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Mapping daily evapotranspiration and dryness index in the East African highlands using MODIS and SEVIRI data

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Abstract

Routine information on regional evapotranspiration (ET) and dryness index is essential for agricultural water management, drought monitoring, and studies of water cycle and climate. However, this information is not currently available for the East Africa highlands. The main purpose of this study is to develop (1) a new methodology that produces spatially gridded daily ET estimates on a (near) real-time basis exclusively from satellite data, and (2) a new dryness index that depends only on satellite data and weather forecast data. The methodology that calculates daily actual ET involves combining data from two sensors (MODIS and SEVIRI) onboard two kinds of platforms (Terra/Aqua – polar orbit satellite and MSG – geostationary orbit satellite). The methodology is applied to the East African highlands, and results are compared to eddy covariance measurements at one site. Results show that the methodology produces ET estimates that have high skills in reproducing the daily fluctuation in ET but tends to underestimate ET on the average. It is concluded that the synergistic use of the polar-orbiting MODIS data and the geostationary-orbiting SEVIRI data has potential to produce reliable daily ET, but further research is needed to improve the accuracy of the results. This study also proposes an operational new dryness index that can be calculated from the satellite-based actual daily ET estimates and reference daily ET estimates based on SEVIRI data and weather forecast air temperature. Comparison of this index against ground measurements of actual daily ET at one site indicates that the new dryness index is operational for drought monitoring.

1 Introduction

Routine information on regional evapotranspiration (ET) and dryness index is essential for agricultural water management, drought monitoring, and studies of water cycle and climate dynamics (Potter et al., 1993; Churkina et al., 1999; Nemani et al., 2002). The MODerate resolution Imaging Spectroradiometer (MODIS) sensor on board Terra

and Aqua satellites has long been recognized for its potential to produce frequent ET maps across the globe. Few researchers have used MODIS data to produce ET maps in different regions for some periods (Nagler et al., 2005; Patel et al., 2006; Mu et al., 2007; Wang et al., 2007; Cleugh et al., 2007; Mallick et al., 2007; Leuning et al., 2008; Venturim et al., 2008). However, despite these limited successes, we still do not have daily ET maps across the East African highlands available to the community. This is because current MODIS-based ET algorithms represent only "instantaneous or snapshot" values (while daily aggregated ET maps are more meaningful and useful), and methods of scaling up the instantaneous value to daily require ground-based measurements of radiation, which are not readily available in the East African highlands. The first objective of this study is to develop a methodology for estimating daily ET exclusively from satellite data through the use of geostationary satellite data.

Dryness indices of land surface provide useful information for agricultural and water resources managements. Among various dryness indices, two meteorological dryness indices are widely accepted and used, the Palmer's Drought Severity Index (PSDI) (Palmer, 1965; Guttman et al., 1992) and the Standardized Precipitation Index (SPI) (Tsakiris and Vangelis, 2004). The PDSI is a "meteorological" drought index that responds to weather conditions that have been abnormally dry or abnormally wet. The PDSI is calculated based on precipitation, temperature and available water content of the soil. The major problem with the PDSI index is that only point measurements with over 15–20 years of record can be used in the calculation of the index and that the spatial coverage of the point meteorological measurement in the East African highlands is scarce. The SPI is another meteorological index that suffers from the same problems as the PSDI index except that it overcomes the time lag problem associated with the PSDI index.

In addition, the major pitfall of both indices is that they contain no economic component which is important to declare drought and seek help from the Government and donors. Yield (economic analysis) is linearly related to accumulative evapotranspiration through the evapotranspiration production functions (Doorenbos and Kassam, 1979).

Therefore, evapotranspiration-based indices of drought or dryness are much more useful for real-world applications. Jackson et al. (1981) developed the Crop Water Stress Index (CWSI) that is determined by actual and potential ETs that require intensive ground-based measurements. The second objective of this study is to develop a dryness index that is based on satellite data and weather forecast data. In this study, we develop and apply a new methodology to calculate daily ET and dryness index over the East African highlands, and assess the accuracy of the results by comparing them against flux tower measurements at one site in Sudan.

