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Remote detection of bare soil moisture using a surface-temperature-based soil evaporation transfer coefficient

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ABSTRACT

An approach for estimating soil moisture is presented and tested by using surface-temperature-based soil evaporation transfer coefficient (h_a), a coefficient recently proposed through the equation $h_a = (T_s - T_a)/(T_{sd} - T_a)$, where T_s, T_{sd}, and T_a are land surface temperature (LST), reference soil (dry soil without evaporation) surface temperature, and air temperature respectively. Our analysis and controllable experiment indicated that h_a closely related to soil moisture, and therefore, a relationship between field soil moisture and h_a could be developed for soil moisture estimation. Field experiments were carried out to test the relationship between h_a and soil moisture. Time series Aqua-MODIS images were acquired between 11 Sep. 2006 and 1 Nov. 2007. Then, MODIS derived h_a and simultaneous measured soil moisture for different soil depths were used to establish the relations between the two variables. Results showed that there was a logarithmic relationship between soil moisture and h_a ($P < 0.01$). These logarithmic models were further validated by introducing another ground-truth data gathered from 46 meteorological stations in Hebei Province. Good agreement was observed between the measured and estimated soil moisture with RMSE of 0.0374 cm^3/cm^3 and 0.0503 cm^3/cm^3 for surface energy balance method at two soil depths (10 cm and 20 cm), with RMSE of 0.0467 cm^3/cm^3 and 0.0581 cm^3/cm^3 for maximum temperature method at two soil depths. For vegetated surfaces, the ratio of h_a and NDVI suggested to be considered. The proposed approach has a great potential for soil moisture and drought evaluation by remote sensing.

1. Introduction

Soil moisture plays a crucial role in surface energy balance, and is a key variable in global energy and hydrological processes study (De Roo et al., 1996). It is a sensitive indicator for monitoring agricultural environments and it is therefore of immense importance to log soil moisture information on a large scale. Accurate evaluation of soil moisture status and its spatial and temporal dynamics have vital applications in a wide range of disciplines, from earth to social sciences (Scipal and Wagner, 2004). Nevertheless, conventional measurement techniques (e.g. gravimetric and time domain reflectometry (TDR)) are generally point-based and require on-site operators and tedious post-processing analyses (Moran et al., 2000). Soil moisture forecasts by the only use of hydrological models over a large area is not always feasible, and it is often overly contingent on a number of local factors, including soil properties and hydraulic characteristics, soil homogeneity and permeability, and so forth.

Numerous studies of soil moisture estimation from remote sensing mainly focus on microwave and optical remote sensing (Ahmad et al., 2010; Das et al., 2008; Ghulam et al., 2007; Mallick et al., 2009; Njoku and Entekhabi, 1996; Paloscia et al., 2006; Pierdicca et al., 2010; Sano et al., 1998; Vivoni et al., 2008; Zhang and Wegehenkel, 2006). Microwave sensors (including active and passive) have extensive weather sensing capabilities and can operate during the whole day and night, consequently they have occupied an important place in monitoring surface soil moisture. However microwave sensors still have some limitations in comparison with the commonly used optical remote sensing data, Moderate Resolution Imaging Spectroradiometer (MODIS). For active microwave sensors with the fine spatial resolution, i.e. Synthetic Aperture Radar (SAR), the temporal resolution is low and the data cost is high. For passive remote sensing sensors with high temporal resolution, its spatial resolution is always very coarse. MODIS has the

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advantage of narrower bandwidth ranges and a wider scan range, and the data is free and available daily (every other day at the equator), when compared with other optical data, for instance Thematic Mapper (TM) data that is limited by its low frequency. MODIS can thereby provide a convenient path to evaluate soil moisture by its thermal or optical bands based on surface temperature or spectral space indices (Fensholt and Sandholt, 2003; Ghulam et al., 2007, 2008; Wang et al., 2007) over a moderate regional scale, which is closely tied to agricultural production, drought monitoring, irrigation schedules, water resources management. Many current methods, such as thermal inertia method (applicable in bare soils), temperature-vegetation indices (e.g. T_s/NDVI, applicable in vegetated area), and Normalization Difference Water Index (NDWI), have certain limitations, such as difficulties in acquiring cloud-free images at both day and night for calculating temperature difference in thermal inertia method, the necessity of relatively large area to meet the boundary requirement in T_s/NDVI method, and the unstable sensitivity of NDWI for soil measurements. It is hereby meaningful and necessary to explore new methods for detecting soil moisture remotely based on soil temperature or spectral variation.

