



Recent Advances in Remote Sensing of Evapotranspiration

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Abstract: Evapotranspiration (ET) plays an important role in coupling the global energy, water, and biogeochemical cycles and explains ecosystem responses to global environmental change. However, quantifying and mapping the spatiotemporal distribution of ET across a large area is still a challenge, which limits our understanding of how a given ecosystem functions under a changing climate. This also poses a challenge to water managers, farmers, and ranchers who often rely on accurate estimates of ET to make important irrigation and management decisions. Over the last three decades, remote sensing-based ET modeling tools have played a significant role in managing water resources and understanding land-atmosphere interactions. However, several challenges, including limited applicability under all conditions, scarcity of calibration and validation datasets, and spectral and spatiotemporal constraints of available satellite sensors, exist in the current state-of-the-art remote sensing-based ET models and products. The special issue on “Remote Sensing of Evapotranspiration II” was launched to attract studies focusing on recent advances in remote sensing-based ET models to help address some of these challenges and find novel ways of applying and/or integrating remotely sensed ET products with other datasets to answer key questions related to water and environmental sustainability. The 13 articles published in this special issue cover a wide range of topics ranging from field- to global-scale analysis, individual model to multi-model evaluation, single sensor to multi-sensor fusion, and highlight recent advances and applications of remote sensing-based ET modeling tools and products.



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1. Overview of Contributions

Evapotranspiration (ET), a key ecohydrological process within the Earth's system, is a crucial component of the water and energy cycles. A number of state-of-the-art remote sensing-based ET products and modeling techniques have been developed in recent decades to better manage water resources and understand the linkage between ecosystem functions and climatic feedbacks [1–3]. However, these remote sensing-based ET products and modeling techniques have numerous challenges, including limited applicability and consistency under diverse conditions [4], the inability of remote sensing methods to measure aerodynamic temperature and conductance [5], limited availability of calibration and validation datasets, and limited spatial and temporal capabilities of available satellite sensors. The 13 papers in this special issue contribute to broad areas of remote sensing of ET to address some of these challenges and further improve ET models and products. We briefly summarize the contributions of the 13 papers below.

Allies, Demarty [6] combined the simplified surface energy balance index (S-SEBI) model and the Evapotranspiration Assessment from SPace (EVASPA) tool to develop an E3S (EVASPA S-SEBI Sahel) model for mapping ET in hot and arid/semi-arid Sahel, a drought-prone and agriculturally important region in Africa. The model improvises the simple land surface temperature (LST)~albedo space-based S-SEBI model by integrating an ensemble approach to derive daily ET estimates from a weighted average of ET from several ET methods. Estimated ET from the model showed good agreement with those from Simple Soil-Plant-Atmosphere Transfer simulations and global land evaporation Amsterdam

Model (GLEAM) global ET products. Though the model is developed for the Sahel region using 1-km resolution MODIS TERRA and AQUA products, it can be easily expanded to other regions and other thermal sensors (e.g., Landsat). In another regional-scale study, Wu, Lakshmi [7] aimed to understand how the magnitude, trend, and spatial pattern of five global ET products (MOD16, JUN10, ZEN14, ZHA15, ZHA16, and GLEAM) varied across the Amazon, a region with high significance for global climate patterns. They aimed to assess the reliability and consistency of multiple ET products. Site-specific evaluation of the five models showed better performance of JUN10, illustrating the significance of using ground measurements in ET reconstruction. However, JUN10 ET estimates for the Amazon basin showed no significant trend over the study period, while other ET products showed significant increasing or decreasing trends. Hence, a significant divergent pattern of ET estimates from these products for the period 1982–2011 led to uncertainty over the actual trend of ET across the Amazon River basin. The study also revealed that these ET products responded better to warming and greening than to brightening and deforestation, likely due to misrepresentation of deforestation in these models. These findings suggest a need for better representation of water balance through the use of terrestrial water storage anomalies from Gravity Recovery and Climate Experiment (GRACE) [8] with updated precipitation and discharge reconstructions and use of downscaled high-resolution soil moisture datasets to better characterize the magnitude, trend, and spatial pattern of Amazon ET.

Javadian, Behrangi [9] studied the global trends in actual ET, potential ET (PET), and precipitation in Google Earth Engine Environment from 2001 to 2018 and reported a significant increasing trend ($14 \pm 5\%$) in actual ET from croplands. The study also introduced an evapotranspiration warning index (ETWI) to explain the sustainability of the ET trend in terms of water balance by combining ET, PET, and precipitation. Country-level trend analysis of cropland ETWI showed potential unsustainable use of agricultural water resources across Thailand, Brazil, and China. Globally, no sustainable actual ET trends were mostly associated with irrigation water use in maize production. Finally, an online open-access application (<https://javadian.users.earthengine.app/view/evapotranspiration-trend-monitoring-v02>; accessed on 1 October 2021) was designed to enable near real-time monitoring and improve the understanding of global water consumption and availability.