2 Data

The proposed methodology (in Sect. 3) requires inputs of MODIS and geostationary-orbiting satellite data to calculate daily actual ET. In addition to these inputs, weather forecast air temperature data are also required to calculate the dryness index. The results of this methodology are validated using ground measurements from an eddy covariance flux site. Here, we discuss these data sources.

MODIS Data – MODIS sensor onboard the Terra and Aqua polar-orbiting satellites has 36 spectral bands over a wide range at moderate resolutions (250, 500, and 1000 m) with almost daily coverage of the Earth (http://modis.gsfc.nasa.gov/). We used three MODIS/Terra land data products: 8-day land surface temperature, yearly International Geosphere-Biosphere Programme (IGBP) land cover map, and 16-day Normalized Difference Vegetation Index (NDVI).

SEVIRI Data – the Spinning Enhanced Visible InfraRed Imager (SEVIRI) sensor onboard the Meteorological Second Generation (MSG) geostationary-orbiting satellite provides 30/15-min observations of land surface and the atmosphere in 12 spectral bands for Europe, South America, and Africa at 3.1 km spatial resolution at nadir (http://www.esa.int/SPECIALS/MSG/). We used five SEVIRI/MSG data products: 30-min downwelling shortwave radiation flux (DSSF), 30-min downwelling long-wave radiation flux (DSLF), 15-min land surface temperature (LST), daily vegetation cover fraction (FVC), and static auxiliary digital elevation (DEM, see Fig. 1) data.

Weather forecast air temperature data – we obtained air temperature at 2 m height ($T_{2\,m}$) from forecasts provided by the European Centre for Medium-range Weather Forecasts (ECMWF) model. The initial 3-hourly $T_{2\,m}$ forecasts at a resolution of about 25 km are linearly interpolated in time to hourly, and bi-linearly interpolated in space to the SEVIRI/MSG resolution. The $T_{2\,m}$ values undergo a further adjustment to correct differences between ECMWF mode surface topography and SEVIRI pixel altitude using a constant lapse rate of 0.67 °C/100 m. See Trigo et al. (2010) for details about ECMWF data.

Ground measurements – we obtained ground measurements of quality-controlled 30-min net radiation, soil heat flux, sensible and latent heat fluxes from the SD-Dem CarboAfrica flux tower site in Sudan (see Fig. 1 for the location map). The SD-Dem site is located at 13.2829° N, 30.4783° E, 610 m above sea level, and is characterized by a sparse acacia savanna land cover, mean annual mean air temperature of 28 °C, and mean annual precipitation of about 320 mm with the majority falling during June to October (Papale et al., 2006; Sjöström et al., 2009). The measurements were available for the period 1 July–29 December 2007.

3 Methodology

The proposed methodology for the estimation of daily actual ET and dryness index is illustrated with a flow chart in Fig. 2. Here, we discuss in detail the algorithms involved.

3.1 Daily actual ET (ET_d)

ET_d (mm/day) is estimated using inputs of daily net radiation (Rn_d) and daily soil heat flux (G_d) derived from SEVIRI and "instantaneous" evaporative fraction (EF) during the daytime derived from MODIS, and making the commonly used assumption that the EF is constant during the daytime (e.g., Brutsaert and Sugita, 1992):

$$ET_d = EF_d \times (Rn_d - G_d) = \frac{1}{\lambda} EF_{MODIS} \times \sum (Rn_{SEVIRI} - G_{SEVIRI}) \quad (1)$$

Where λ is the latent heat of vaporization, the subscript SEVIRI indicates that the data comes from the 30-min SEVIRI product, the subscript MODIS indicates that the data comes from the MODIS product which is typically available as "instantaneous" 8-day composite product, and the summation sign represents the summation of the 30-min data during a given day. Each of the terms involved in Eq. (1) are described below.

EF_{MODIS} is derived exclusively from MODIS data using the following equation:

$$EF_{MODIS} = \frac{ET_{MODIS}}{Q_{MODIS}} \quad (2)$$

where $Q(= Rn - G)$ is the available energy. We obtained ET_{MODIS} and Q_{MODIS} using our recently developed algorithm known as Sim-ReSET (Sun et al., 2009) that requires three MODIS products as input: land surface temperature, NDVI and land cover type.

