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Multi-scale dynamics and environmental controls on net ecosystem CO_2 exchange over a temperate semiarid shrubland

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ABSTRACT

Our understanding of the variability in net ecosystem CO_2 exchange (*NEE*) across different timescales is still limited, as terrestrial carbon cycle models often mismatch data at multiple timescales. Especially, multi-scale environmental controls on *NEE* are less well understood in semiarid shrublands than in mesic ecosystems. We collected eddy-covariance measurements of *NEE* over five years (2012–2016) from a semiarid shrubland in northern China, and then used continuous wavelet transform (CWT), wavelet coherence (WTC), and partial wavelet coherence (PWC) analysis to investigate how photosynthetically active radiation (*PAR*), air temperature (T_a), vapor pressure deficit (*VPD*), and soil water content (at 30-cm depth, SWC_{30}) modulate the variability of *NEE* in the time-frequency domain. CWT revealed that *NEE* not only had clear daily and annual periodicities, but also oscillated strongly at intermediate scales (days, weeks to months). At the 1-day period, *NEE* showed significant WTC with *PAR*, T_a, and *VPD* during growing seasons, with *NEE* leading *PAR* by about 1.0 h and leading T_a and *VPD* by over 3.5 h. At the 1-year period, *NEE* also showed strong WTC with *PAR*, T_a, and *VPD* throughout time, with *NEE* lagging T_a by 19 days and lagging *PAR* and *VPD* by about 40 days. At intermediate periods, non-continuous areas of significant WTC were observed between *NEE* and environmental factors, notably between *NEE* and *PAR* at 4–32-day periods during growing seasons. PWC revealed a greater modulating effect of *PAR* than that of T_a on *NEE* at intermediate periods. However, the intermediate-scale *PAR* effects were largely weakened during spring or summer drought periods (i.e., low SWC_{30}). In addition, drought events were identified as hotspots of WTC between *NEE* and SWC_{30} at monthly or longer timescales. This study highlights the need for a multi-scale approach to understanding the temporal dynamics of *NEE*. Modeling efforts should take into account these multi-temporal correlations between *NEE* and environmental factors in order to improve model-data agreement across timescales.

1. Introduction

Drylands (semiarid and arid areas) cover nearly half of the Earth's land surface (Huang et al., 2017), and they have been expanding in many regions around the world due to climate change and human activities (Berg et al., 2016; Huang et al., 2016). Recent studies highlight an important role of semiarid ecosystems in driving the global climate-carbon (C) cycle feedbacks (Poulter et al., 2014; Ahlström et al., 2015; Huang et al., 2017). Despite the importance of drylands, C exchange and its influencing factors across different timescales (i.e., hours to years) are less well understood in such ecosystems than in mesic forests and grasslands, limiting our ability to predict terrestrial C dynamics under changing climatic conditions.

Net ecosystem CO_2 exchange (*NEE*) between the atmosphere and ecosystems is simultaneously modulated by a variety of biophysical factors (e.g., radiation, temperature, precipitation, soil moisture, and vegetation) over multiple temporal scales (i.e., from seconds to years to decades) (Fig. 1). These factors exhibit a wide range of amplitudes and phases, which modulate the spectral properties of *NEE* (Stoy et al., 2005, 2009). At the hourly scale, precipitation events and changes in wind and cloud are likely to drive *NEE* dynamics through their effects on radiation, temperature, soil moisture, and stomatal conductance (Stoy et al., 2005). At the daily scale, *NEE* is driven primarily by diel cycles of solar radiation, temperature, and vapor pressure deficit (*VPD*) (Jia et al., 2014; Ouyang et al., 2014). At timescales from multi-days to multi-months, synoptic weather patterns, passages of fronts and

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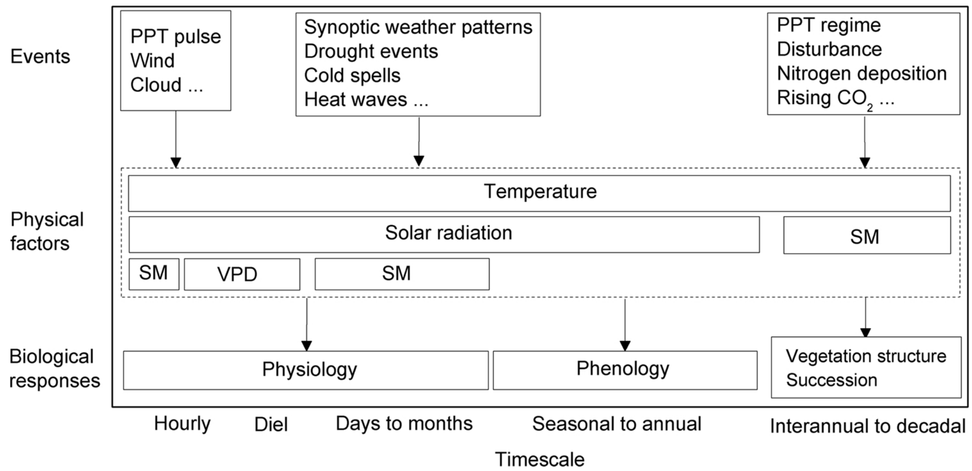

Fig. 1. A conceptual description of biophysical factors that drive net ecosystem CO_2 exchange (*NEE*) over multiple timescales. Driving factors of *NEE* included in this diagram are by no means exhaustive. Abbreviations: PPT, precipitation; SM, soil moisture; VPD, vapor pressure deficit.

