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Analysis and estimation of tallgrass prairie evapotranspiration in the central United States

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ABSTRACT

Understanding the factors controlling evapotranspiration (ET) of spatially distributed tallgrass prairie is crucial to accurately upscale ET and to predict the response of tallgrass prairie ecosystems to current and future climate. The Moderate Resolution Imaging Spectroradiometer (MODIS)-derived enhanced vegetation index (EVI) and ground-based climate variables were integrated with eddy covariance tower-based ET (ET_{EC}) at six AmeriFlux tallgrass prairie sites in the central United States to determine major climatic factors that control ET over multiple timescales and to develop a simple and robust statistical model for predicting ET. Variability in ET was nearly identical across sites over a range of timescales, and it was most strongly driven by photosynthetically active radiation (PAR) at hourly-to-weekly timescales, by vapor pressure deficit (VPD) at weekly-to-monthly timescales, and by temperature at seasonal-to-interannual timescales at all sites. Thus, the climatic drivers of ET change over multiple timescales. The EVI tracked the seasonal variation of ET_{EC} well at both individual sites ($R^2 > 0.70$) and across six sites ($R^2 = 0.76$). The inclusion of PAR further improved the ET-EVI relationship ($R^2 = 0.86$). Based on this result, we used ET_{EC}, EVI, and PAR (MJ m^{-2} d^{-1}) data from four sites (15 site-years) to develop a statistical model ($ET = 0.11$ PAR + 5.49 EVI − 1.43, adj. $R^2 = 0.86$, $P < 0.0001$) for predicting daily ET at 8-day intervals. This predictive model was evaluated against additional two years of ET_{EC} data from one of the four model development sites and two independent sites. The predicted ET ($ET_{EVI+PAR}$) captured the seasonal patterns and magnitudes of ET_{EC}, and correlated well with ET_{EC}, with R^2 of 0.87-0.96 and RMSE of 0.35-0.49 mm d^{-1}, and it was significantly improved compared to the standard MODIS ET product. This study demonstrated that tallgrass prairie ET can be accurately predicted using a multiple regression model that uses EVI and PAR which can be readily derived from remote sensing data.

1. Introduction

Evapotranspiration (ET) is a key component of the hydrologic cycle as approximately two-thirds of the precipitation received by the land surface is returned to the atmosphere via ET (Baumgartner et al., 1975) and it links atmospheric, hydrological, and ecological processes (Pielke et al., 1998). Understanding of the biological and climatic controls of ET has been a focus of climate change research for the past few decades (Brümmer et al., 2012). Currently, the eddy covariance (EC) technique is a widely used method for measuring ET at spatial scales of 100 s of meters (Baldocchi et al., 1988; Rana and Katerji, 2000) across temporal scales of hours to years (Baldocchi et al., 2001a). The concurrent measurement of climate variables at EC sites allows the examination of the driving factors that govern the variability of ET. Several studies have shown that ET is controlled by a number of climate variables such as solar radiation, air temperature (T_a), soil water content (SWC), vapor pressure deficit (VPD), and biological factors such as leaf emergence/development (Hu et al., 2009; Monteith, 1965; Priestley and Taylor, 1972; Stoy et al., 2006; Wagle et al., 2016a; Zha et al., 2010). Still, a lack of detailed information exists concerning cross-site vari-

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ability in ET and its response to major climatic factors at multiple timescales within widely distributed tallgrass prairie, a native and largely distributed ecosystem across central North America and considered a unique grassland unmatched elsewhere in the world (Changnon et al., 2002). Currently, it is the most endangered ecosystem in North America, occupying less than 4% of its pre-settlement area (~60 million ha) (Samson and Knopf, 1996). However, tallgrass prairie grasslands still provide habitat to support numerous grassland birds and other sensitive species, and contribute heavily for livestock production in several states of the United States. Thus, quantifying the extent to which ET varies in its response to climatic factors at multiple timescales within widely distributed tallgrass prairie ecosystems is crucial to move beyond site-level ET measurements to realistic estimates of water budgets over large areas (*i.e.*, regions or continents) and to predict the responses of tallgrass prairie ecosystems to current and future climate. To interpret EC time series data and assess the contributions of processes over multiple timescales, wavelet cross-correlation analysis is a suitable quantitative tool (Katul et al., 2001). This current study performs the wavelet cross-correlation analysis to draw new insights on the response of ET from six widely distributed tallgrass prairie ecosystems across the central United States to common climatic drivers over multiple (hour-to-interannual) timescales.

