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Mapping evapotranspiration with vegetation index-temperature difference method using the products of the moderate resolution imaging spectroradiometer

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Keywords
Remote sensing
Evaporative Fraction
Evapotranspiration
NDVI
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ABSTRACT

Evapotranspiration (ET) is a crucial variable to monitor agricultural water consumption, map irrigated agriculture and identify agricultural droughts. ET maps can be used to analyze agricultural water use practices of farmers, identify irrigated farms and drought-stricken regions. In this study, a simple model capable of producing evaporative fraction (EF) and then ET from minimal remotely sensed and meteorological inputs in a trapezoidal framework is presented. So far, the model has successfully validated against ground data collected at three different eddy-covariance (ECOR) flux towers in the US. Overall, this methodology shows promise to estimate ET from field to regional scales in regions with limited data like Turkey.

1. INTRODUCTION

Evapotranspiration (ET) is the second largest component in water balance after precipitation and an indispensable surface variable to monitor agricultural water use and droughts (Anderson et al. 2013; Mueller et al. 2011). Therefore, monitoring ET is an immediate concern especially for a country like Turkey which agriculture heavily relies on water supply through irrigation to grow agricultural crops during dry summers.

ET is a combination of evaporation from soils and transpiration from plants. While surface soil moisture, surface available energy and atmospheric resistance to water vapor transport drive evaporation rate from soil, transpiration is controlled by a combination of factors including moisture availability in the plant's root zone, available energy, and atmospheric and canopy resistances to water vapor transport (Monteith 1965).

In recent years, remote sensing products and methods have become a promising tool to map spatially continuous ET information across the Earth's surface (Aksu and Arikan 2017) thanks to a key remotely sensed surface variable, Land Surface Temperature (T_s). T_s is a good indicator of plant stress caused by moisture deficiencies in the plant root-zone (Anderson and Kustas 2008). When soil moisture is not adequate to meet plant demands, stomata in the plant leaves is closed. Afterwards, photosynthesis and transpiration are slowed, thereby causing canopy temperature to rise. Elevated plant canopy temperatures, considered as a sign of non-transpiring vegetation, can be detected from space. Therefore, the ET models based on remotely sensed thermal data capitalize on these features of T_s to develop ET estimates from space.

2. MATERIALS and METHOD

2.1. Material

The 16-day NDVI composites obtained by the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument onboard the Terra satellite as well as daily T_s products acquired by the MODIS instrument mounted on both the Terra and Aqua satellites were retrieved from the Land Processes Distributed Active Archive Center (LPDAAC; https://lpdaac.usgs.gov/). The vegetation products acquired by the MODIS instrument are in 1-km spatial resolution and found to be very consistent to represent vegetation information (Huete et al. 2002). In the same way, the errors of T_s products were generally within ±1 K according to validation with in situ T_s observations of various land-cover types such as bare soil, grassland, open water and rice fields around the world (Wan et al. 2002; Wang, Liang, and Meyers 2008).

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Daily minimum (T_{min}) and maximum (T_{max}) air temperatures were obtained from the Daily Surface Weather and Climatological Summaries (Daymet, Version 2) dataset (Thornton et al. 2014). Later, daily average air temperature (T_a) datasets were produced from daily T_{min} and T_{max} datasets by calculating the arithmetic mean of T_{min} and T_{max} .These products are in 1-km spatial resolution, as well.

2.2. Method

Moran et al. showed (1994) that the measurements of fractional vegetation cover (*f*r) and surface minus air temperature ($T_s - T_a$) would theoretically compose a trapezoidal shape (Fig. 1) and named the concept, vegetation index-temperature trapezoid (VITT). Going left to right within this shape, soil moisture conditions change from wet to dry. The edges of this shape represent hydrological extremes (wet and dry conditions). A computer program in Python programming language were written to locate the critical points, P1, P2, P3 and P4 as shown in Fig. 1. All the computation in the model were fully automated and it doesn't require human intervention. Detailed information about the model can be found in these works (Yagci et al. 2017; Yagci and Santanello 2018).

