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Spatiotemporal pattern of terrestrial evapotranspiration in China during the past thirty years

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A R T I C L E I N F O

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A B S T R A C T

Evapotranspiration (ET) is one of the most important fluxes in terrestrial ecosystems that regulate atmosphere–hydrosphere–biosphere interactions. Several studies have suggested that global ET has significantly increased in the past several decades, and that such increase has exhibited big spatial variability, but there are few detailed studies on the spatio-temporal change in ET over China. Here, we developed a high-resolution data-oriented monthly ET product in China between 1982 and 2015 by integrating remote-sensing and the eddy covariance technique observed ET data in a machine learning approach (model tree ensemble, MTE). We showed that the mean annual ET over China is 552 ± 14 mm yr^{-1}, which is comparable to the estimate from a MTE-derived product based on water balance, but is larger than that from both previous MTE-derived global product and process-based land surface models. ET in China significantly increased with a rate of 10.7 mm yr^{-1} per decade over the past 30 years ($p < 0.05$). The largest increases in ET (> 60 mm yr^{-1} per decade) occurred in the eastern periphery of Sichuan, southern Taiwan, and central China, which was attributed to the increases in temperature and solar radiation, as well as the enhanced vegetation productivity. About 22% of the area showed a decreasing trend in ET, mainly in parts of southeastern, southwestern, and northeastern China. The regional decrease in ET was likely due to decreasing precipitation and/or vegetation browning. Although our finding of the significant increase in China's ET at the country scale is supported by five different ET products, there are still less agreement on the change in ET at the regional scale among different ET products.

1. Introduction

Terrestrial evapotranspiration (ET) is an important flux in the global ecosystem that links water, energy, and carbon cycles (Sellers et al., 1997; Trenberth et al., 2007; Wang and Dickinson, 2012). There is a general consensus that global annual ET has increased significantly

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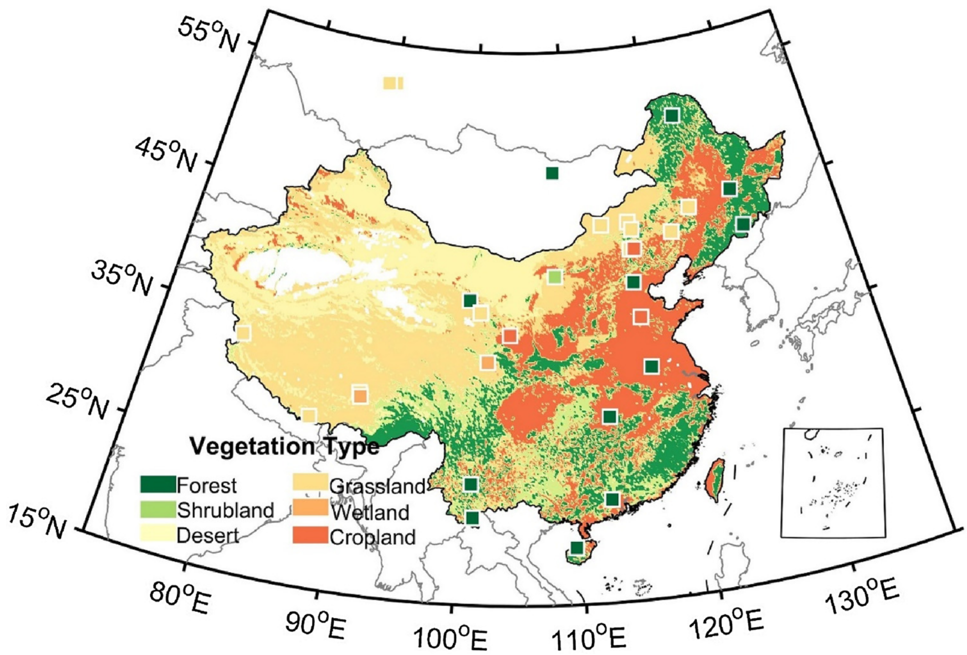

Fig. 1. Distribution of the 36 eddy covariance tower sites used in this study. Background colour shows the vegetation type: forest, shrubland, desert, grassland, wetland, and cropland.

