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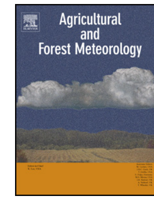

Multi-scale decomposition of turbulent fluxes above a forest canopy

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ABSTRACT

Multi-scale properties of upward and downward component contributions to the turbulent fluxes of momentum, sensible heat, water vapor, and CO_2 over a forest canopy in different atmospheric stability conditions are examined. The technique uses an innovative wavelet cospectral decomposition of fluxes into their positive and negative components. Results show that both the frequency of occurrence and the intensity of upward and downward events in the wavelet cospectra, as well as the upward and downward global wavelet cospectra, are intimately tied to the scale of motion. The average frequency of occurrence of the events in both directions was close to 50% at small scales, with the main component dominating at larger scales. The averaged normalized global intensity of the main component of scalar wavelet cospectrum has a prominent peak at 30–70 s varying with the interested fluxes and the atmospheric stability, and decreases sharply for larger scales and more gradually for smaller scales. The intensity of the minor component is almost constant in the fine scales, and decreases to almost zero as the scale increases. Results from these analyses are indirectly supported by techniques such as the quadrant-hole analysis and the Fourier cospectrum. These properties suggest that the main component of wavelet cospectrum dominating at larger scales has a more important contribution to fluxes than the minor component. These results support the idea that the scalar exchange takes place mostly through the action of large-scale eddies.

1. Introduction

The atmospheric boundary layer contains turbulent eddies which transport energy, trace gases and other substances instantaneously at a large range of spatial and temporal scales. A variety of tools have been used to study their properties. For example, methods such as the quadrant-hole analysis separates the time series of two variables into four quadrants according to their variation from their average values, and the contribution of each "quadrant" (or upward and downward transports) to the overall flux can be evaluated in time domain. The Fourier transform is another tool often used, which transforms turbulent time series from time domain to frequency domain. It reveals frequency information that is an average over the entire processed time period.

The wavelet transform is a local transform that provides information on scale, intensity and location of features in a time series. Not surprisingly, the method naturally lends itself to the detection of intermittent, non-stationary turbulence and coherent motions above forest (Boldes et al., 2003; Turner et al., 1994; Zhang et al., 2007) or crop canopies (Brunet and Collineau, 1994; Prueger et al., 2012) or heterogeneous landscapes (Vadrevu and Choi, 2011), and within forests (Boldes et al., 2003, 2007; Brunet and Irvine, 2000) and in the nocturnal stable boundary layer (Cuxart et al., 2002; Poulos et al., 2002; Salmond, 2005; Staudt et al., 2011; Terradellas et al., 2001, 2005).

Wavelet cospectra have also been used to characterize multi-scale properties of turbulent fluxes of momentum, heat, water vapor, and CO_2. Katul et al. (2001) used the wavelet technique to analyze fluxes above a pine forest at scales ranging from fractions of seconds to years. They separated the time scales into three ranges: turbulent time scales from fractions of seconds to minutes, well described by existing turbulence theories; meteorological time scales from hours to weeks, used in coupled physiological and transport models; and seasonal to interannual time scales, reflecting the seasonal variation in land-surface fluxes and forcing variables. Scanlon and Albertson (2001) applied a wavelet analysis to time series of carbon dioxide and water vapor measured above a forest (about 1.28 h) during daytime unstable conditions and found that the dominant eddies contributing to fluxes between the canopy and the atmosphere were about 63 m in diameter, about 4.5 times the forest height. Using wavelet analysis of eddy-covariance data measured at 23 m above the Amazon rainforest (30 m high),

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von Randow et al. (2006) also found that the peak scale contributions to *uw* and *wT* covariance were at time scales of about 1 min or length scales of 100–200 m.

Despite various applications of the wavelet technique, one important property of the wavelet transform has been largely overlooked: A cross-wavelet coefficient at a given scale can be either positive or negative at different points in a time series. The property reflects eddies in different sizes moving instantaneously upward and downward in different frequencies. It allows the separation of positive and negative values when calculating a time-averaged wavelet cospectrum. This provides the upward and downward contributions to turbulent fluxes in both scale (frequency) and time domains (Turner, 1998; Scanlon and Albertson, 2001). This method cannot be used with the Fourier transform because the Fourier transform gives only the mean spectral or cospectral decomposition averaged over the entire time duration of the processed time series. This method also differs from the quadrant-hole analysis of time series of eddy-covariance data which detects time scales and strengths of sweeps and ejections in the time domain (Yue et al., 2007). Although Hudgins et al. (1993) detected the scales of upward and downward events in momentum and sensible heat fluxes over an open ocean, but those events were positive and negative values in global wavelet cospectra (i.e., positive or negative average values over the whole processed time duration), not the separation of the positive and negative components when averaging over time.

In an effort to understand the role of different scales of motion on surface-atmosphere exchange, this paper investigates the multi-scale upward and downward properties of the momentum, sensible heat, water vapor, and CO_2 transport above a forest canopy. By separating the wavelet cospectra of flux data into upward and downward components, their contribution to fluxes as a function of scale are examined. This study also assesses the properties of the frequency of occurrence and the intensity of each upward and downward component. These multi-scale properties are first examined in daytime weakly unstable atmospheric conditions, and then compared in different stable and unstable conditions.