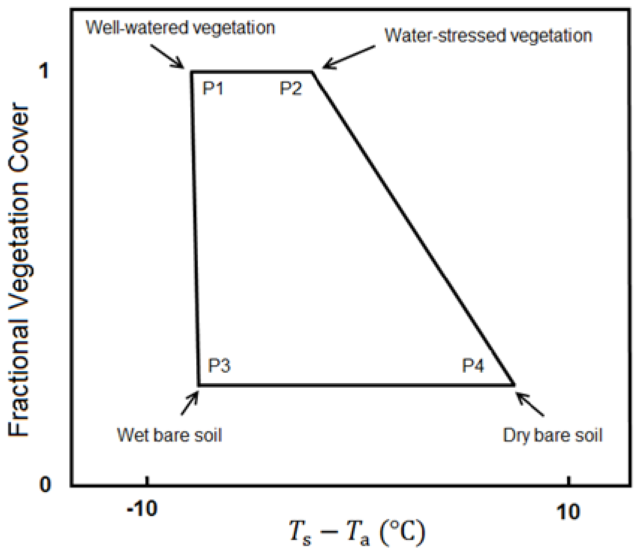

Figure 1. A theoretical trapezoidal space that would from the relationship between surface minus air temperature ($T_s - T_a$) and Fractional Vegetation Cover (*f*r)

2.3. Study Area

All three validation sites are in the US. The first site, US-Skr: Shark River Slough (Tower SRS-6) Everglades, is registered in AmeriFlux dataset. The flux tower is situated in the protected wilderness area by the Shark River in the Everglades National Park, Florida, U.S.A. The site is characterized by mangrove forests whose heights range from 15 to 20 m. The climate is humid subtropical and characterized by a mild, dry season (October–May) and warm, very wet season (June–September).

The other two validation sites, EF-14 and EF-21, in the US Southern Great Plains (SGP) were selected to validate model estimates. These sites were established by the Department of Energy's under the Atmospheric Radiation Measurement (ARM) program. The crop type at EF-14 site is winter wheat, while forest (e.g., mixed deciduous forest) dominates the EF-21 site. According to Köppen–Geiger classification, both validation sites are characterized by temperate humid climate with hot summers (Cfa).

3. RESULTS

The scatterplots that show validation done at flux towers, US-Skr, EF-14 and EF-21, are given in Fig. 2, Fig. 3 and Fig. 4, respectively. The observation count (N) and errors measures, such as Bias and Root Mean Square Error (RMSE) are shown in Table 1 and Table 2 for T_s products of MODIS-Terra and MODIS-Aqua, respectively. EF is a unitless measure, while ET has a unit of Watts per meter square (Wm^{-2}).

