Normalized cospectra ( $Co_{uw}$ ) of  $u'w'$ , covariance between longitudinal ( $u$ ) and vertical velocity,  $a_{uw}$  and  $G_{uw}(\zeta)$  are spectral constant and stability function.

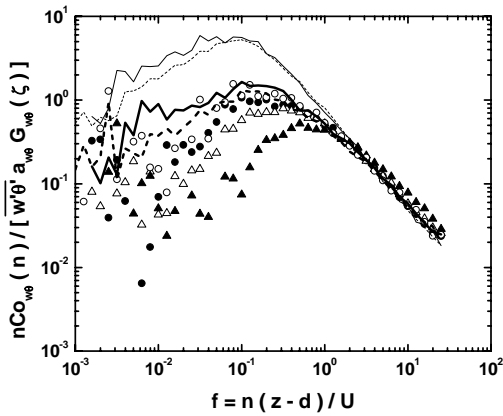


Figure 3 Same as Figure 2 but for covariance  $w'\theta'$ ,  $\theta$  is temperature. Thinner curves are the same as in Figure 2.

The transfer function of the first-order sensor (Eugster & Senn 1995, Horst 1997) was fit to the ratio of spectra and cospectra of  $CO_2$  and water vapor to those of the temperature (Figure 4). Water vapor fluctuations have a greater reduction than  $CO_2$ . Unlike Eugster and Senn (1995), the transfer functions are not the same for the spectra and cospectra of the same scalar. The time constant for  $CO_2$  is smaller in 2000 than in 1999, whereas for water vapor, it is greater in 2000. Leuning and Judd (1996) showed that dirtier and older tubes have a greater time constant for water, not much so for  $CO_2$ . Thus, smaller time constant for  $CO_2$  in 2000 could be due to higher flow rate as the long tube was not changed, whereas, larger time constant for water vapor in 2000 indicates the dirty tube effect is much stronger than slightly increased flow rate. The time constants are also somewhat different between day and night (not shown).

From June through August, flux corrections using these transfer functions (Figure 5) are, on average,

about 2% (day) and 5% (night) for  $CO_2$ , about 8% for latent heat (LE) during the day (nighttime LE is small). These corrections are on similar order of magnitude as effects of inadequate averaging time and sampling rate discussed elsewhere.

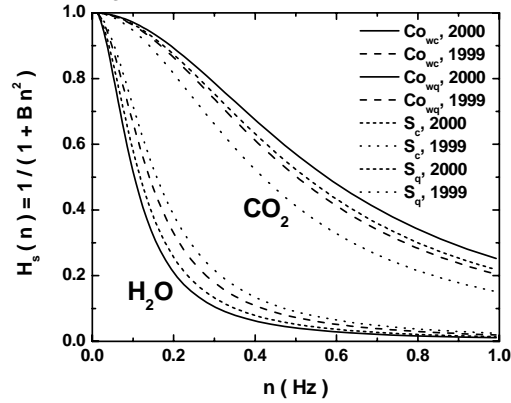


Figure 4 Transfer functions for spectra and cospectra.

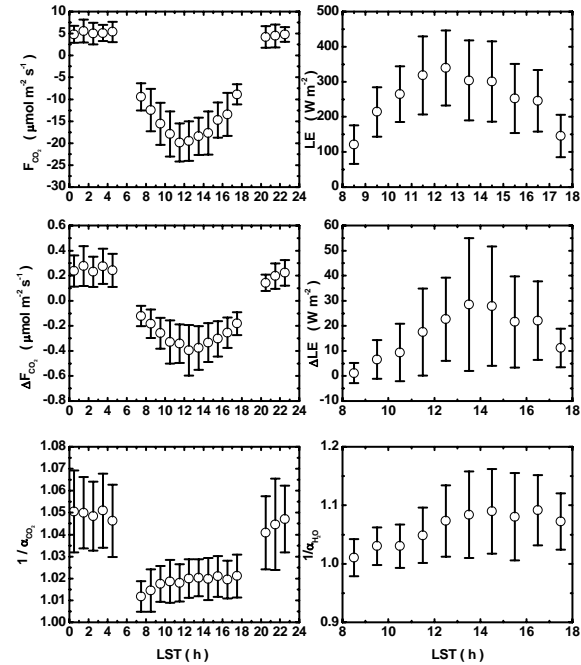


Figure 5 Ensemble averages of uncorrected flux (top), flux correction (middle) and correction factor (bottom).

**Acknowledgement:** Funded by NIGEC-DOE.

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