2. Theory

2.1. Wavelet transform and wavelet cospectrum

The continuous wavelet transform of a discrete sequence x_n is defined as the convolution of x_n with a scaled and translated wavelet function $\Psi(\eta)$ (Torrence and Compo, 1998):

$$W_n(s) = \sum_{n'=0}^{N-1} x_{n'} \psi^* \left[\frac{(n'-n)\delta t}{s} \right], \tag{1}$$

where $W_n(s)$ is the wavelet coefficient at the wavelet scale s and the localized time index n, and $\Psi^*(\eta)$ is the complex conjugate of the wavelet function depending on a non-dimensional "time" parameter $\eta = (n'-n)\delta t/s$, where $n = 0, 1, \ldots, N-1$ with N being the number of points in the time series with time step δt.

The total energy is conserved under the wavelet transform (Torrence and Compo, 1998), i.e.,

$$\sigma^2 = \frac{\delta j \delta t}{C_\delta N} \sum_{n=0}^{N-1} \sum_{j=0}^{J} \frac{|W_n(s_j)|^2}{s_j}, \tag{2}$$

where σ^2 is the variance of the discrete sequence x_n, and C_δ is the scale-independent reconstruction factor and is a constant for each wavelet function, for example, 0.776 for the Morlet wavelet function (Torrence and Compo, 1998). Therefore, the relative energy contribution at scale s to the total energy can be calculated as

$$E_{\text{norm}}(s) = \frac{\sum_{n=0}^{N-1} |W_n(s)|^2/s}{\sum_{n=0}^{N-1} \sum_{j=0}^{J} |W_n(s_j)|^2/s_j}. \tag{3}$$

A local cross-wavelet spectrum of two time series X and Y is defined by the product of their wavelet transforms (Torrence and Compo, 1998), i.e.,

$$W_n^{XY}(s) = W_n^X(s) W_n^{Y*}(s), \tag{4}$$

where (*) indicates a complex conjugate.

Analogue to the Fourier cospectrum (Stull, 1988), the local wavelet cospectrum can be defined as the real part of the cross-wavelet spectrum at scale s and location n (Strunin and Hiyama, 2005), i.e., the sum of the product of real parts of wavelet transform of the two variables and the product of their imaginary parts,

$$Co_{W\,n}^{XY}(s) = \Re(W_n^{XY}(s)) == W_n^{Xr}(s) W_n^{Yr}(s) + W_n^{Xi}(s) W_n^{Yi}(s). \tag{5}$$

When the two variables and wavelet function are real, the cross-wavelet spectrum is real and there is no difference between the cross-wavelet spectrum and the wavelet cospectrum (Hudgins et al., 1993). Then the coefficients of imaginary part are zero, and Eq. (5) leaves only the first term on the right side, becoming the same as in Turner (1998) and Scanlon and Albertson (2001) where the Haar wavelet was used.

Similar to the fact that the sum of the Fourier cospectrum over all frequencies equals the covariance of the two variables (Stull, 1988), the local wavelet cospectrum reflects the contribution to the covariance between X and Y from the scale s and the location n. Analogue to Eq. (2),

$$COV = \frac{\delta j \delta t}{C_\delta N} \sum_{n=0}^{N-1} \sum_{j=0}^{J} \frac{Co_{W\,n}^{XY}(s_j)}{s_j}. \tag{6}$$

Thus, the local contribution to the covariance by wavelet cospectrum, normalized by the standard deviation of X and Y (i.e., σ_X and σ_Y from Eq. (2)), is given by

$$R_{W\,n}(s) = \frac{Co_{W\,n}^{XY}(s)/s}{\left(\frac{1}{N} \sum_{n=0}^{N-1} \sum_{j=0}^{J} |W_n^X(s_j)|^2/s_j \frac{1}{N} \sum_{n=0}^{N-1} \sum_{j=0}^{J} |W_n^{Y*}(s_j)|^2/s_j \right)^{1/2}}, \tag{7}$$

and global normalized wavelet cospectrum contribution can be calculated as

$$R_W(s) = \frac{\frac{1}{N} \sum_{n=0}^{N-1} Co_{W\,n}^{XY}(s)/s}{\left(\frac{1}{N} \sum_{n=0}^{N-1} \sum_{j=0}^{J} |W_n^X(s_j)|^2/s_j \frac{1}{N} \sum_{n=0}^{N-1} \sum_{j=0}^{J} |W_n^{Y*}(s_j)|^2/s_j \right)^{1/2}}, \tag{8}$$

which represents the wavelet correlation coefficient at scale s.

By definition, the wavelet cospectrum at a given scale can take either a positive or a negative value at any local time index, reflecting either the contribution of upward or downward component to the turbulent flux at the particular scale and time location. When averaging wavelet cospectra over time, positive and negative values at different time locations can be separated for each scale and the contributions of both upward and downward components to the flux cospectrum can be evaluated. The total of both the two components represents the net transport of the upward and downward motions (Turner, 1998).