Soil water is closely correlated with evaporation (E). To effectively estimate E, in the study of Qiu et al. (1998), he supposed there was a small surface area (<100 cm^2) of a dry and deep soil column, which was isolated from the surrounding drying soil, and he also assumed that the air temperature, humidity, wind speed, and other atmospheric variables of the surrounding field were not significantly modified by the presence of the dry soil column. Because there was no water in the dry soil column, latent heat flux (LE) was negligible. Derived by energy balance equation and aerodynamic resistance of dry soil described above, and verified by experiment, he proposed the 3T model based on infrared-thermometer-measured surface temperature (Qiu et al., 1998, 1999):

$$E = R_n - G - (R_{nd} - G_d)\frac{T_s - T_a}{T_{sd} - T_a} \quad (1)$$

The temperature term on the right hand of Eq. (1) is a dimensionless term and is defined as h_a:

$$h_a = \frac{T_s - T_a}{T_{sd} - T_a} \quad (2)$$

where R_n is the net radiation, G is the soil heat flux, T_s is the surface temperature. T_a is air temperature, R_{nd}, G_d and T_{sd} are the net radiation, soil heat flux and the temperature for the reference dry soil, respectively (Qiu et al., 1999, evaporation rate is zero). Qiu named h_a as soil evaporation transfer coefficient. Here in the model, 3T refers to T_s, T_a and T_{sd}, the 3T model was regarded as "a very informative and a significant step towards using remote sensing to truly measure hydrologic processes" (Qiu et al., 2006).

The soil evaporation transfer coefficient (h_a) could determine the soil evaporation rate and the lower and the upper boundaries of evaporation. Theoretically, Eqs. (1) and (2) demonstrate that the value of h_a is located within the range of $0 \le h_a \le 1$, assuming the drying soil dries continuously until its water content is zero, we can get $T_s = T_{sd}$, $R_n = R_{nd}$, $G = G_d$, then $h_a = 1$ and $E = 0$, in other words, its water content and evaporation rate are equal to those of the reference site (dry soil) in each land pixel. The lower boundary of the evaporation rate is determined by the maximum value of h_a, which is controlled by soil water status. When there is no water shortage in the soil, then $T_s = T_a$, and h_a has a minimum value of zero and E can reach its maximum value ($E = R_n - G$). This upper boundary of evaporation is controlled by the atmospheric condition (Qiu et al., 2006). From these relationships, soil water status can be evaluated in terms of h_a variation.

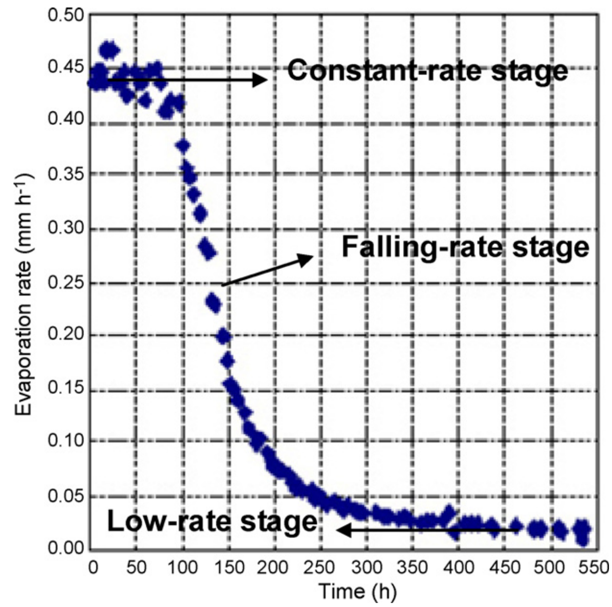

Fig. 1. Changes in soil evaporation rate with time under constant radiation, temperature and humidity conditions (air temperature 25 °C, relative humidity 50%, light intensity 80,000 lx) (cited from Qiu et al., 2006).

Because h_a can be calculated using surface and air temperature, both of which are obtainable with remote sensing (Qiu et al., 2003), it is implied that h_a holds useful information for the remote estimation of soil moisture. Thereby, in this study, MODIS data was used to acquire land surface temperature: T_s and $T_{sd.}$ Then, h_a was obtained by introducing ground measured air temperature to develop a method for the evaluation of soil moisture. The major objectives of this paper are: (1) to investigate the relation between h_a and soil moisture; (2) to test the reliability of h_a remotely sensed method for the prediction of soil moisture. Full description of a new approach for estimating soil moisture by using h_a, the study region and satellite data is provided in Section 2. In following section, good relationship between h_a and soil moisture, and good test of this method are observed. In last section, some issues and shortages are discussed and concluded focused on the performance of the coefficient in the estimation of soil moisture.

2. Methods

2.1. Theoretical background and hypothesis

Given that all other environmental factors (temperature, humidity, wind velocity, etc.) remain constant, soil evaporation rate decreases along with time due to evaporation of soil moisture. Qiu et al. (2006) investigated the variation between evaporation and time (Fig. 1), and later classified soil evaporation process into 3 stages (Qiu and Ben-Asher, 2010): (1) constant-rate stage, when soil water content is saturated and the soil evaporation rate is high (approaching a near-horizontal line); (2) falling-rate stage, when evaporation decreases near logarithmically with time; (3) low-rate stage, when evaporation is very low due to low soil water content. During the falling-rate phase, evaporation is negatively correlated with h_a. Considering the above relationship, we also divided the curve of h_a and soil moisture into three stages: the constant-rate stage of h_a, the increasing-rate stage of h_a, and the low-rate stage of h_a. Under natural field conditions, soil moisture is occasionally at the extremes (more higher than field-capacity or lower than wilting-point), but rather usually exists between the two extremes. Based on the above hypothesis, h_a will then be supposed to have a logarithmic correlation with soil water content, which the function