Journal of Hydrology 563 (2018) 576–585

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

On the attribution of changing crop evapotranspiration in arid regions using four methods

Sien Li[a,*], Shaozhong Kang[a], Lu Zhang[b], Jianhua Zhang[c]

[a] Center for Agricultural Water Research in China, China Agricultural University, Beijing, China
[b] CSIRO Land and Water, GPO Box 1666, Canberra, ACT 2601, Australia
[c] School of Life Sciences and State Key Laboratory of Agrobiotechnology, The Chinese University of Hong Kong, Hong Kong

ARTICLE INFO

This manuscript was handled by Marco Borga, Editor-in-Chief, with the assistance of Yongqiang Zhang, Associate Editor

Keywords:
Climatic change
Evapotranspiration
Maize
Penman-Monteith model
Vegetative control

ABSTRACT

Accurate evaluation of the relative contribution of climatic and vegetative drivers on land evapotranspiration (ET) is critical for interpreting the ET controlling mechanism, modeling and predicting. However, how to accurately separate and estimate the contribution of climatic and vegetative changes on ET variation remains uncertain. Our study attempted to interpret the interannual variation in ET during 2007–2013 over a maize field in northwest China, using four methods simultaneously, such as the Penman-Monteith (PM) model, the modified crop coefficient method, the Priestly-Taylor (PT) model and the regression linear model.

Results indicate that compared to the ET in 2007, the ET decreased averagely by 12, 30, 29, and 73 W m^{-2} in 2008, 2011, 2012 and 2013, respectively. All models yielded similar results and showed that the vegetative controls played a more important role in regulating ET relative to climatic drives, and that more than half of decrease in ET was caused by vegetative factors, while the differences in net radiation, water vapor pressure deficit and air temperature among years were lesser source of variation in ET. Furthermore, the advantage and disadvantage of the four methods were discussed.

Our study confirmed the great effect of vegetative drivers in regulating crop ET, highlighted the importance of estimating canopy conductance accurately in ET modeling and prediction, and provided new approaches for separating the climatic and vegetative contribution on ET changes.

1. Introduction

Evapotranspiration (ET) is controlled by climactic and vegetative drivers, both of which are projected to change on multiple spatial and temporal scales due to the coupled effects of climate change and anthropogenic ecosystem management (Pielke et al., 1998; Houghton et al., 2001; Wear and Greis, 2002; Foley et al., 2003; Stoy et al., 2006). Thus, studying the relative roles of vegetation vs. climate on ET is critical for predicting how water cycling will respond to future climatic and biological changes, such as radiation, air temperature and humidity, and crop variety changes (Stoy et al., 2006; Roderick et al., 2007; Zheng et al., 2009; Meng and Mo, 2012; Li et al., 2013a).

Until recently, many methods have been developed to isolate the relative contribution of physical and biological drivers on ET. Wilson and Baldocchi (2000) used the linear perturbation analysis approach to estimate the percentage in ET due to changes in surface conductance, humidity deficit, net radiation and energy balance closure errors. Stoy et al. (2006) combined the eddy covariance measurements with a linear perturbation analysis method to separate the contribution of physical and biological factors on ET in three ecosystems in the southeast US. They also compared the linear perturbation analysis with the Penman-Monteith model and found the good agreement between the two approaches. Roderick et al. (2007) used a generic physical model based on mass and energy balances to attribute pan evaporation changes to changes in radiation, temperature, humidity and wind speed. Yang and Yang (2011) separated the contribution to annual runoff by combining Budyko equation and Penman equation. In 2012, they quantified the contributions of climatic factors to Epan using partial derivatives and found that the decrease in Epan was mainly determined by changes in radiation and wind speed. The study provided a new insight for understanding the effect of climatic change on evaporation (Yang and Yang, 2012). Meng and Mo (2012) applied an approach based on Budyko-type equation to separate the contributions of climatic factors to changes in annual runoff from 1960 to 2008, through multiplying their partial derivatives by the slopes of trends in climate factors. Li et al. (2013a) evaluated the relative role of climatic and biological control on energy partition based on solving the partial derivation of the Penman-Monteith model. In a latest paper of Gong et al. (2014), they used a

