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Evaluating the complementary relationship for estimating evapotranspiration using the multi-site data across north China

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A B S T R A C T

The ability to predict actual evapotranspiration flux (λE_a) by physically based evaporanspiration (ET) model is limited globally due to the difficulty in validating the site-specific model parameters. Thus, the approaches for estimating λE_a using only routine meteorological variables play a critical role in understanding and predicting hydrological cycle in the context of climate change. In this study, the performance of a complementary relationship (CR) method (Granger and Gray, 1989; GG model) on different timescales (daily and half-hourly) was evaluated using a high-quality dataset of selected 12 eddy covariance flux towers, which encompassed a number of cropland, grassland, evergreen needleleaf forest, desert shrub and wetland sites across northern China. The results indicated that the GG model is applicable in estimating daily λE_a for most ecosystems across northern China. However, significant underestimations of daily λE_a were found for the croplands (Daman and Dunhuang sites) and the desert shrub (Ejina) in the arid northwest China, which may be attributed to the enhanced λE_a by horizontal advection and the deep root water-uptake, respectively. By using the Monin-Obukhov similarity theory with a surface energy balance constraint, the model performance on half-hourly timescale was satisfactory for the 12 tower sites with R^2 ranging from 0.54 to 0.81 and the slopes of Deming regression line between measured and simulated λE_a from 0.77 to 1.14. Indeed, the study highlights the need for further investigation of the timescale dependence of the CR-based ET models.

1. Introduction

Evapotranspiration (ET) is an important land surface process in climatology and a nexus for modeling terrestrial water, energy and carbon cycles (Jung et al., 2010). Thus accurate estimation of ET (or λE_a, i.e., latent heat flux, where λ is the latent heat of vaporization) on a daily or subdiurnal time steps is crucial to a wide range of problems in hydrology (Xu and Singh, 2005; Zhu et al., 2013), agronomy (Zhu et al., 2014a), macroecology (Fisher et al., 2011), and weather and climate prediction (Wang and Dickinson, 2012). In this paper, ET or λE_a is used interchangeably depending on whether water or energy flux is the primary consideration. There exist a multitude of one- or two-source physically based models to estimate λE_a (Penman, 1948; Monteith, 1965; Shuttleworth and Wallace, 1985; Lhomme and Chehbouni, 1999). Unfortunately, validating site-specific model parameters such as the aerodynamic, canopy, and soil resistances remains challenging (Salvucci and Gentine, 2013), resulting in their practical use at regional or global scales to be limited (Xu and Singh, 2005). Hence, it is important to find a way to derive λE_a using standard meteorological variables without detailed knowledge of the surface states (e.g., leaf area, soil texture, soil moisture and stomatal conductance) (Brutsaert, 2005; Crago and Crowley, 2005; Salvucci and Gentine, 2013).

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For this purpose, a complementary relationship (CR) was first proposed by Bouchet (1963) forming the basis for the development of several ET models. These include the complementary relationship areal evapotranspiration (CRAE) model (Morton, 1983) and the advection-aridity (AA) model (Brutsaert and Stricker, 1979). It should be noted that the CR between actual and potential evapotranspiration was constrained to be symmetric in the CRAE and AA models. Despite considerable work, some studies claim that the assumed symmetric nature of the CR may be invalid for certain conditions (Kahler and Brutsaert, 2006; Szilagyi et al., 2009; Pettijohn and Salvucci, 2006, 2009; Crago and Qualls, 2013). Thus, many researchers have attempted to develop rigorous derivations of the CR (Crago and Qualls, 2013). Granger and Gray (1989) first derived an asymmetric CR to estimate λE_a by using a procedure similar to that of Penman (1948) (hereafter referred to GG model). Interestingly, Szilagyi (2007) obtained the same operational ET model as the GG model although through different theoretical considerations of Granger and Gray's (1989). Over the past decades, numerous studies were carried out to either evaluate or compare the performance of the CR-based ET models. For example, Crago and Crowley (2005) illustrated that the GG model performed by far the best among the six CR-based ET models in a comparative study. Also, it has been reported that significant bias (i.e., underestimation of λE_a for dry conditions and overestimation of λE_a for wet conditions) may result in the AA model (Ali and Mawdsley, 1987; Crago and Brutsaert, 1992; Qualls and Gultekin, 1997; Hobbins et al., 2001). However no similar observations were found for the GG model (Han et al., 2011; Xu and Chen, 2005). Recently, Anayah and Kaluarachchi (2014) reported that the GG model was the most attractive when compared to the CRAE and AA models across 34 global sites. In our prior evaluation studies, the performance of the GG model was quite satisfactory among five commonly used ET models (see details in Supplement 1). Thus, in this study we mainly focus on the GG model as a physical framework to investigate the possibility of deriving a time series of λE_a with only standard meteorological data.