Rn_{SEVIRI} is derived exclusively from SEVIRI data using the following equation:

$$Rn_{SEVIRI} = (1 - \alpha_{SEVIRI}) R^{\downarrow}_{S-SEVIRI} + R^{\downarrow}_{L-SEVIRI} - \varepsilon_{SEVIRI} \sigma T^4_{s-SEVIRI} \quad (3)$$

where α is albedo, ε is emissivity, $R^{\downarrow}_S$ is downwelling shortwave radiation, $R^{\downarrow}_L$ is downwelling long-wave radiation, and T_s is surface temperature. $R^{\downarrow}_S$, $R^{\downarrow}_L$, and T_s are directly from SEVIRI product. Both α and ε are estimated by means of SEVIRI FVC data (Sun et al., 2009).

G_{SEVIRI} is also derived exclusively from SEVIRI using the following equation:

$$G_{SEVIRI} = Rn_{SEVIRI}[f_{veg-SEVIRI} \Gamma_{veg} + (1 - f_{veg-SEVIRI}) \Gamma_{soil}] \quad (4)$$

where f_{veg} is the fractional vegetation cover (FVC), Γ_{veg} and Γ_{soil} are the ratios of soil heat flux to net radiation for vegetation and bare soil. Both of them can be approximately considered as constants, 0.1 and 0.4, respectively (Sun et al., 2009).

Matching MODIS and SEVIRI pixels – MODIS data are available at 1 km spatial resolution in sinusoidal projection while SEVIRI data are available at 3.1 km spatial resolution at nadir in geostationary satellite view (GEOS) projection. We reprojected and resampled MODIS data to match the SEVIRI data.

3.2 Dryness Index (DI)

Jackson et al. (1981) developed the CWSI which is determined from actual and potential ET. The potential ET is typically calculated by multiplying the reference evapotranspiration (ET_0) by the crop coefficient (K_c) (Allen et al., 1998). However, it is difficult to estimate K_c from SEVIRI data due to the crop type heterogeneity in the large SEVIRI pixel. We propose a new dryness index (DI) that avoids K_c as follows:

$$DI = \begin{cases} 1 - \frac{ET_d}{ET_0}, & \text{for } ET_0 \geq ET_d \\ 0, & \text{for } ET_0 < ET_d \end{cases} \quad (5)$$

We estimated ET_0 using the modified Makkink equation. The modified Makkink equation is a suitable alternative for Penman's equation for the determination of ET_0 (de Bruin and Lablans, 1998) as follows:

$$ET_0 = c\frac{1}{\lambda}\frac{\Delta}{\Delta+\gamma}\sum R^{\downarrow}_{S-SEVIRI} \quad (6)$$

where c is a constant (0.65 suggested by de Bruin, 1998), γ is the psychrometric constant (kPa/°C), and Δ is the slope of the saturation vapor pressure curve at air temperature (kPa/°C). We obtained T_{2m} from forecasts provided by the ECMWF model. Then Δ is determined by means of T_{2m}, and γ is determined by means of the DEM data:

$$\Delta = \frac{4098[0.6108\exp(\frac{17.27T_{2m}}{237.3+T_{2m}})]}{(237.3+T_{2m})^2}$$

$$P_a = 101.3(1 - 0.0065\frac{z}{293})^{5.26}$$

$$\gamma = 0.665 \times 10^{-3} P_a \quad (7)$$

where P_a is the atmospheric pressure (kPa), z is the elevation above sea level (m). A detailed description of the ET_0 algorithm is available in de Bruin et al. (2010).

4 Results

We applied our methodology to obtain satellite-based estimates of dryness index and daily actual and references ETs for the Northeast Africa for the year 2007. Figure 3 shows sample maps for different seasons. Since ET_0 is controlled by solar radiation, air temperature, and air pressure, its values are comparatively low in mountainous regions with high altitudes (shown in brown and blue colors in Fig. 3). During the rainy season in Ethiopia, daily actual ET values are high (shown in blue) and dryness index values are low (shown in green), as expected.