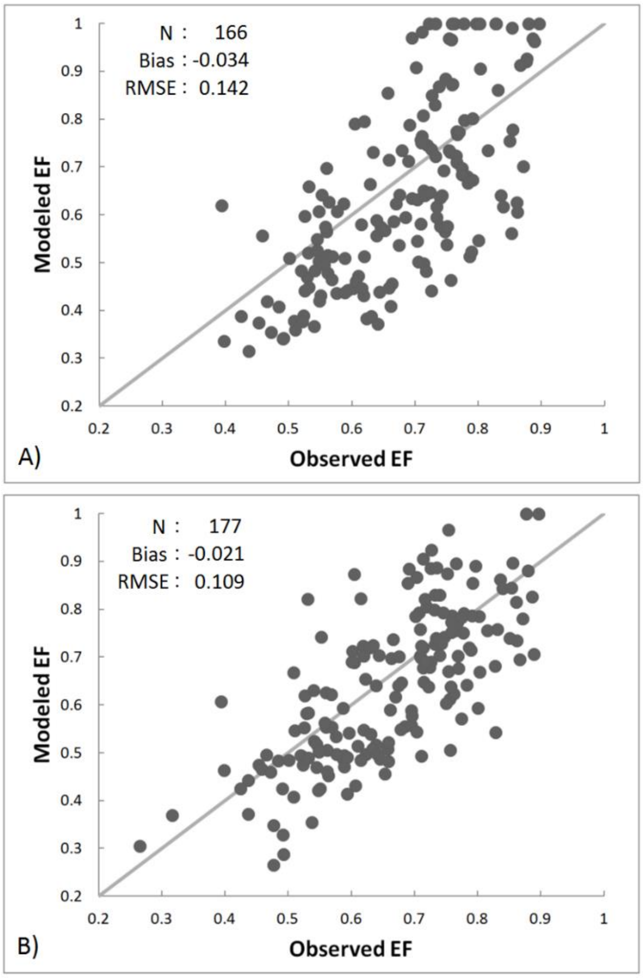

Figure 2. The validation of the Terra-based (A) and Aqua-based (B) evaporative fraction (EF) against eddy covariance tower-based EF at US-Skr in 2009.

The results indicates that the model was able to reproduce EF and ET variability at US-Skr station in 2009 (Fig. 2) as well as EF-14 and EF-21flux stations in 2011 (Fig. 3 and Fig. 4). Both EF and ET results when the model is run with the T_s products from MODIS-Aqua satellite, were more accurate in comparison to the model results of the T_s products from MODIS-Terra satellite. The MODIS instrument mounted on the Terra satellite collects morning surface temperature, while afternoon surface temperature is acquired by the MODIS instrument onboard the Aqua satellite.

Table 1. Validation of EF (unitless) and ET (Wm^{-2}) using T_s products acquired by the MODIS-instrument on board the Terra satellite. EF validation was done at US-Skr site, while ET validation was carried out at EF-14 and EF-21 sites. N is the number of observations, while RMSE is root mean square error.

Site	N	Bias	RMSE
US-Skr	166	-0.034	0.142
EF-14	132	-4.648	0.532
EF-21	244	50.674	49.886

Table 2. Validation of EF (unitless) and ET (Wm^{-2}) using T_s products acquired by the MODIS-instrument on board the Aqua satellite. EF validation was done at US-Skr site, while ET validation was carried out at EF-14 and EF-21 sites. N is the number of observations, while RMSE is root mean square error.

Site	N	Bias	RMSE
US-Skr	177	-0.021	0.109
EF-14	135	2.237	-2.174
EF-21	249	39.304	34.902

4. DISCUSSION

Estimation ET is a crucial task to budget water in agriculture and monitor water consumption by farmers to irrigate their crops especially in countries which possess semi-arid climates like Turkey. It is not feasible and economical to keep account of agricultural water use using point-based tower observations. Satellite observations of vegetation condition and skin temperature of the Earth's surface are required to overcome this daunting task.

5. CONCLUSION

According to the validation carried out at the eddy covariance (ECOR) flux towers in two study areas with different climates characteristics across the US, the model was able to generate spatially continuous daily EF and ET from minimal remotely-sensed and meteorological inputs in a trapezoidal framework both cloud-free and partial-cloudy conditions.

The model outputs can be used to monitor agricultural water consumption, calibrate, and validate of hydrological, climate, and land surface models and track agricultural drought.

Given the models' success in the study areas across the US, the author was awarded a Career Development Program (CAREER) grant from the Scientific and Technological Research Council of Turkey (TÜBİTAK) to further test the model and produce ET maps in the study areas of Turkey.

