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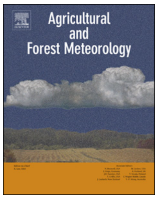

Optical-based and thermal-based surface conductance and actual evapotranspiration estimation, an evaluation study in the North China Plain

Xiaolong Hu[a], Liangsheng Shi[a,*], Lin Lin[a], Baozhong Zhang[b], Yuanyuan Zha[a]

[a] State Key Laboratory of Water Resources and Hydropower Engineering Sciences, Wuhan University, Wuhan, Hubei, 430072, China
[b] State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing, 100038, China

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ABSTRACT

Accurate estimation of surface conductance (G_s) and evapotranspiration (ET) from remote sensing data has received increasing interest, but the data interpretation method requires further development. The objective of this study is to evaluate the capability of optical and thermal information to quantify G_s and ET in the frame of the Penman-Monteith model. We evaluated the three remote sensing data-based retrievals of daily G_s and ET using Moderate Resolution Imaging Spectroradiometer (MODIS) data and eddy covariance measurements at three sites in the North China Plain. The G_s models were established on the basis of (1) single vegetation index (VI), including normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI), (2) temperature vegetation dryness index (TVDI), and (3) combination of VI and TVDI. The results demonstrated that the combination of NDVI and theoretical TVDI achieved the best accuracy of quantifying G_s and ET. The single VI-based model also performed well. The empirical TVDI-based model failed to estimate G_s and ET since there existed significant uncertainties in the calculation of the dry and wet edge. In contrast, the theoretical TVDI with an apparent seasonal pattern was of more value to acquire G_s and ET due to its explicit physical mechanism. From this study, the combination of VI and TVDI, as well as single VI, were recommended to build alternative approaches to acquiring ET. These G_s models highly rely on remote sensing data and thus show promising potential in regional-scale application.

1. Introduction

Evapotranspiration is the nexus of the water (evaporation), energy (latent heat flux) and carbon cycles (transpiration-photosynthesis tradeoff). It is reported that the global land ET is more than $60 \times 10^3\,km^3$, returning about 60% of annual land precipitation to the atmosphere (Mu et al., 2011; Jung et al., 2010; Oki and Kanae, 2006; Fisher et al., 2017). Information on ET has been widely investigated in a variety of scientific explorations and social applications. In agricultural ecosystems, ET is the primary way of water consumption on cropland. Accurate estimation of the ET over large irrigated agricultural areas is of critical importance to agricultural water resource assessment and management during food production.

The North China Plain is the most important agricultural production area in China but suffering from the severe water crisis such as groundwater depletion. The high water consumption in agriculture is acknowledged as the dominant cause (Hu et al., 2016). Some studies employed in situ measurements, such as weighing lysimeter, eddy covariance system and large aperture scintillometer, to quantify ET in cropland (Liu et al., 2002; Lei and Yang, 2010; Liu et al., 2013; Shen et al., 2013). Although these in-site measurement techniques offer precise information for ET at the field or smaller scale, they are not able to describe the spatial variation of ET in regional scale.

The marked advancement of remote sensing technology provides us with temporally and spatially continuous information of the land surface. Uniting space-based and ground-based observation makes it possible to monitor large-scale ET. Generally, five main remote sensed-based algorithms have been developed to estimate regional ET over the past several decades, including (1) regression model (Wang and Liang, 2008; Wang et al., 2010); (2) triangle or trapezoid method (Price, 1990; Tang et al., 2010; Long and Singh, 2012; Minacapilli et al., 2016); (3) surface energy balance model (Norman et al., 1995; Bastiaanssen et al., 1998; Su, 2002; Yang and Shang, 2013); (4) scaling of potential evapotranspiration (Fisher et al., 2008; Guerschman et al., 2009); and (5) Penman-Monteith model (Cleugh et al., 2007; Mu et al., 2007, 2011; Leuning et al., 2008; Zhang et al., 2010; Yan et al., 2012). Additionally, few studies have attempted to improve the accuracy of ET estimation by integrating multiple models simultaneously (Wu et al., 2012; Chen

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[*] Corresponding author.
E-mail address: liangshs@whu.edu.cn (L. Shi).

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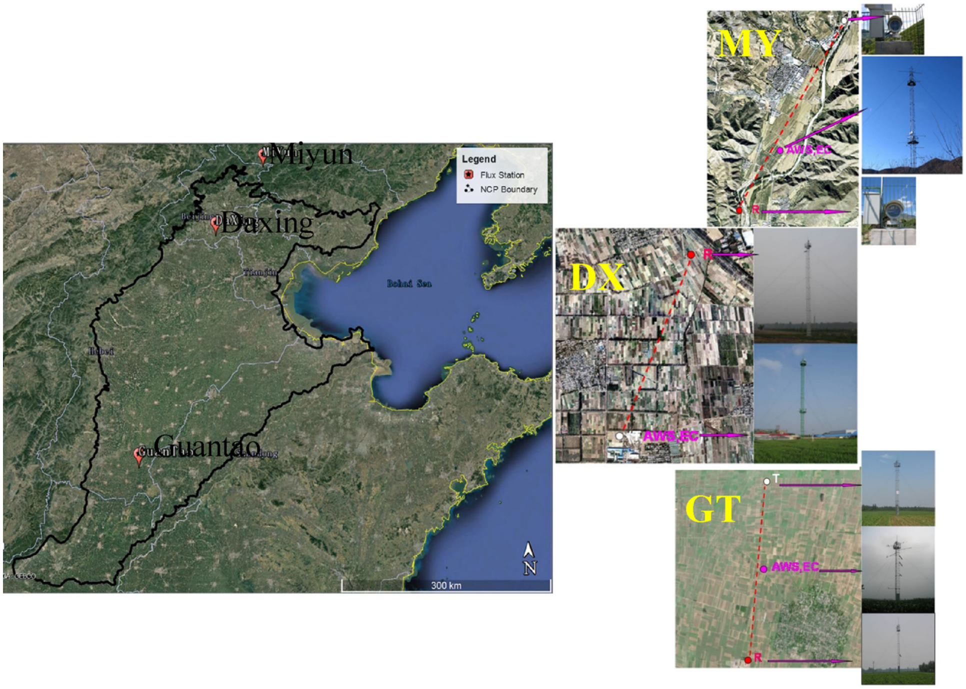