As EC sites and networks are limited in spatial scale and cover only a small portion of the tallgrass prairie areas, it is necessary to develop reliable methods to estimate ET over large tallgrass prairie areas. Satellite remote sensing can complement the restricted coverage of the global land surface by ground-based observation networks. Consequently, satellite remote sensing is generally considered as the most promising tool to estimate ET over large areas (Gowda et al., 2008). Predicting ET from remote sensing data falls broadly into two approaches: i) physical models based on the surface energy balance (SEB) concept (Gillies et al., 1997) and ii) empirical or statistical models based on the relationship between ET, vegetation indices, and climate variables (Choudhury et al., 1994; Nagler et al., 2005a), and most recently based on parameterized ecosystem water use efficiency (EWUE) using enhanced vegetation index (EVI) (Wagle et al., 2016a). These physical and empirical approaches have been extensively reviewed previously (Cleugh et al., 2007; Kustas and Norman, 1999; Mu et al., 2007; Mu et al., 2011). In past two decades, several SEB models have been developed to estimate large-scale ET (Allen et al., 2007; Bastiaanssen et al., 1998; Roerink et al., 2000; Senay et al., 2013; Su, 2002). A recent study (Bhattarai et al., 2016) that evaluated five SEB models in a humid subtropical climate suggests that the performance of different SEB models could vary with varying climate, land cover types, and soil moisture conditions. In addition, relatively complex computation of several land surface variables and turbulent heat fluxes, and requirement of many parameters with detailed information can significantly affect the precise partitioning of energy components and consequently the reliability of ET estimates by SEB models when input data are not readily available (Liou and Kar, 2014). Thus, when ground-based data are available, the empirical approach is more robust and a suitable scaling tool rather than solving complex physical models (Glenn et al., 2008). In the empirical approach, vegetation indices are directly used in scaling ET rather than using them to compute several canopy properties to be used as parameters in physical models (Bonan, 1993; Glenn et al., 2007). Cleugh et al. (2007) used the Moderate Resolution Imaging Spectroradiometer (MODIS) remote sensing data and provided regional ET estimates for evergreen forest and tropical savanna in Australia using a Penman-Monteith approach (Monteith, 1965). Mu et al. (2007) revised the algorithm proposed by Cleugh et al. (2007) and produced the MOD16 global ET product (ET_{MOD16}) at 1 km spatial resolution for 109 million km^2 of global vegetated land areas at 8-day intervals using ground-based global meteorology and MODIS data. The ET_{MOD16} algorithm was further improved (Mu et al., 2011).

In the past decade, several studies have established the potential of using empirical/statistical methods derived from remotely sensed vegetation indices and EC data to extrapolate EC measurements of carbon and water vapor fluxes over large spatial scales (Cleugh et al., 2007; Jung et al., 2010; Nagler et al., 2005a; Nagler et al., 2005b; Papale and Valentini, 2003; Wylie et al., 2003; Yang et al., 2007; Yang et al., 2006; Zhou et al., 2008). Wylie et al. (2003) developed a statistical algorithm by combining normalized difference vegetation index (NDVI) and EC data over a sagebrush-steppe ecosystem to map regional carbon fluxes. Following the same approach, Nagler et al. (2005a,b) predicted ET using EVI and T_a for riparian vegetation of western rivers in the U.S., and thus, suggesting the potential of integrating EVI with ground-based climate variables for better estimates of ET. Based on these results, along with the results of our previous study (Wagle et al., 2014) that showed a strong correlation between tower-based gross primary production (GPP_{EC}) and EVI in three AmeriFlux tallgrass prairie sites, we hypothesized that a robust relationship could be established by integrating EVI and major climate variables with ET_{EC} of tallgrass prairie across the central United States to accurately estimate ET. The approach of developing statistical algorithms by combining remote sensing and ground-based climate data to estimate ET has not been applied to the tallgrass prairie. It is essential

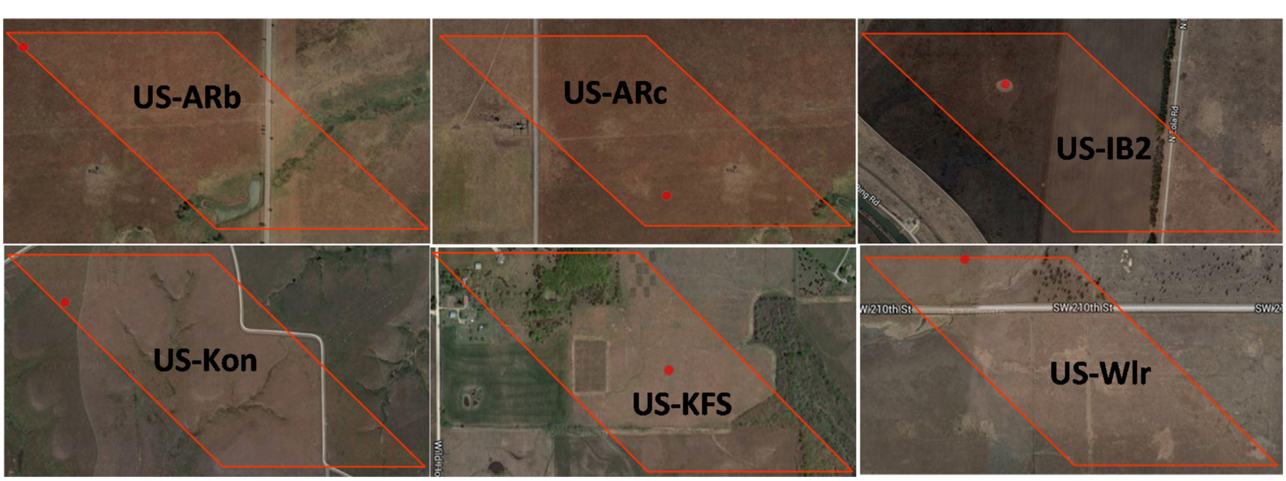

Fig 1. Landscapes of six AmeriFlux tallgrass prairie sites. The red boarder lines represent the size of one Moderate Resolution Imaging Spectroradiometer pixel (500 m spatial resolution) and the red dots represent the location of the flux towers (for interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).