The accuracy of our results was assessed through comparison with ground-based measurements. In Fig. 4, the satellite-based daily actual ET estimates are compared with ground-based measurements at the SD-Dem site in Sudan. There is a good correlation (R^2=0.87) between our satellite-based estimates and ground measurements, however, the satellite estimates tend to underestimate the daily actual ET by about 30%. The mean absolute error (MAE) is 0.88 mm/day, which is better than the 1∼1.5 mm/day range reported in other validation studies of satellite ET estimation (e.g., Carlson et al., 1995; Gómez et al., 2005, Sánchez et al., 2008). In Fig. 5, the daily satellite-based dryness index estimates are compared against ground-based daily actual ET measurements at the SD-Dem site. There is a good correlation (R^2=0.86) between the two, indicating that the satellite-based dryness index estimates are reasonable. Ideally, the dryness index should be 100% when daily actual ET is 0, and should decrease with increasing ET. Our results are consistent with this expectation:

the dryness index estimate is 114% when ET is 0, and decreases with increasing ET with a good correlation (R^2=0.86). Validation of the satellite-based daily reference ET estimates in the Ethiopian highlands is addressed by de Bruin et al. (2010) who reported satisfactory results on the accuracy of the satellite-based estimates.

5 Discussion

Our results reveal that the synergistic use of MODIS and SEVIRI data has the potential to provide realistic values of daily actual ET, daily reference CT, and daily dryness index. However, the resulting daily ET values, calculated using our algorithm, tend to underestimate as compared to the eddy covariance measurements at the SD-Dem site. The discrepancy between the two values could be caused by factors, such as, algorithm limitation and the mismatch between the SEVIRI pixel and flux tower footprint, among others. In the following, we discuss these issues in further detail.

Error in net radiation – the daily net radiation is estimated by summing up the 30-min net radiation obtained from the SEVIRI data during the day. In cloudy sky conditions, the useful radiation and surface temperature data are not available, and this leads to underestimation of the daily net radiation on cloudy days. Validation results reported by LSA-SAF (2008) indicate that the SEVIRI LST values tend to overestimate surface temperature, and this leads to underestimation of the daily net radiation. LSA-SAF (2009) also reported underestimation of the SEVIRI downwelling shortwave radiation, which again leads to underestimation of the daily net radiation. Underestimation of daily net radiation leads to underestimation of actual daily ET, and this is consistent with our finding that our algorithm tends to underestimate the daily actual ET.

Errors in Evaporative Fraction – EF is estimated by means of the VI-Ts diagram in the Sim-ReSET model (Sun et al., 2009). It is difficult to establish a correct VI-Ts diagram in dry seasons or regions due to the lack of pixels with full ranges of VI and surface moisture (Sun et al., 2008). Misclassifying a moderately dry pixel as a wet pixel results in overestimating EF, and thus overestimating ET.

Mismatch between satellite and flux tower footprints – there is a large discrepancy between the satellite-based ET resolution (3.1 km at nadir) and the footprint of flux tower (ten or hundred meters). In semi-arid areas of Africa, such as the savanna regions where vegetation is sparse, the footprint of eddy covariance flux tower can be too smaller than the mean distance of individual trees or bushes (Hoedjes et al., 2007). In addition, flux towers are often set up close to vegetation areas, thus they tend to give higher ET measurements than spatially averaged values.

6 Conclusions

We proposed a methodology to estimate actual ET, reference ET and dryness index on a daily time scale. The method combines information from the once-daily polar-orbiting satellite data of MODIS/Terra and the 15/30-min geostationary-orbiting satellite data of SEVIRI/MSG. Daily actual ET is estimated from "instantaneous" EF (MODIS-based), and daily net radiation and soil heat flux (SEVIRI-based). Daily reference ET is estimated from downwelling shortwave radiation (SEVIRI-based) and air temperature (ECMWF weather forecast product). We also proposed a new measure of drought, the dryness index which is calculated from the ratio between actual and reference daily ET.

We applied the methodology over the East African highlands, and calculated the daily actual ET, reference daily ET and dryness index for the year 2007. We compared the results against eddy covariance measurements of ET at the SD-Dem flux tower site in Sudan. Results show that there is a good agreement (R^2=0.87 and MAE=0.88 mm/day) between our satellite-based daily ET values and the eddy covariance measurements, however, our estimates tend to underestimate the actual daily ET values by about 30%. We have discussed possible sources of this underestimation.