* Corresponding author.
E-mail address: lisien@cau.edu.cn (S. Li).

https://doi.org/10.1016/j.jhydrol.2018.06.034
Received 15 February 2018; Received in revised form 22 May 2018; Accepted 15 June 2018
Available online 18 June 2018
0022-1694/

model similar to the crop coefficient method of FAO56 to evaluate the effects of vegetation change on ET in a semiarid shrubland of the Loess Plateau, China. Yang et al. (2014) estimated the error of Mezentsev-Choudhury-Yang equation for assessing the contribution of climate change to runoff based on the Budyko hypothesis.

The previous studies generally used one method to separate the climatic and vegetative control. The results lacked of comparison and whether the result was accurate is uncertain. For example, the Penman-Monteith model and the partial derivative method are widely used to quantify the relative contribution of climatic and vegetative changes on ET. However, whether the approach is reliable and accurate remains uncertain. Other ET models, such as the Priestly-Taylor (PT) method, the crop coefficient method and the empiric linear models can be used to estimate ET, but whether they can quantify and interpret ET changes, still requires further study.

Thus we attempted to separate the contribution of climatic and vegetative changes on ET using four approaches simultaneously, namely PM, PT, the modified crop coefficient methods and the empirical linear ET model, and examine the reliability of different methods in evaluating contributions of all drives. The long-term ET data for maize measured by the eddy covariance method during 2007–2013 were adopted to analyze the interannual variation in crop ET, and interpret the mechanism of interannual variation from different perspectives.

2. Models for quantifying the variability in evapotranspiration

2.1. Quantifying the climatic and vegetative controls on ET variability using the Penman-Monteith model

The Penman-Monteith (PM) model can be written as (Monteith, 1965):

$$\lambda ET = \frac{\Delta(R_n - G) + C_p \rho_a VPD/r_a}{\Delta + \gamma + \gamma \cdot r_c/r_a} \tag{1}$$

where λET is the crop evapotranspiration ($W\,m^{-2}$), λ is the latent heat of vaporization ($J\,Kg^{-1}$), *is*is the slope of the saturation water vapor pressure versus temperature curve ($KPa\,K^{-1}$), R_n is the net radiation ($W\,m^{-2}$), G is the soil heat flux ($W\,m^{-2}$), C_p is the specific heat of dry air at constant pressure ($J\,kg^{-1}\,K^{-1}$), ρ_a is the air density ($kg\,m^{-3}$), VPD is the water vapor pressure deficit (KPa), r_a is the aerodynamic resistance ($s\,m^{-1}$), γ is the psychrometric constant ($Pa\,K^{-1}$), r_c is the canopy resistance ($s\,m^{-1}$). The aerodynamic resistance r_a can be expressed as (Paulson, 1970; Businger et al., 1971):

$$r_a = \frac{[\mathrm{In}(z/z_0) - \Psi_h][\mathrm{In}(z/z_0) - \Psi_m]}{k^2 u} \tag{2}$$

where z is the reference height (m), z_0 the roughness length of the crop relative to momentum transfer (m), k is the von Karman constant (0.41), ψ_h is the stability correction function for heat and water transfer, ψ_m is the stability correction function for momentum transfers. These stability correction functions are taken from the models of Paulson (1970). u is the wind speed at the reference height ($m\,s^{-1}$). According to Monteith (1965), z_0 can be estimated as 0.13 h_c, where h_c is the mean crop height (m).

Thus ET can be expressed as a continuous function of four climatic and one vegetative variables (Stoy et al., 2006):

$$ET = f(R_n - G,\ VPD,\ T_a,\ r_a,\ r_c) \tag{3}$$

Our study adopted the partial derivative method to calculate the variation in ET. The method also has been used to examine the changes in pan and potential evaporation by previous studies (Roderick et al., 2007; Meng and Mo, 2012; Li et al., 2013a). According to the method, ET variation can be estimated as:

$$\Delta ET = \frac{\partial ET}{\partial(R_n - G)}\Delta(R_n - G) + \frac{\partial ET}{\partial VPD}\Delta(VPD) + \frac{\partial ET}{\partial T_a}\Delta(T_a) + \frac{\partial ET}{\partial r_a}\Delta(r_a) + \frac{\partial ET}{\partial r_c}\Delta(r_c) \tag{4}$$

$$\frac{\partial ET}{\partial(R_n - G)} = \frac{\Delta}{\Delta + \gamma + \gamma \cdot r_c/r_a} \tag{5}$$

$$\frac{\partial ET}{\partial VPD} = \frac{C_p \rho_a / r_a}{\Delta + \gamma + \gamma \cdot r_c/r_a} \tag{6}$$

$$\frac{\partial \mathrm{ET}}{\partial \mathrm{T}_a} = \left(\frac{R - G}{\Delta + \gamma + \gamma \cdot \frac{r_c}{r_a}} - \frac{\Delta(R_n - G) + C_p \frac{\rho_a VPD}{r_a}}{\left(\Delta + \gamma + \gamma \cdot \frac{r_c}{r_a}\right)^2} \right) \frac{\partial \Delta}{\partial \mathrm{T}_a} \tag{7}$$

$$\frac{\partial ET}{\partial r_a} = \frac{\Delta(R_n - G)}{(\Delta + \gamma) r_a + \gamma \cdot r_c} - \frac{\Delta(R_n - G) r_a + C_p \rho_a VPD}{((\Delta + \gamma) r_a + \gamma \cdot r_c)^2}(\Delta + \gamma) \tag{8}$$

$$\frac{\partial ET}{\partial r_c} = -\frac{\Delta(R_n - G) + C_p \rho_a VPD/r_a}{(\Delta + \gamma + \gamma \cdot r_c/r_a)^2} \cdot \frac{\gamma}{r_a} \tag{9}$$

Thus the sum of changes in ET due to climatic variables can be calculated as:

$$\mathrm{P(C)} = \frac{\partial ET}{\partial(R_n - G)}\Delta(R_n - G) + \frac{\partial ET}{\partial VPD}\Delta(VPD) + \frac{\partial ET}{\partial T_a}\Delta(T_a) + \frac{\partial ET}{\partial r_a}\Delta(r_a) \tag{10}$$

While the change in ET due to vegetative controls can be defined as:

$$P(B) = \frac{\partial ET}{\partial r_c}\Delta(r_c) \tag{11}$$

The error of the method can be estimated as:

$$Error = \Delta ET_{measured} - P(C) - P(B) \tag{12}$$

In our study, ΔET between the five years was measured by the eddy covariance system. The partial derivations of ET to the variables were calculated with the measured meteorological data. We chose the meteorological data which made the least error of Eq. (12). The actual value of canopy resistance was obtained by the re-ranged Penman-Monteith model (Li et al., 2013a).

2.2. Quantifying the climatic and vegetative controls on ET variability using the modified crop coefficient method

The crop coefficient method can be expressed as follows (Allen et al., 1998):

$$ET_c = K_c ET_0 \tag{13}$$

where ET_c represents the crop water requirement ($mm\,d^{-1}$), K_c the crop coefficient, ET_0 the reference crop water requirement ($mm\,d^{-1}$). When the soil water is adequately supplied, the measured crop evapotranspiration can be nearly considered as the water requirement of maize. Thus, we can estimate K_c as the ratio of ET_c to ET_0. ET_0 was calculated by the standard method recommended by FAO 56 manual (Allen et al., 1998). In our study, we normalized ET_c and ET_0 by dividing R_n simultaneously:

$$ER = \frac{\lambda ET_c}{R_n} = K_c \frac{\lambda ET_0}{R_n} \tag{14}$$

where $\lambda ET_c/R_n$ represents the ratio of energy partition into evapotranspiration. The variability in ET_c/R_n can be calculated as:

$$\Delta\left(\frac{\lambda ET_c}{R_n}\right) = \Delta(K_c)\frac{\lambda ET_0}{R_n} + K_c \Delta\left(\frac{\lambda ET_0}{R_n}\right) + Error\left(K_c, \frac{\lambda ET_0}{R_n}\right) \tag{15}$$

Thus the changes due to climatic controls can be expressed as: