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Dual-model approaches for evapotranspiration analyses over homo- and heterogeneous land surface conditions

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ABSTRACT

Accurate spatio-temporal estimation of evapotranspiration (ET) is fundamental to understand land–atmosphere interactions and hydrological processes. Although various ET models based on remote sensing (RS) techniques have been presented, recent relevant studies suggest that more validation work should be conducted in regions with differences in land and meteorological properties. In this study, two RS-based models, the Surface Energy Balance System (SEBS) and Revised Remote Sensing Penman–Monteith (R-RSPM) model, were assessed over two biogeophysically different catchments on the Korean peninsula: a rice paddy agricultural field and a mixed forest area. We independently applied three approaches considering different scaled applications of a single source energy budget model (SEBS): point scale SEBS (SEBS-P), regional scale SEBS (SEBS-R), and R-RSPM. We incorporated diverse compositions of forcing datasets, Moderate Resolution Imaging Spectroradiometer (MODIS) satellite-based RS data, and Global Land Data Assimilation System (GLDAS) data and *in situ* meteorological data. Instantaneous flux measurements computed by the three approaches were evaluated with *in situ* flux measurements based on the eddy covariance (EC) system. The instantaneous net radiation estimates of all approaches were satisfactory, exhibiting strong correlations (0.68–0.99 of R^2) with *in situ* measurements over different topographical sites. For latent heat flux (*LE*), all three approaches yielded similar trends of results at both cropland (CMC) and mixed forest (SMC) sites indicating that estimates of *LE* were overestimated. However, considering the serious lack of energy closure exhibited by the EC system in SMC, *LE* showed reasonable agreement (biases of 11–50 W/m^2 and Root Mean Square Error (RMSE) of 78–95 W/m^2) with *in situ* measurements adjusted by the Bowen ratio (BR) method. For daily ET analyses using the R-RSPM model, instantaneous *LE* was empirically scaled up to daily ET, and the estimates of ET from all three approaches had good agreement with BR-corrected *in situ* daily ET, even in SMC (with biases of −0.07 to 0.67 mm/day). By comparing *H* from two different SEBS applications (SEBS-P and SEBS-R), we concluded that GLDAS datasets exhibit robust quality as input data as well as near real time benefits. Through sensitivity analyses of a single source energy budget model (SEBS), canopy height turned out to be one of most critical parameters which can directly result in the misparameterization of roughness height for a tall canopy site. The results of this study support the applicability of RS-based ET models over homo- and heterogeneous regions, and suggest that further studies are required for exploring the accurate parameterization of roughness height over areas of tall and heterogeneous vegetation to improve the performance of SEBS.

1. Introduction

Evapotranspiration (ET), which is associated with surface energy dynamics and the water cycle, is one of the most critical hydrological components for the understanding of land surface and atmosphere interactions and hydrological processes (Brutsaert, 1982). The accurate spatio-temporal estimation of ET is essential

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for precise quantification of the water balance for water resources planning and management, optimizing crop production, and evaluating the effects of changing land use on water yields at the local and/or meso-scales (Glenn et al., 2007; Gowda et al., 2008; Irmak et al., 2005). Daily ET varies seasonally and spatially across the globe based on surface energy fluxes as well as vegetative type, weather, and wind conditions (Hanson, 1988; Su et al., 2003). Thus, ET is the most dominant factor of water balance, especially in water scarce regions or areas where water supplies fluctuate seasonally (Gowda et al., 2008).

East Asia experiences monsoon rainfall during the summer season (from June to August) due to the influence of the North Pacific subtropical high on the climate over the Asian continent (Kim et al., 2002). The Korean peninsula, as part of East Asia, annually receives approximately more than 70% of its total precipitation during the summer monsoon phase, while dry atmospheric conditions remain dominant during other seasons (fall, winter, and spring). However, the impact of current climate change on the global water cycle may accelerate this unbalanced pattern (Bae et al., 2007; Kim et al., 2007). Furthermore, human population increases and mobility in specific regions, such as mid-western and southeastern metropolitan areas, has directly increased the spatial and temporal variation of water stress over the last couple of time spans (Chang et al., 2007).

Under such devastating conditions, efficient management of water resources at the regional scale is more challenging. Thus, to formulate a robust counterplan against water resource deficiencies, reliable water budgets should be defined through spatial modeling approaches based on precise quantification of hydrological components such as ET. However, the imperative role of ET in water management has been less addressed than that of other hydrological components (*i.e.*, precipitation) in South Korea. The Korean peninsula has very distinctive land characteristics, in that more than 70% of the land surface is classified as mountainous area covered with heterogeneous vegetation components. Therefore, precise and careful studies of ET are essential, because patterns of ET over such terrain may appear more complex and diverse spatio-temporally than those over homogeneous terrain.