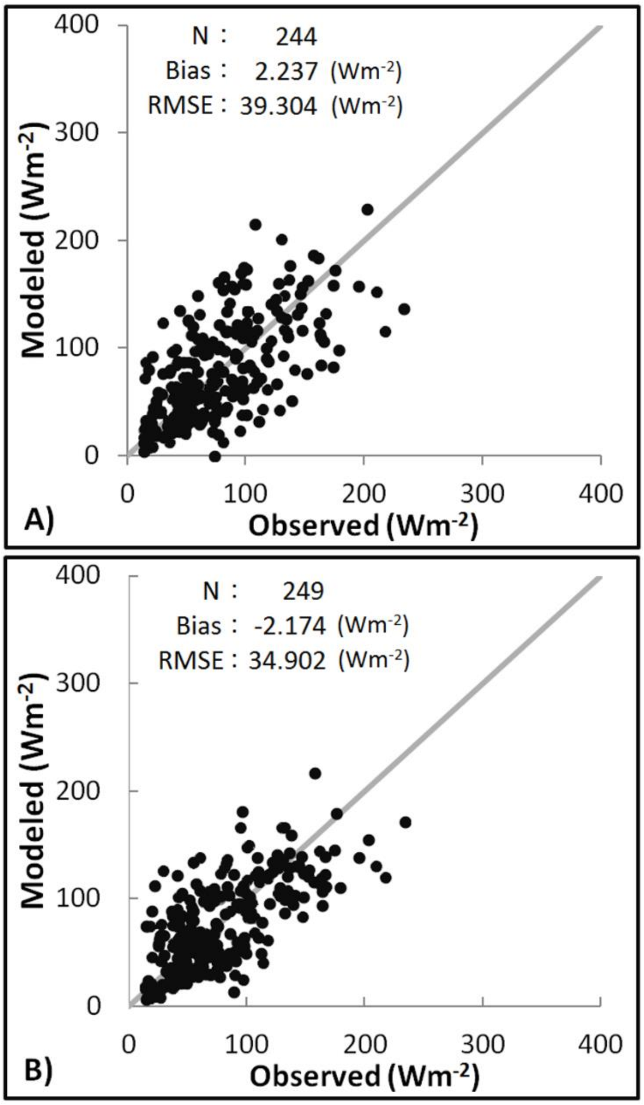

Figure 3. The validation of the Terra-based (A) and Aqua-based (B) evapotranspiration in Wm^{-2} units (ET) against eddy covariance tower-based ET at EF-14 in 2011.

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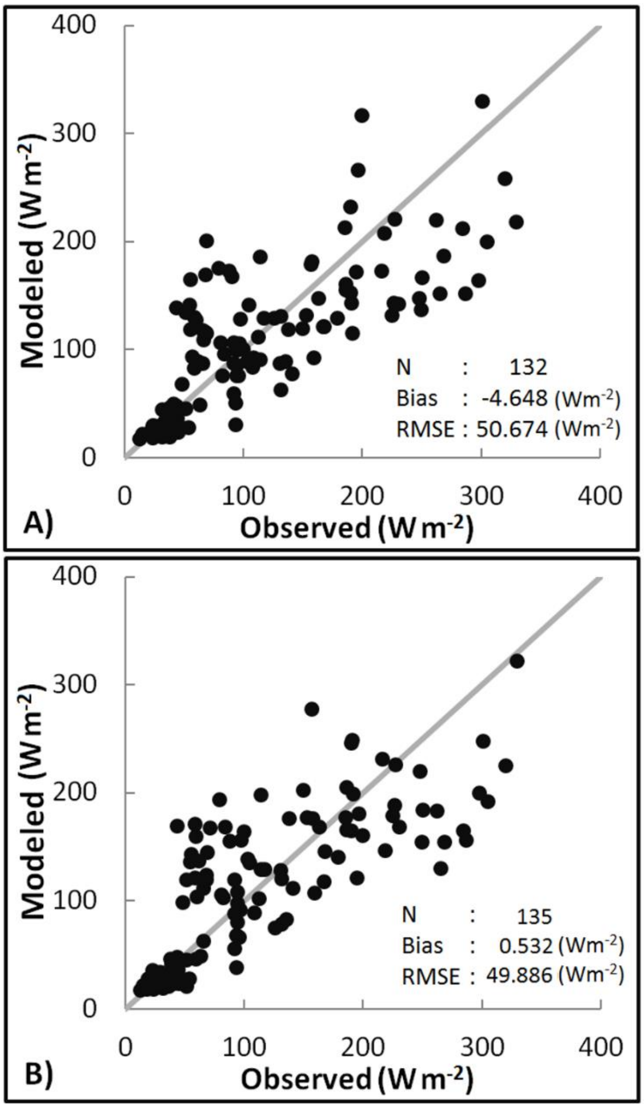

Figure 4. The validation of the Terra-based (A) and Aqua-based (B) evapotranspiration in Wm^{-2} units (ET) against eddy covariance tower-based LE at EF-21 in 2011.

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