S. Ha, R. Diak [10] evaluated the applicability of numerical weather prediction output from Rapid Refresh (RAP) and High-Resolution Rapid Refresh (HRRR) systems in conjunction with remotely sensed net radiation from the Geostationary Operational Environmental Satellite for near real-time monitoring of hourly ET over Iowa. The evaluation of four ET models (RAP, HRRR, RAP-GOES, HRRR-GOES; depending upon the source of meteorological forcing data) using hourly observations from two eddy covariance (EC) towers in central Iowa showed a good performance of the HRRR-GOES with the potential to expand over other regions in the U.S. Cha, Li [11] integrated a SEBAL model with trapezoid and sinusoidal methods to estimate seasonal ET at a 30 m Landsat resolution covering agricultural lands of the Kai-Kong River Basin in Xinjiang, China. Daily ET estimates from SEBAL were comparable with PM-based ET, and both methods captured highly variable seasonal ET across the study region. The authors conclude that the proposed sinusoidal method when integrated with time-series MODIS images can be useful for deriving seasonal crop ET in arid regions.

Acharya, Sharma [12] applied one of the widely used thermal ET models, Mapping ET at high resolution with an internalized calibration (METRIC) model, to map daily, monthly, and seasonal ET across nine irrigation districts in the semi-arid to an arid intermountain region of Big Horn Basin, Wyoming. Hourly modeled ET in sugar beet, dry bean, and barley explained >90% of variations in observed ET from the Bowen ratio energy balance system. The monthly ET estimates were within 3–6% of the observed monthly ET. A companion paper by Acharya and Sharma [13] compared four SEB models, namely SEBAL (surface energy balance algorithm for land), METRIC, S-SEBI, and SEBS (surface energy balance system) for the same study region and period (2017–2019). Based on the

NSE, METRIC performed better than the other three models (i.e., NSE = 0.9 from METRIC vs. NSE = 0.65–0.76 from other models). While all four models showed good capability to predict ET from the irrigated fields in Wyoming, most models overestimated ET under dry conditions. These findings correspond well with previous studies [14,15] that most remote sensing-based SEB models typically underperform in dry conditions, most likely due to improper characterization of aerodynamic conductance and the difference between aerodynamic and radiometric temperatures [15–17].

The potential issues associated with spatial (MODIS) and temporal (Landsat) resolutions have recently drawn interest towards modeling ET using a data fusion approach or considering the new sensors, such as Sentinel (especially Sentinel-2 and Sentinel-3) that can provide high-resolution images (10–20 m) with much finer temporal resolution (~5 days). Li, Huang [18] applied TSEB on Landsat and Landsat-MODIS fused images from STARFM to estimate multi-year daily 100 m ET, evaporation (E), and transpiration (T) from crops and natural vegetation across the middle reaches of Heihe River Basin in China. Daily ET estimates were within 0.85 mm day^{-1} when evaluated across EC flux tower sites, covering from irrigated cropland to natural desert, and were able to capture seasonal patterns of ET, E, and T at field-scale with reasonable seasonal and spatial variability. Further, the modeled crop E/ET and T/ET were comparable with observations in terms of both magnitude and temporal dynamics, except for the early growing season when the actual E was reduced by plastic film mulching. Overall, the findings from this study suggest that integrating TSEB and STARFM models can provide a useful tool for monitoring plant water consumption in both agricultural and natural ecosystems in the Heihe River Basin and other regions of the world.