pressure systems, cold spells, and heat waves can alter radiation, temperature, and water conditions, causing physiological responses and thus variations in *NEE* (Baldocchi et al., 2001; Hong and Kim, 2011). At seasonal and annual scales, *NEE* dynamics are largely affected by plant phenology and annual cycles of sunlight and temperature (Stoy et al., 2005; Ouyang et al., 2014). At interannual to decadal timescales, *NEE* may respond to climate change and variability, ecological dynamics (e.g., disturbance and succession), and environmental changes (e.g., nitrogen deposition and rising atmospheric CO_2) through changes in canopy structure or species composition (Stoy et al., 2005). Despite these understandings, process-based models rarely satisfactorily predicted *NEE* dynamics across varying timescales (Stoy et al., 2013), indicating the necessity to improve our knowledge on the variability of *NEE*. Quantifying the multi-temporal relationships between CO_2 fluxes and environmental factors is necessary for a full understanding of the climate change impacts on terrestrial C cycle (Stoy et al., 2009; Vargas et al., 2012), and could assist in the parameterization and validation of C cycle models across different timescales (Vargas et al., 2010, 2012; Stoy et al., 2013).

Current understanding on the multi-scale variability of *NEE* is mainly derived from forest ecosystems. Few studies are available on *NEE* dynamics and its controlling factors across multiple timescales in dryland ecosystems. The large uncertainty in predicting the C balance of semiarid ecosystems (Biederman et al., 2017) reflects a lack of mechanistic understanding on C dynamics across multiple timescales. Environmental controls on *NEE* in dryland areas can be different from those in mesic forests and grasslands in several ways (Jia et al., 2014, 2016a; Poulter et al., 2014). Firstly, extremely high temperature, solar radiation, and *VPD* during daytime in summer can induce partial stomatal closure, depress *NEE*, and thus shift diurnal *NEE* peaks toward morning hours (Fu et al., 2006; Jia et al., 2014). Rain pulses (and related "Birch effect") were also observed to trigger fast *NEE* responses at timescales less than a day (Huxman et al., 2004; Jarvis et al., 2007; Jia et al., 2014). Secondly, dryland ecosystems are frequently subject to droughts, wet-dry cycles, and sand storms (Huang et al., 2017), which all affect *NEE* dynamics at daily to seasonal scales. Thirdly, semiarid shrublands and steppes usually show larger seasonal and interannual variability in temperature, precipitation, and therefore in *NEE* than do mesic ecosystems (Biederman et al., 2017). Consequently, *NEE* in dryland ecosystems may have distinct spectral characteristics and multi-temporal correlations with environmental factors.

It is challenging to detect the detailed information on times, timescales, and lags of covariance between *NEE* and related environmental factors by just visually examining their time series (Baldocchi et al., 2001). Conventional analyses (e.g., correlation) suggest that biophysical controls on CO_2 fluxes vary with timescales (Fu et al., 2006; Zhang et al., 2007; Jia et al., 2014). Spectral analyses, such as Fourier or wavelet transforms, have yielded valuable insights into the temporal dynamics of *NEE* and its biophysical controls (Baldocchi et al., 2001; Qin et al., 2008; Ouyang et al., 2014). Fourier transform is well suited for stationary signals whose spectral components do not vary over time. However, CO_2 flux measurements are non-stationary in nature (Vargas et al., 2010; Ouyang et al., 2014). Moreover, scale-dependent controls on *NEE* are not constant over time, but vary within and between seasons (Cazelles et al., 2008). In contrast to Fourier transform, wavelet methods can be used to analyze transient dynamics for the association between two time series (Grinsted et al., 2004; Cazelles et al., 2008). Therefore, they are a powerful tool for exploring the variability of *NEE* and its biophysical controls. Unfortunately, few studies (if any) have applied wavelet techniques to multi-year *NEE* measurements in dryland ecosystems.

We collected half-hourly eddy-covariance (EC) measurements of *NEE* over five years (2012–2016) from a semiarid shrubland in northern China. The shrubland ecosystem lies at the south edge of the Mu Us Desert, an ecotone between semiarid and arid climates. From the mid-20th century, anthropogenic disturbances (e.g., over-grazing) have caused severe vegetation degradation in this area (Chen and Duan, 2009). Rehabilitation practices in the past two decades have promoted a dramatic expansion of shrubland distribution, which is considered a sign of desertification reversal (Jia et al., 2016b). Our previous studies have explored the diurnal, seasonal, and interannual variations of *NEE* in the shrubland ecosystem (Jia et al., 2014, 2016a). In this study we used continuous wavelet transform (CWT), wavelet coherence (WTC), and partial wavelet coherence (PWC) analysis to investigate how photosynthetically active radiation (*PAR*), air temperature (T_a), *VPD*, and soil water content modulate the variability of *NEE* (i.e., amplitudes and phases) in the time-frequency domain. We specifically addressed timescale-dependent controls and investigated whether and how their effects vary with time. We tested the hypotheses that *NEE* shows consistent daily and annual variations as influenced by cycles of solar radiation; and that *NEE* dynamics at intermediate timescales are affected by fluctuations in soil moisture, which in turn are determined by seasonal precipitation patterns.

2. Materials and methods

2.1. Study site

This study was conducted at the Yanchi Research Station (37°42′31″N, 107°13′37″E, 1530 m a.s.l.) of Beijing Forestry University.