Nevertheless, there are still limitations in the application of the GG model. First, the nonlinear relationship between the relative evapotranspiration ratio and the drying power in Granger and Gray's original work (1989) was derived based on limited data points (158) of λE_a in absence of measurements from wet environments. Thus, its applicability over a wide range of land types and climatic conditions need to be further investigated (Long and Singh, 2010). Secondly, the GG model has mostly been used on a specific timescale, namely monthly (Xu and Singh, 2005; Anayah and Kaluarachchi, 2014), daily (Han et al., 2011) and subdiurnal (Crago and Crowley, 2005). However, systematic comparisons of its performances on different timescales are relatively sparse and its dependence on timescales is not fully understood (Crago and Qualls, 2013). Finally, the arid northwestern China is characterized by a widely distributed Gobi desert interspersed with many oases of different sizes and shapes (Zhu et al., 2014a). Land surface processes of this heterogeneous region are much more complex than in other regions (Wang and Mitsuta, 1992). Thus, the applicability of the GG model in such regions needs to be investigated in details.

In the present study, the objective is to understand and evaluate the performance of the GG model in estimating λE_a at two different timescales (i.e., daily and half-hourly). This effort is achieved by using a collection of high quality eddy covariance flux tower data across a variety of land surface types and conditions in northern China. The main research questions of this study include: (1) determine if the nonlinear relationship between the relative evapotranspiration ratio and the drying power proposed by Granger and Gray (1989) is suitable for different land cover types and climatic conditions; (2) evaluate the performance of the GG model at different timescales, and (3) identify the main sources of uncertainty in computing λE_a using the GG model.

2. Materials and methods

2.1. Study sites

One of the principal limitations in the evaluation of ET models is the availability of accurate and descriptive input forcing data (Baldocchi et al., 2004). The Coordinated Enhanced Observation Project (CEOP) in arid and semi-arid regions in northern China (http://observation.tea.ac.cn/) provides a high-quality dataset of surface fluxes and meteorological data, and makes them an appropriate source for model evaluation. In this study, the model was tested against 12 eddy covariance (EC) flux sites representing a range of vegetation/land cover types in northern China that included cropland, grassland, wetland, desert shrub and forest. These datasets are listed in Table 1. For croplands, two sites (Dunhuang and Daman) are located in the arid northwest China and the others in semi-arid northern China. For grasslands, Arou is an alpine meadow site, Yuzhong represents a typical steppe, Dongsu represents a desert steppe, while Tongyu represents a degraded grassland. For forest and shrub ecosystems, Guantan is a sub-alpine spruce (*P. crassifolia*) forest site, and Ejina represents a typical desert shrub (*Tamarix* spp.). The Maqu alpine wetland is located on the Qinghai-Tibet Plateau and is classified as a semi-humid climatic zone.

2.2. Measurements and data processing

The EC systems were mounted on towers ranging from 2 to 25 m above the various canopy heights (Table 1). Each EC system consisted of a three-dimensional sonic anemometer (CSAT3, Campbell Scientific Inc., UT, USA) that measured instantaneous horizontal (u, v), vertical (w) wind speeds and sonic air temperature fluctuations and an open path infrared gas analyser (Li-7500, LI-COR Inc., USA) that measured the water vapour density and carbon dioxide concentrations fluctuations. The EC instruments were sampled at a frequency of 10 Hz and data were continuously recorded on a data logger (CR5000, Campbell Scientific Inc.). Post-processing calculations were performed using the EdiRe (University of Edinburgh, http://www.geos.ed.ac.uk/abs/research/micromet/EdiRe) software package that included spike detection, lag correction of H_2O/CO_2 relative to the vertical wind component, sonic virtual temperature conversion, planar fit coordinate rotation, the WPL (Webb et al., 1980) density fluctuation corrections and frequency response corrections (Xu et al., 2014). Data gaps (usually no more than 25% of total observations) due to instrument malfunction, power failure and bad weather conditions were filled using an artificial neural network (ANN) and mean diurnal variations (MDV) methods (Falge et al., 2001). The gap-filled daily mean actual latent heat flux (λE_a) by the two methods were quite similar to the observed values (see details in Supplement 1). The energy closure which may be affected by many factors is still a key indicator to assess the quality of the flux data. Liu et al. (2011) examined the energy closure at the different sites of the CEOP sites. Overall, the energy balance closure (the sum of sensible heat and latent heat against available energy) for half-hourly data ranged from 81% to 90% with a mean about 85% across all EC flux towers. On daily basis, the energy balance closure slightly improved and ranged from 85% to 98% with a mean of 92%.

Continuous ancillary measurements also included standard hydro-meteorological variables. These included rainfall (TE525MM, Campbell Scientific Instruments Inc.), air temperature, relative humidity (HMP45C, Vaisala Inc., Helsinki, Finland), wind speed/direction (034B, Met One Instruments Inc., USA), downward and upward solar and longwave radiation (PSP, The EPPLEY Laboratory Inc., USA), soil temperature (Campbell-107, Campbell Scientific Instruments Inc.) and moisture (CS616,