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Original Research Article

Disentangling the confounding effects of PAR and air temperature on net ecosystem exchange at multiple time scales

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A B S T R A C T

Net ecosystem exchange of CO_2 (NEE) in temperate forests is modulated by multiple microclimatic factors. The effects of these factors vary across time scales, with some correlated to produce confounding effects. Photosynthetically active radiation (PAR) and air temperature (Ta) are among the two most important drivers of NEE in temperate forests and are highly correlated because of their similar diel and annual cycles. In this study, we attempted to disentangle the confounding effects of them on NEE at multiple time scales. We applied innovative spectral analysis techniques, including the continuous wavelet transformation (CWT), cross wavelet transformation (XWT), wavelet coherent (WTC), and partial wavelet coherence (PWC), on a seven-year time series (2004–2010) of PAR, Ta, and NEE from the Ohio Oak Openings Ameriflux site (N 41.5545°, W 83.8438°), USA. We found that PAR was the primary driver at short time scales (*e.g.*, multi-hour and daily), while Ta dominated NEE at long time scales (*e.g.*, seasonal to annual). At the daily scale, PAR co-varied with NEE without time lag, while Ta lagged PAR for 2–3 h during growing seasons, which could be explained by the strong dependence of NEE on photosynthesis, which has a similar time lag of 2–3 h of Ta to PAR. At the daily scale, during the non-growing seasons, NEE varied little and co-varied with Ta and PAR with no high common power. At the annual scale, Ta co-varied with NEE with no time delay, but PAR led NEE by about one month. This can be explained by the strong dependence of leaf area index (LAI) on Ta as well as the lag between the LAI/biomass development and the progress of sunlight. We also found that NEE distributes most of its variation at seasonal and annual scales, suggesting that Ta is more important than PAR in determining the annual and long-term carbon budget.

1. Introduction

Our knowledge about the variability of the net ecosystem exchange (NEE) of CO_2 in terrestrial ecosystems at multiple time scales remains poor; yet, it is critical to global modeling analyses for quantifying the terrestrial carbon cycle (Stoy et al., 2009). NEE is simultaneously modulated by multiple physical and biological forcing factors that constantly change over time with unique magnitudes and frequencies (Baldocchi et al., 2001; Baldocchi and Wilson, 2001; Stoy et al., 2005, 2009). The daily and seasonal progressions of sunlight and temperature, precipitation events, the seasonal changes of plant structure, and the decadal successions of plants are obvious examples. Ecosystem functions (*e.g.*, NEE) respond to these forcing factors and their variability is the transferred variability of these drivers.

The response of NEE to each environmental driver varies by time scale. At the hourly scale, NEE variations are likely to be forced by changes in photosynthesis, stomatal conductance, and respiration that are controlled by sunlight and temperature (Baldocchi et al., 2001) as well as precipitation events (Stoy et al., 2005). At the daily scale, they are forced mostly by daily rhythms of solar radiation, air and soil temperature, humidity, and atmospheric CO_2 concentration (Baldocchi et al., 2001; Jarvis et al., 1997). Weather patterns/changes associated with the passages of high- and low-pressure systems, fronts, and precipitation can cause weekly fluctuations in NEE (Baldocchi and Wilson, 2001; Stoy et al., 2005). At

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monthly, seasonal, and annual scales, NEE experiences the effects of seasonal changes in sunlight, temperature, soil water balance, leaf dynamics, phenology, drought/wet events, and growing season duration (Baldocchi et al., 2001; Goulden et al., 2004; Stoy et al., 2005, 2009). At multi-year scales, long-term climatic changes (*e.g.*, *El Nino*, *La Nina* cycles) and ecological dynamics (*e.g.*, succession) and environmental changes (*e.g.*, N deposition, CO_2 fertilization) may be more responsible for the NEE variations (Baldocchi et al., 2001; Stoy et al., 2005). Despite this general knowledge, few efforts have been made to thoroughly examine the changes of variations in NEE and its drivers across multiple time scales.

Ecosystem models that synthesize terrestrial carbon exchange often represent an explicit hypothesis on how an ecosystem transfers variability from microclimatic drivers to ecological responses, such as NEE and energy fluxes. However, Stoy et al. (2013) evaluated the wavelet coherence between measurements and several NEE models at multiple time scales and found that the mechanisms for diurnal and annual NEE variability require further improvement to correctly simulate the magnitudes of fluxes. This suggests that some of the explicit hypotheses might be wrong or not accurate enough, partially due to the fact that the modulating effects of the microclimatic drivers may vary across time scales and drivers might be correlated to produce confounding effects. Temperature (*e.g.*, Ta), radiation (*e.g.*, PAR), and water (*e.g.*, precipitation) are among the most important microclimatic drivers that modulate the magnitude and frequency of carbon fluxes in temperate forests (van Dijk et al., 2005) and have always been important variables in ecosystem models (Liu et al., 1997; Urbanski et al., 2007; Xiao et al., 2004). However, among the three, PAR and Ta are highly correlated at multiple time scales because they have similar diurnal and seasonal cycles and thus may produce strong confounding effects. This inspired us to further confirm, refine, and adjust the effects of Ta and PAR on NEE across time scales (especially daily, seasonal, and annual scales). Here, we collected seven years of meteorological and flux measurements at the Oak Openings site in northwest Ohio with the objectives to explore the variability of NEE at multiple temporal scales and to disentangle the effects of Ta and PAR on regulating NEE. We excluded precipitation in our analysis because: (1) its effects have been reported in our previous studies (Noormets et al., 2008; Xie et al., 2014), (2) it is a stochastic event and lacks regular daily and seasonal patterns, and (3) it is weakly correlated to Ta and PAR. However, we included leaf area index (LAI) to assist our analysis because it is the most important biological driver of NEE and is highly correlated with PAR and Ta at seasonal to annual scales (Chen et al., 2002).

