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Seasonal trends of satellite-based evapotranspiration algorithms over a complex ecosystem in East Asia

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ABSTRACT

Accurate land surface evapotranspiration (ET) estimations over a heterogeneous ecosystem are important to understand the interaction between the land surface and atmosphere including practical applications in integrated water resources management. Though numerous studies have been adopted and developed based on remote sensing technology to make a more accurate prediction of regional ET distribution, there has been still degree of uncertainty due to high spatio-temporal variability of the ecohydrologic parameter. This study suggested the revised remote sensing-based Penman–Monteith (Revised RS-PM) model and Trapezoid Interpolation Model (TIM) using only remotely sensed data as input data to assess applicability over complex topography in East Asia. Ground observations at the two flux sites having different land surface conditions were used to evaluate intra-annual seasonality in 2008. Both models represented temporal compatibility yielding biases of −74.25–38.79 W m^{-2} and Root Mean Square Error (RMSE) values of 68.96–90.90 W m^{-2} while the models consistently overestimated ET at the forests due to large amount of interception relatively restraining sufficient water supply to the plants. The revised RS-PM showed slight overestimation due to the overvalued Leaf Area Index (LAI) as an input parameter and classified parameterization in transpiration calculation. This algorithm was developed for global mapping of ET so that errors occurring from vegetation parameterization are inevitable. TIM reproduced higher ET than the measurements in a non-growing season since remotely sensed Normalized Difference Vegetation Index (NDVI) as an input parameter could be affected by cloud contamination. In contrast to the dormant season, the revised RS-PM estimated a larger amount of ET distribution than TIM in the growing season. A conservative estimation of TIM was mainly caused by the structural characteristics. Relationships between the land surface temperature and NDVI were contextually used to determine both maximum and minimum limits of the Priestley–Taylor parameters in the image data. Determination of the contextual relationship should be carefully conducted to achieve reliable estimations. Results of a sensitivity analysis shows that the net radiation (R_N) plays the most significant role in both models (±17–20% for ET by ±20% change of R_N). Variation of LAI impacted ET mostly in the revised RS-PM in a dormant season due to a logarithmic relationship between canopy conductance and LAI. TIM, on the other hand, was barely affected by LAI because of the simple structure of the algorithm including the Priestley–Taylor equation. The results suggest that the models can be applied to a regional scale with heterogeneous topography over long term periods if the input data handling is carefully conducted. In particular, the models can be usefully applied where ground ancillary data are not readily available.
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1. Introduction

Evapotranspiration (ET) including evaporation from a land surface and transpiration from photosynthesis of vegetation is a sensitive factor in the hydrologic cycle (Brutsaert, 1982). This hydrologic component is mainly determined by the available energy and water, and atmospheric transport mechanism, which are parts of the land surface–atmosphere interaction (Batra et al., 2006). ET can be utilized as an indicator of global climate change, water resources management, ecological applications, weather forecasting, natural disasters (e.g. floods, droughts), and irrigation planning (Batra et al., 2006; Fisher et al., 2008; Jiang et al., 2009). In terms of hydrologic perspectives, accurate characterization of ET is important to better understand hydrologic partitioning between the land surface and the atmosphere (Brutsaert, 1982).

ET is directly observed using an evaporation pan and a lysimeter, and empirically measured using eddy covariance techniques. While these ground-based observations can represent accurate measurements of

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ET, such conventional methods have a scientific limit to extend to a regional scale due to high variability (Choi et al., 2009; Wang et al., 2006). Previous studies also showed that the eddy covariance techniques did not close the energy balance and essentially caused large uncertainty (Brotzge & Crawford, 2003; Dugas et al., 1991; Goulden et al., 1998; Mahrt, 1998; Moore, 1976; Prueger et al., 2005; Twine et al., 2000). Remote sensing technology can be an alternative method to implement over large areas (Su, 2002).

There have been major studies conducted to accurately estimate ET over several decades. The Penman–Monteith (P-M) method (Monteith, 1965) is the most widely used approach which theoretically combines energy and aerodynamic considerations. This method has been generally regarded as a robust approach since the model is not mostly dependent to any specific meteorological input variables. Cleugh et al. (2007) employed remotely sensed data in ET estimation and suggested the P-M model's superiority at an evergreen forest and a tropical savanna in Australia using Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery. Though the simple surface conductance algorithm in the model and the quality of the MODIS vegetation indices may cause errors, the model successfully estimated monthly evapotranspiration in Australia from 2001 to 2004 at the continental scale. Mu et al. (2007) modified the Remote Sensing-based P-M (RS-PM) model (Cleugh et al., 2007) to produce the MODIS-based global land surface ET at 1-km resolution. Through the revised algorithm, errors were significantly reduced by the four refinements: (1) adopting vapor pressure deficit and minimum air temperature constraints to compute stomatal conductance, which is defined as the rate of incoming carbon dioxide or outgoing water vapor through the leaf's stomata, (2) employing Leaf Area Index (LAI) for canopy conductance estimation, (3) changing the calculation method of vegetation cover fraction using Enhanced Vegetation Index (EVI) instead of Normalized Difference Vegetation Index (NDVI), and (4) adding a procedure of soil evaporation. The ET estimations using both Global Modeling and Assimilation Office (GMAO) and ground meteorological data were validated with 19 AmeriFlux eddy covariance flux tower measurements. The validation result showed that there was a progress with higher accuracy (Root Mean Square Error (RMSE): 48.2 to -1.3 W m^{-2} driven by GMAO data) than the RS-PM as well as justifying use of GMAO input data. The MODIS-based global ET model was further enhanced by Mu et al. (2011) with (1) using the fraction of absorbed photosynthetically active radiation (FPAR) for the calculation of vegetation cover fraction instead of an equation of EVI, (2) considering nighttime ET, (3) modifying the soil heat flux calculation method proposed by Jacobsen and Hansen (1999), (4) improving estimates of stomatal conductance, aerodynamic resistance, and boundary layer resistance, (5) dividing dry and wet canopy surfaces for evaporation on canopy surface, and (6) separating soil surface into the wet and moist. The revised model performed better than their previous study (Mu et al., 2007) at 46 eddy AmeriFlux eddy covariance flux towers.

