



Estimating high spatiotemporal resolution evapotranspiration over a winter wheat field using an IKONOS image based complementary relationship and Lysimeter observations



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ABSTRACT

Mapping high spatiotemporal resolution evapotranspiration (ET) over large areas is important for water resources planning, precision irrigation and monitoring water use efficiency. However, both traditional field measurement and aerodynamic estimation mainly focus on obtaining local ET. Remote sensing observations usually can be used to retrieve instantaneous ET at a low spatial resolution over region or global scale. Therefore, using field measurements and high resolution image data to generate high spatiotemporal resolution ET is becoming an important research direction. In this study, the complementary relationship model (CR) was tested together with meteorological data to estimate actual ET, and the results were validated by the Lysimeter observation. Furthermore, CR model combined with high resolution IKONOS data was used to estimate instantaneous field scale ET that was then transferred to daily ET. The cumulative evapotranspiration (ET) of winter wheat during the reproductive period from March through June of 2011 was 469.12 mm, essentially corresponding to the annual precipitation in the study area. The highest accuracy of estimating ET by CR model with remote sensing data was in May ($R^2 = 0.863$, RMSE = 0.103 mm). The transferred daily ET by a self-preservation of evaporative fraction (EF) approach from the CR modeling instantaneous ET was consistent with The Lysimeter measurements for all four months, March through June, 2011 ($R^2 = 0.937$, RMSE = 0.668 mm). The experimental results demonstrate that CR model can be used to accurately estimate actual ET with both meteorological data and high resolution remote sensing data at a regional scale.

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1. Introduction

Evapotranspiration (ET) transfers large volumes of water from soil evaporation and vegetation transpiration to the atmosphere. Mapping ET at high resolution over large areas is important for water resources planning and precision irrigation (Souch et al., 1996; Batchelor, 1999; Bouwer, 2002). As a result of historical efforts, accurate estimation of ET becomes possible by a number of methods using surface meteorological and sounding observations. However, these methods represent only local processes and thus suffer insuperably difficulty of mapping ET in large areas due to land surface heterogeneity and dynamic nature of heat transfer processes (Carlson et al., 1994; Kustas and Norman, 1996, 2000). Therefore many attempts (e.g., Xu and Singh, 2005; Liu

et al., 2006; Venturini et al., 2008) have been made to minimize the use of ground observations for estimating spatial distribution of ET at a regional scale. Satellite remote sensing is a promising tool for this purpose. Nevertheless, most of the existing techniques of estimating ET based upon satellite remote sensing are not satisfactory because the satellite monitoring of ET has not been feasible at a high spatial resolution (i.e., ~1–10 m). Routine remote sensed ET at ~1–5 km resolution is too coarse to support precision agriculture or precision irrigation for individual agricultural fields (Granger, 2000; Allen et al., 2007). Over the past a couple of decades, many important advances have been made in the area of high resolution remote sensing (e.g., commercial IKONOS and Quick Bird satellites), which offer unique data for analyses of the structure and function of environmental ecosystems (Chen et al., 2004). However, most of remote sensed surface temperature data still have coarse resolution, such as Geostationary Environmental Satellite (GOES) having 4 km resolution, Advanced Very High Resolution Radiometer (AVHRR) having nominally 1.1 km

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resolution and Moderate-Resolution Imaging Spectroradiometer (MODIS) having 1 km resolution (Kustas et al., 2003; Yang et al., 2010). Therefore, a vital challenge we also face is to how to obtain surface temperature at a similar spatial resolution as IKONOS (4 m) (Anderson et al., 2004; Yang et al., 2011). Moreover, for a relative small area (e.g., an area covered by a scene of IKONOS 11 km $\times$ 11 km) usually only limited ground data are available due to no meteorological stations located in such a small area. Under such conditions, there is a realistic problem of how to calculate the local area ET if only high resolution of visible and near-infrared (NIR) remote sensing image and limited meteorological observation are available.

Over the past years, several models have been developed to estimate ET for a wide range of surface conditions and spatiotemporal scales. Most of them are various versions derived from Penman's equation (Penman, 1948) and Priestley–Taylor's equation (Priestley and Taylor, 1972). Few of these ET estimation models have taken advantage of a complementary relationship between actual and potential evapotranspiration (Bouchet, 1963), which has been widely evaluated and validated by many researchers to calculate near-instantaneous, daily, monthly or annual evaporation at a local or regional scale (e.g., Hobbins and Ramírez, 2001; Hobbins et al., 2001; Ramírez et al., 2005; Crago and Crowley, 2005; Xu and Singh, 2005; Liu et al., 2006; Venturini et al., 2011). A primary advantage of evaporation models based on the complementary relationship is that they generally require only energy measurements along with meteorological measurements at just one height. Variables such as soil moisture content or stomatal resistance for those models are not needed because the surface dryness can be inferred from the air dryness (Venturini et al., 2008). The models derived using the complementary relationship concept mainly include advection-aridity (AA) model (Brutsaert and Stricker, 1979), complementary relationship areal evapotranspiration (CRAE) model (Morton, 1978), and Granger and Gray (GG) model (Granger and Gray, 1989). In this study, the AA model was proposed to test and to map high spatiotemporal resolution evapotranspiration using Lysimeter (a large equipment used for measuring evapotranspiration) observations and IKONOS image data. The AA model had been effectively used to calculate regional evapotranspiration for a small, rural catchment over an arid region. The model was found to yield a good match with energy budget estimates. The AA model computes the actual evaporation rate where the aridity of the land surface is deduced from the atmosphere so that no site specific calibration is necessary. Based on the Bouchet (1963) hypothesis and the AA model, the complementary model was found to be reliable for evaporation estimation on a short time step (20 min) (Brutsaert and Sugita, 1992; David and Jennifer, 2005). Usually, the AA model were used to estimate daily ET, however, when short-term (<1 h) estimates of the fluxes are desired, the effect of atmospheric stability must be concerned (Parlange and Katul, 1992).