Fig. 1. The location of three eddy covariance flux stations (From WestDC, http://westdc.westgis.ac.cn/).

et al., 2015; Yao et al., 2014, 2017). Among these methods, the Penman-Monteith model with a precise and straightforward physical mechanism is considered as the preferable algorithm and has been intensively employed in the fields of agriculture, hydrology, remote sensing, etc. The urgent challenge of applying the Penman-Monteith model is the parameterization of bulk surface conductance. The conception of G_s originates from the big-leaf model (Monteith, 1965), which assumes the land surface as a uniform layer. In principle, the G_s should be furtherly subdivided into canopy surface conductance and soil surface conductance (Shuttleworth and Wallace, 1985), while there is usually no distinction between bulk surface conductance and canopy surface conductance in the large scale (Monteith and Unsworth, 2008) since the transpiration typically is the primary component. Understanding of the relationship between stomatal conductance/surface conductance and environmental factors is gradually deepened from two aspects.

On the one hand, the variation of stomatal conductance is determined by environmental variables, and conductance at the field scale is linked with leaf area index (LAI). Thus, it is logical to parameterize G_s by meteorological data and LAI. Jarvis (1976) firstly employed photon flux density, temperature, vapor pressure deficit, leaf water potential and ambient CO_2 concentration to parameterize stomatal conductance. Stewart (1988) further extended Jarvis stomatal conductance model to canopy scale using LAI and meteorological observations including solar radiation, specific humidity deficit, temperature, and soil moisture deficit. The Jarvis-Stewart model has been widely applied in ET estimation (Cleugh et al., 2007; Mu et al., 2007, 2011; Zhang et al., 2010; Yan et al., 2012). Also, similar models such as Leuning model (Leuning et al., 2008) and Irmak-Mutiibwa model (Irmak and Mutiibwa, 2010) have been proposed. However, these methods have several limitations: firstly, the nonlinearity of environmental stress functions increases the difficulty of acquiring model parameters; secondly, the interdependence of environmental variables (such as air temperature and vapor pressure deficit) may result in misestimates the model parameters (Wang et al., 2014); thirdly, spatial meteorological data are not directly measured but interpolated with sparse station measurements, which introduces additional uncertainty. Given the ability of remote sensing indexes to capture the vegetation and soil properties, for example, LAI and canopy moisture, some latest studies introduced vegetation index and passive microwave index to estimate G_s (Yebra et al., 2013; Barraza et al., 2015, 2017; Bai et al., 2017).

On the other hand, the G_s controls ET and eventually affects the land surface temperature, which implies that the surface temperature can be valuable information to estimate G_s. Smith et al. (1988) and Shuttleworth and Gurney (1990) developed the theoretical relationship between foliage temperature and canopy conductance for sparse crops on the basis of Shuttleworth-Wallace model. However, this relationship is over-complex and of limited applicability. Jones (1999a,b), Leinonen et al. (2006) and Guilioni et al. (2008) simplified the model by introducing dry and wet reference temperatures and employed the temperature index to estimate stomatal conductance at the leaf scale. Recently, Berni et al. (2009), Autovino et al. (2016) and Amazirh et al., (2017) applied similar methods to the field-scale problem.

As stated above, the G_s can be quantified from the perspective of its controlling factors or consequent effects (such as surface temperature). Therefore, it is interesting to investigate which way is better to estimate G_s and ET in regional scale. In this work, we utilized eddy covariance measurements in the North China Plain as well as MODIS Terra/Aqua vegetation index and land surface temperature products to conduct the study. The major objectives are to (1) propose three different forms of G_s models, by using the optical-based vegetation index, thermal-based TVDI, and jointly using the optical and thermal index, respectively. Optical-based surface conductance model has been studied by Yebra et al. (2013). However, to the best of our knowledge, the latter two models have not been investigated by the previous study; (2) evaluate the role of vegetation index and surface temperature index in estimating G_s and ET. This study will build an alternative approach for accurately acquiring the temporal and spatial estimation of actual evapotranspiration.

2. Material and methods

2.1. Sites information

Three sites in the North China Plain including Guantao (GT, 115.1274E, 36.5150 N, elevation: 30 m), Daxing (DX, 116.4271E,