under the impacts of climate change and human activities over the past three decades (Jung et al., 2010; Douville et al., 2012; Mueller et al., 2013; Zeng et al., 2012, 2014). However, large uncertainty still exists in the magnitude and even the sign of the ET trend at the regional scale (Jung et al., 2010; Miralles et al., 2014; Zeng et al., 2012, 2014), which refers to a national basis in this study. ET estimation can be quite different with inconsistent forcing data (e.g. sources, resolutions, accuracy, processing methods (Mueller et al., 2013; Badgley et al., 2015) and different models that can have divergent performance associated with model structures and parameterization schemes (Pan et al., 2015). In addition, the limited global long-term observations impede us to validate the model estimation and understand the potential mechanisms (Chen et al., 2014; Mao et al., 2015). Such uncertainty leads to some disagreements about spatial and temporal characteristics of ET, such as the regional ET trend as well as its drivers. Reducing uncertainty in the regional ET variation is one of the prioritized studies of the water cycle, carbon cycle, land–atmosphere interaction, as well as water management (Kustas and Norman, 1996; Bastiaanssen, 2000; Mueller et al., 2013; Jasechko et al., 2013). Previous studies attempted to reduce uncertainty by different approaches, such as applying more direct observations and integrating multiple models (e.g., Yao et al., 2017)

Several approaches have been used to investigate the global ET change based on a combination of satellite and ground observations (Mu et al., 2007; Jung et al., 2010; Zhang et al., 2010; Mu et al., 2011; Yan et al., 2012; Zeng et al., 2012, 2014). In particular, data-driven models have been applied to generate a global ET dataset using the eddy covariance measurements (Jung et al., 2009, 2010). Unlike process-driven land surface models that are complex and subject to uncertainty from model-specific structure and parameter schemes (Pan et al., 2015; Rigden and Salvucci, 2015; Yao et al., 2017), this data-driven method depends less on theoretical and empirical assumptions. In addition, the eddy covariance technique provides direct observations of ET at the site level, whereas the flux tower is not uniformly distributed and very few flux sites are available over some climate change hotspot regions (e.g., tropical and arctic regions). This inhomogeneous distribution results in large uncertainties in ET estimates at both regional and global scales. China encompasses a wide range of climate and vegetation types; yet, only nine flux tower sites in China have been used in the global ET dataset reconstructed using the eddy covariance technique (Jung et al., 2010). This could lead to a large uncertainty in the global and China ET estimates.

In this study, we collected observations from 36 flux tower sites covering almost all ecosystem types in China and applied model tree ensemble (MTE) algorithms to reconstruct a monthly ET dataset over China with a spatial resolution of 0.1° from 1982 to 2015. The MTE method has been proven to be robust of extrapolating ET to the regions not covered by eddy covariance towers (Jung et al., 2010). Compared with the sophisticated models, this empirical method links the ET to various driving variables that can be obtained easily (Zhang et al., 2016a). This method is complementary to process-based models because there is a large spread in current model estimates of ET (Jung et al., 2011). We improved the China's ET estimates through using more in-situ measurements, eliminating the problem of solar radiation (which is a key limitation in Jung's ET product, 2010), as well as realizing a higher spatial resolution and a longer time period.

We compared our ET estimates with global ET datasets, including a data-driven empirical model with ET measurements calculated using the eddy covariance technique (Jung et al., 2009), a data-driven empirical model with ET observations from terrestrial water balance (Zeng et al., 2014), and three datasets from process-based land surface models (the Community Atmosphere Biosphere Land Exchange (CABLE), (Wang et al., 2010b); the Organizing Carbon and Hydrology In Dynamic Ecosystems Environment (ORCHIDEE), Krinner et al., 2005; and the Version 4 of the Community Land Model with coupled Carbon and Nitrogen cycles (CLM4CN), Oleson et al., 2010). We discussed the uncertainty and limitations of ET products through comparing the spatial and temporal characteristics of ET.

2. Material and methods

2.1. Data sources

2.1.1. Data from the eddy covariance flux tower sites

The global network of micrometeorological flux measurement sites (FLUXNET) provides ground measurements of carbon, water, and energy fluxes, as well as meteorological, plant, and soil data, on a continuous and long-term basis (Baldocchi et al., 2001). The eddy