A spectral analysis of NEE and its driving force are especially well-adapted to achieve our study objective. The Fourier transform (FT) technique can be applied to analyze the frequency spectrum of the time series and determine the magnitude of frequencies, but not on the timing of particular frequency components (Massel, 2001). Thus, the FT is only appropriate for stationary signals with constant frequency components present throughout the records. The non-stationary nature of the flux measurements requires time-varying statistics that can decompose signals into the time-scale domain. A recently developed method, the Hilbert–Huang transform (HHT), does a good job tackling non-stationary and nonlinear data (Huang and Wu, 2008), but it is only empirically based and is at its early stage with difficulties in dealing with two or more time series simultaneously. Alternatively, a suite of wavelet analysis tools is ideally suited to the analysis of multiple non-stationary signals (Cazelles et al., 2008; Grinsted et al., 2004; Torrence and Compo, 1998). The continuous wavelet transform (CWT) that employs a finite basis function, *a.k.a.*, ‘‘mother wavelet’’, which is translated (shifted) and dilated (expanded and contracted) across a signal, can quantify the time series signal variance across both time and frequency. In addition, a cross-wavelet analysis (XWT) is able to expose the common power and relative phase in the time–frequency space of two time series. The wavelet coherence transform (WTC), a measure of wavelet coherence, can detect the significant coherence against noise, even when the common power is low between the two time series. The partial wavelet coherence (PWC), a technique similar to partial correlation, can identify the resulting wavelet coherence between two time series after eliminating the influence of a third common dependence (Ng and Chan, 2012). Because of these unique features, we employed them in this study to achieve our study objectives. We hypothesized that PAR is the major driver at short scales (*e.g.*, 12-h, day) and Ta is the major driver at long scales (season, year). Specifically, we: (1) quantified the variability of NEE across multiple time scales and (2) investigated the scale-dependent relationships between Ta/PAR and NEE.

2. Methods

2.1. Site characteristics

Our study site is located in a 70-year-old oak-dominated forest within Oak Openings Preserve Metropark near Toledo (N 41.55°, W 83.84°) in northwest Ohio, USA. The forest comprises a mosaic of oak (*Quercus* spp.) woodlands, maple (*Acer* spp.) floodplains, remnants of oak savanna, and barrens and prairie (Brewer and Vankat, 2004). The topography is flat with an elevation range of 200–205 m. The long-term mean annual air temperature is 9.2 °C and the annual total precipitation is 840 mm (Noormets et al., 2008). The height of the dominant trees is ~24 m, with an average canopy height of ~20 m. An open-path eddy-covariance (EC) system was mounted on the top of a 34-m tower surrounded by uniform canopy in all directions with similar species and age composition (Xie et al., 2014).

2.2. Flux measurement

Turbulent exchanges of CO_2 (Fc) between the forest and the atmosphere were measured using the EC method (Lee et al., 2004) since November, 2003. The EC system consists of a LI-7500 infrared gas analyzer (IRGA; Li-COR Biosciences, Lincoln, NE, USA) that measures high-frequency CO_2 densities and a 3-dimensional sonic anemometer (CSAT3; Campbell Scientific, Inc. (CSI), Logan, UT, USA) that measures wind speed/direction. Raw data spikes (>6 standard deviations) were removed; wind coordinates were rotated to mean streamline plane calculated from wind data over an entire year (Wilczak et al., 2001) and temperature was corrected for changes in atmospheric humidity and pressure (Schotanus et al., 1983). Each 30-min mean flux value was then calculated as the covariance of vertical wind speed, air temperature, and CO_2 densities using the Webb–Pearman–Leuning correction (Massman and Lee, 2002; Webb et al., 1980). The warming of the IRGA above air temperature was corrected to 30-min fluxes (Grelle and Burba, 2007). The 30-min NEE (μmol CO_2 m^{-2} s^{-1}) was calculated as the sum of turbulent flux and the CO_2 storage was estimated as mean rate of 30-min change in $\mathbf{CO_2}$ concentrations measured within the canopy.

To exclude outliers and bad data, all 30-min flux data from the EC tower was quality checked, including stationarity, integral turbulence characteristics, and friction velocity thresholds (Noormets et al., 2008). As a result, gaps exist for long time series NEE (Table 1). The gaps were filled using a dynamic