In the light of increasing importance of the complementary approach, therefore, the objectives of this study are: (1) to analyze variations of ET monthly and at growth stages from Lysimeter measurements; (2) to evaluate the complementary relationship at high spatial resolution (on an order of 1–10 m) and temporal resolution (on an order of 10^3 s) using Lysimeter measurement data collected at different crop growth stages; and (3) to assess temporal upscaling of estimated ET by the AA model from instantaneous to daily-sums measured ET by Lysimeter and by IKONOS image.

2. Study area and data

2.1. Study area

In this study, the experiment was conducted during March–June, 2011. The experimental area is located at the

China National Experimental Station for Precision Agriculture, Changping District, Beijing, China (40°10'31"N to 40°11'18"N, 116°26'10"E to 116°27'05"E) (Fig. 1). The study area belongs to the North China Plain, where the number of winter wheat cultivated area account for one fifth of total winter wheat plant areas in China. In the study area, the annual average ground temperature is approximately 14.5 °C; the maximum frozen soil depth is 0.8 m; and the study area belongs to temperate continental monsoon climate zone with an annual average frost-free day of around 185 d, an annual average sunshine duration of 2600 h, and an annual average precipitation of 543 mm. The main crops are winter wheat and summer maize as a two crop per year rotation system. Winter wheat (*Triticum aestivum* L.) is sown at the beginning of October and harvested in mid-June of the following year. The quartic irrigation is arranged during experiment period, including turning green (45 mm), jointing stage (60 mm), heading stage (60 mm) and filling stage (75 mm), respectively.

2.2. Data

2.2.1. Ground measurement data

A large constructed Lysimeter was deployed in the farmland within the study area and the soil around the equipment has the same character as the local farmland (Fig. 2). The large Lysimeter is with a suspended multiple weighed types. It has a steel box with designed size of 3.0 m $\times$ 3.0 m $\times$ 2.5 m, with a weight of about 12 t. In order to represent field soil property, the steel box was filled in by cutting original soil monolith taken from near place. Considering a possible influence resulting from the equipment isolation on micro-meteorological elements, the soil surface inside the Lysimeter was kept flush with the surrounding field surface in order to reduce structure size of underground compartment for weighing and measuring systems. The precision of evapotranspiration measurements of Lysimeter's weighting systems is very high, and it can reach 0.05 mm. Therefore it is favorable for monitoring daily variation of the evapotranspiration.

The same cultivation practices such as tillage depth, sowing date and seed number and varieties as well were applied to the large Lysimeter site and its surrounding farmland. The large Lysimeter and its surrounding farmland were irrigated with same frequency and amount, as the other farmland in the study area.

Meteorological data at a height of 2 m were recorded by the agro-meteorological station near by the Lysimeter, including air temperature, relative air humidity, net short wave radiation, net long wave radiation, wind velocity and atmospheric pressure. From February through October, 2011, weight data generated by the Lysimeter and the meteorological data were automatically stored in a data logger. The equipment was programmed to take weight readings every second (60 readings per minute), and recordings were made every 15 min, hourly and daily.

2.2.2. IKONOS image pre-processing

As an important sensor, IKONOS, the multispectral sensor collects blue (445–516 nm), green (506–595 nm), red (632–698 nm), and NIR (757–853 nm) bands with 4 m resolution, 11-bit radiometric resolution, and a swath width of 11 km (Dial et al., 2003). In this study a scene of IKONOS image was acquired at 11:16 Beijing local time (Sun azimuth angle: 149.315°; Sun angle elevation angle: 63.646°; an average off nadir view elevation angle: 77.952°), May 6, 2011. It was corrected radiometrically using the relative spectral response filters and the radiometric calibration coefficients delivered with the data (Bowen, 2002; Space Imaging, 2002). Surface reflectance was then calculated with the MODTRAN-4 radiative transfer code (Berk et al., 1999) using sun photometer measurements. The IKONOS image was georeferenced using 16 ground control points (GCPs) measured with a GPS (± 1 m accuracy) using

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