Conventional methods based on field measurements such as the Bowen ratio, water balance, and eddy covariance techniques offer approaches for estimating ET and other surface energy fluxes due to their high accuracy over homogeneous areas (Li et al., 2009). However, the extrapolation of field ET to meso-scales is practically expensive, time consuming, and complex to obtain various land and surface parameters over heterogeneous terrain composed of diverse terrestrial ecosystems (Idso et al., 1975). There are some existing approaches to make the use of field ET measurements feasible at meso-scale (Jung et al., 2009), but they may not be sufficient for reflecting the complexity of water balance in real world.

Several economically feasible remote sensing methods, from empirical regression to physical-based algorithms, have been developed over the past few decades for the indirect estimation of ET by predicting spatially distributed heat fluxes from point to continental scales (Allen et al., 2007; Bastiaanssen et al., 1998; Jiang and Islam, 2001; Wang et al., 2007; Kustas and Norman, 1999; Menenti and Choudhury, 1993; Su et al., 1999). Single and dual source energy balance models, which are based on remote sensing techniques in combination with surface or atmospheric data, vary in complexity depending on algorithm, data requirements, basic assumptions, and accuracy (Choi et al., 2011; Gowda et al., 2008; Hwang and Choi, 2013; Li et al., 2009). Single source models such as the Surface Energy Balance Index (SEBI; Menenti and Choudhury, 1993), and its derivatives such as the Surface Energy Balance Algorithm for Land (SEBAL; Bastiaanssen et al., 1998), the Simplified Surface Energy Balance Index (S-SEBI; Roerink et al., 2000), the Surface Energy Balance System (SEBS; Su, 2002), and Mapping Evapotranspiration with Internalized Calibration (METRIC; Allen et al., 2007) are of substantial interest to bio-geophysical and hydrological researchers due to their simplicity, less ground-based input, and computational efficiency when compared with Two Source Energy Balance (TSEB; Norman et al., 1995) model and Two Source Time Integrated Model (TSTIM; Anderson et al., 1997; Kustas et al., 2007; Li et al., 2009).

SEBAL (Bastiaanssen et al., 1998) and METRIC (Allen et al., 2007) were developed to map ET over large scales by solving the energy balance as a residual of latent heat flux (*LE*) with minimum ground based measurements. Both models offer the advantage of automatic internal calibration for the computation of sensible heat using radiative transfer models, which excludes the need for atmospheric correction of surface temperatures (Allen et al., 2005). These radiative transfer models used an equation to calculate differences between aerodynamic and land surface temperatures by utilizing hydrologically contrasted hot and cold points in satellite images. Overall, METRIC is substantially similar with SEBAL; however, the main difference is the assumption that the cold point identified in METRIC have the similar bio-geophysical characteristics with the alfalfa reference crop whereas in SEBAL cold point temperature is often assigned from local water body. SEBI evaluates regional ET from the relative evaporative fraction using planetary boundary layer (PBL) scaling as proposed by Menenti and Choudhury (1993), based on the redefined Crop Water Stress Index (CWSI) for locating wet and dry points in the observation area.

Several studies that evaluated remote sensing (RS)-based ET models showed that the performances of such models were reliable at small scales for specific regions in which land surface characteristics remained homogenous (Choi et al., 2009; French et al., 2005; Timmermans et al., 2007). However, these studies also suggested that more validation work should be conducted in unstudied regions with a variety of land and meteorological characteristics for better assessments of possible uncertainties in remote sensing surface energy balance models. The validation of RS-based ET at large scales is difficult, due to discrepancies of spatial and temporal resolution between ground measurements and remote sensing datasets (Ershadi et al., 2013; Ferguson et al., 2010). Furthermore, some RS-based ET models even may not be readily utilized because highly specialized personnel are required to operate model with credibility. For instance, METRIC and SEBAL require local calibration by the user to select cold and hot pixels in specific scenes (Kustas and Anderson, 2009).

SEBS (Su, 2002), which is based on the SEBI concept, is currently the most adequate model for the estimation of atmospheric turbulent heat fluxes at meso-scales over homogeneous surfaces (Jia et al., 2003; Ma et al., 2013; Van Der Kwast et al., 2009). SEBS estimates the evaporation fraction (EF) using remotely sensed data with thermal aerodynamic roughness length and similarity theories in limiting cases (*i.e.*, dry and wet limits) for mapping ET at local and regional scales in complex frameworks. Due to the physical model characterization of the processes, SEBS exhibits unique characteristics compared to other energy balance models (Kustas and Anderson, 2009; Li et al., 2009). The formulation of EF on the basis of energy balance in theoretically defined wet and dry conditions and pixel by pixel based calculations of radiation balance are additional distinctive features of SEBS, which reduce uncertainty based on surface temperature or meteorological variables and calculation times, respectively (Li et al., 2009; Su, 2002). The performance of the SEBS model has been validated globally for homogeneous areas of low vegetation cover in different meteorological and ecological settings. Although a few researchers evaluated the performance of SEBS at tall canopy areas and suggested more appropriate application on such areas (Timmermans et al., 2013), however, more validation should be conducted on heterogeneous woodlands and