In contrast with the revised RS-PM model, the Trapezoid Interpolation Model (TIM) revised the Priestley–Taylor (P-T) model by using a contextual relationship of remote sensing-based land surface temperature (T_S) and vegetation index to estimate actual ET (Batra et al., 2006; Jiang & Islam, 2001; Wang et al., 2006). T_S and NDVI represented a negative relationship because of the cooling effects near the land surface by canopy transpiration in the previous studies (Goward & Hope, 1989; Goward et al., 1985; 2002; Hope, 1988; Hope & McDowell, 1992; Hope et al., 1986; Nemani & Running, 1989; Nemani et al., 1993; Price, 1990; Prihodko & Goward, 1997; Smith & Choudhury, 1991). This correlation reflects that the T_S–NDVI relationship is largely involved with ecoclimatological phenomena (Karnieli et al., 2010). In particular, the T_S–NDVI slope is related to moisture availability (Gillies & Carlson, 1995; Gillies et al., 1997; Nemani & Running, 1989), canopy resistance (Gillies & Carlson, 1995; Goetz, 1997), ET (Prihodko & Goward, 1997), and near-surface air temperature (Goward et al., 2002). A characteristic trapezoidal pattern of T_S and NDVI has conceptual boundaries for energy fluxes (Jiang & Islam, 1999; Jiang et al., 2009). The capability of reasonable ET estimation over large areas with less complexity and fewer input parameters makes this model a promising technique. TIM was applied with various scales and proven as a reliable method in the previous studies (Batra et al., 2006; Choi et al., 2009; Jiang & Islam, 2001; 2003; Jiang et al., 2009; Stisen et al., 2008; Venturini et al., 2004; Wang et al., 2006). Venturini et al. (2004), and Batra et al. (2006) constructed T_S–NDVI trapezoids to investigate applicability of ET estimation over large areas. Wang et al. (2006) combined the thermal inertia method and the T_S–NDVI spatial variation method to retrieve reasonable evaporative fractions over south-central Kansas and north-central Oklahoma in the U.S.

Whereas a large number of remote sensing-based ET studies have been presented under various climate conditions, there have been few studies to estimate ET in East Asia using satellite observations, yet. Jang et al. (2010) linked the revised RS-PM model with the 5th Generation Mesoscale Meteorological Model (MM5) developed by Pennsylvania State University and the National Center for Atmospheric Research (Grell et al., 1995). MODIS-derived meteorological and radiation variables including ET were compared to flux tower measurements in Korea and Japan, and were found to be in good agreement (RMSE: 84.1–119.2 W m^{-2}). However, the MOD04 aerosol product used to estimate the downward shortwave radiation in the model has a serious limitation that its retrieval rate is very low. Jang et al. (2010) thus applied gap filling methods to resolve it, but this might be a major source of errors. Choi et al. (2011) estimated and intercompared surface energy balance fluxes by three energy balance models, namely TIM, the Mapping Evapotranspiration at High Resolution with Internalized Calibration (METRIC), and the Two-Source Energy Balance (TSEB), using the Landsat-5 Thematic Mapper (TM) image at watershed scale (Allen et al., 2007; Jiang and Islam, 1999). Distributions of the energy fluxes by the three models showed relatively larger spatial discrepancies (Bias range: -150–150 W m^{-2}) compared to one another in areas with partial vegetation cover. Even though the study areas were classified as complex topography and hydrometeorology, most of the ET models were applied using different sources of meteorological input data. Careful employment of the input data was necessary to reduce spatio-temporal uncertainty.

The main objective of this study is to suggest two ET algorithms that only need remotely sensed data as input data. Considering that the most remote sensing-based ET models are not applicable where ground observations are not readily available, this study can be used as a practical source to apply over various fields. We also spatially and temporally compare the ET estimates from the two structurally different schemes to investigate unique characteristics of the models over the entire year of 2008. Though the models completely follow fully verified methods, input parameters and the deriving methods of the components may be totally different since the study area, the Korean Peninsula in East Asia, is covered with various land cover types. ET estimates are compared with both the other model's and ground measurements to identify intra-annual trends. Geographic and topographic impacts on the ET estimations are also aimed to be identified in the study. The Korean peninsula has a very heterogeneous topography; mostly mountainous areas with various slopes, dense croplands and urban areas, and the areas highly influenced by the ocean. The regional analysis of spatio-temporal trend of ET reveals how such conditions have an effect on ET. For example, land cover classification and vegetative information are the significant factors to determine ET that taking account of these properties would lead to reliable estimation.

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