Two papers in this special issue explored the utility of the Sentinel data for monitoring ET from vineyards in a Mediterranean climate. First, Bellvert, Jofre-Čekalović [19] assessed the utility of the sharpened LST images from Sentinel-2 and Sentinel-3 and the Priestly Taylor (PT) version of the two-source energy balance model (TSEB) [20,21] (TSEB-PT_{S2+3}) to estimate the spatiotemporal variability of actual T and water stress in a vineyard in Spain. Specifically, they explored the feasibility of TSEB-PT_{S2+3} and two additional versions of the TSEB model, one using the aggregated TIR data at the vine+inter-row level (TSEB-PT_{airb}) and another based on the contextual method that directly retrieves soil and canopy temperatures (TSEB-2T) by comparing T estimates from the models against those from a vine water consumption model and relating crop water stress index (CWSI) with in situ stem water potential. The potential T was estimated based on the two-layer Shuttleworth–Wallace model (S–W) for calculating CWSI. While the contextual-based TSEB-2T appeared to perform marginally better than the TSEB-PT_{S2+3}, the findings indicated the potential application of the TSEB with sharpened LST obtained from the Sentinel-3 and Sentinel-2 satellites and the S–W model for estimating both actual and potential T from grapevines in a dry climate. Second, García-Gutiérrez, Stöckle [22] evaluated two Penman–Monteith (PM) based approaches, namely, Penman–Monteith–Stewart (RS-PMS) and Penman–Monteith–Leuning (RS-PML), on the visible bands of Sentinel-2 in a Cabernet Sauvignon vineyard located in central Chile. Model outputs were compared with observations from an EC system and outputs from two thermal ET models (METRIC and TSEB-PT) using Landsat 7 and Landsat 8. The RS-PMS model outperformed all models with an RMSE of 0.52 mm day^{-1} and the model was particularly useful in assessment and monitoring of vineyard drip irrigation in terms of crop coefficient (Kc) estimation, as biases were within 10% compared to those based on EC tower observations. These results showed good promise of using Sentinel-2 and Sentinel-3 sensors for monitoring field-scale ET at finer temporal resolutions.

Remote sensing-based ET products have the potential for studying vegetation greenness and health over space and time. Nagler, Barreto-Muñoz [23] utilized the remotely sensed measurements of the two-band Enhanced Vegetation Index (EVI2; a proxy for greenness); daily ET (mm day^{-1}) using EVI2 (ET(EVI2)); and an annualized ET based on EVI2, the Phenology Assessment Metric (PAM ET), an annualized ET using Landsat time-series to evaluate trends in riparian ecosystem health across five riparian reaches of the Lower

Colorado River (LCR). The study revealed a declining trend in riparian health and its water use from riparian ecosystems from the Hoover to the Morelos Dam within LCR since 2000. Compared to the 2000s, the daily and annual ET declined by over 27% ($\sim 1 \text{ mm day}^{-1}$) and 18% ($170.91 \text{ mm yr}^{-1}$) in the last decade, and this decline was largely attributed to deterioration of biodiversity, wildlife habitat, and other key ecosystem services in the U.S. portion of the LCR. To understand the impacts of different land management activities on ET at different spatiotemporal scales under differently managed prairie pastures, Bajgain, Xiao [24] measured ET in co-located introduced managed pasture and native prairie pasture during the 2015 and 2016 growing seasons using EC systems and compared the MODIS-derived ET at four different spatial scales at 30 m (ET_{MOD30}), 200 m (ET_{MOD200}), 500 m (ET_{MOD500}), and 1000 m ($ET_{MOD1000}$) with the EC-measured ET (ET_{EC}). The ET_{MOD30} showed a better agreement with ET_{EC} than did the ET_{MOD200} , ET_{MOD500} , and $ET_{MOD1000}$, most likely due to the inability of ET products at coarser spatial scales to capture spatial heterogeneity of vegetation growth impacted by various management activities within the EC footprint area. Thus, it is crucial to integrate flux measurements and high-resolution remote sensing data that are comparable to EC footprints depending on the heterogeneity of landscape surrounding the flux tower for the modeling or upscaling of ET. Ahmed, Paul-Limoges [25] revealed a contrasting impact of drought and heatwave on ecosystem ET between the North and South of Europe as well as on ecosystem types by utilizing readily available MOD16 ET products in conjunction with meteorological data from the European Centre for Medium-Range Weather Forecasts. They assessed how the combined heatwave and drought in 2018 affected spatiotemporal changes in ET across European ecosystems along a climatic gradient in Europe. Results suggested that ET was strongly reduced (up to 50% compared to a 10-year reference period) in areas with extreme anomalies in surface air temperature and precipitation in central, northern, eastern, and western Europe. The increased temperatures in northern Europe resulted in a notable decline in ET from agricultural areas, mixed natural vegetation, and non-irrigated agricultural areas in this region.

Though the focus of this special issue was very specific, the published papers in this issue represented diverse ET modeling approaches and their applications. Contributions included the development of novel models to the improvement of existing ones, and a broad range of applications from estimating vegetation water use to assessing vegetation health and drought impacts. Additionally, integration of multiple sensors or multi-sensor image fusion approaches, as highlighted by some studies in this special issue, can address limitations associated with spatiotemporal capabilities of the currently available satellite sensors. The use of newly available sensors such as sentinel-2 and sentinel-3 can play an important role in field-scale monitoring of actual ET or crop water status across key agricultural zones in the world. The topics covered in this special issue provide valuable insights into the development, improvement, and applications of remote-sensing-based ET models and products to support efforts to sustainably manage water resources under a changing climate.

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