Based on the findings of this study, we conclude that the synergistic use of the polar-orbiting MODIS data and the geostationary-orbiting SEVIRI data has potential to produce reliable daily ET (actual or reference) and a measure of drought exclusively from satellite data and weather forecast data. We have presented a methodology of

combining these datasets. Our methodology has a good skill in reproducing the daily temporal fluctuations of ET, but tends to underestimate actual daily ET. Further research is needed to improve the accuracy of the methodology, especially in cloudy sky conditions.

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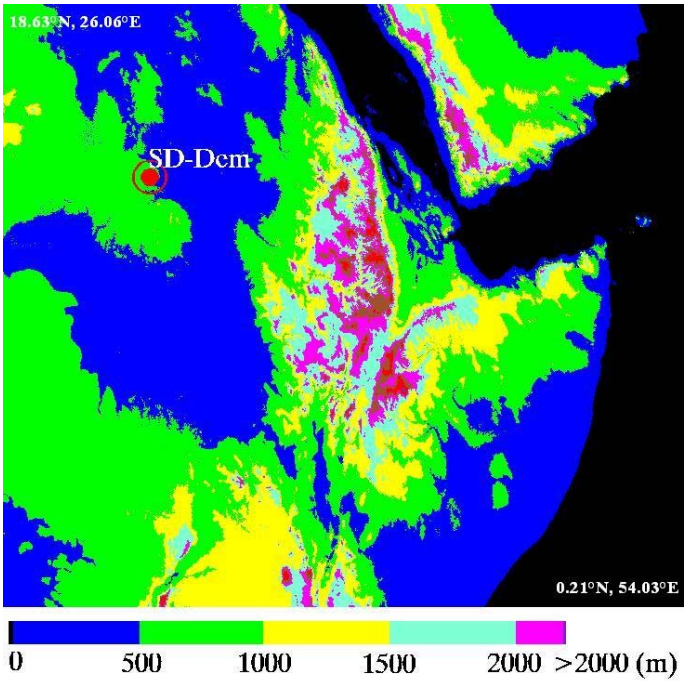

Fig. 1. Digital elevation map of the study region, and location of the SD-Dem validation site in Sudan.

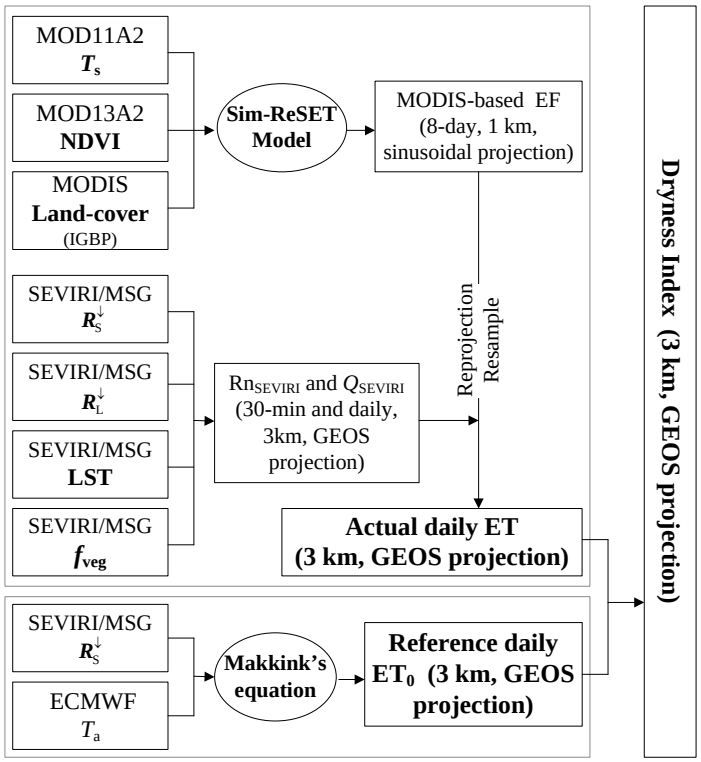

Fig. 2. Flowchart of the proposed methodology to estimate daily actual ET, daily reference ET, and daily dryness index.

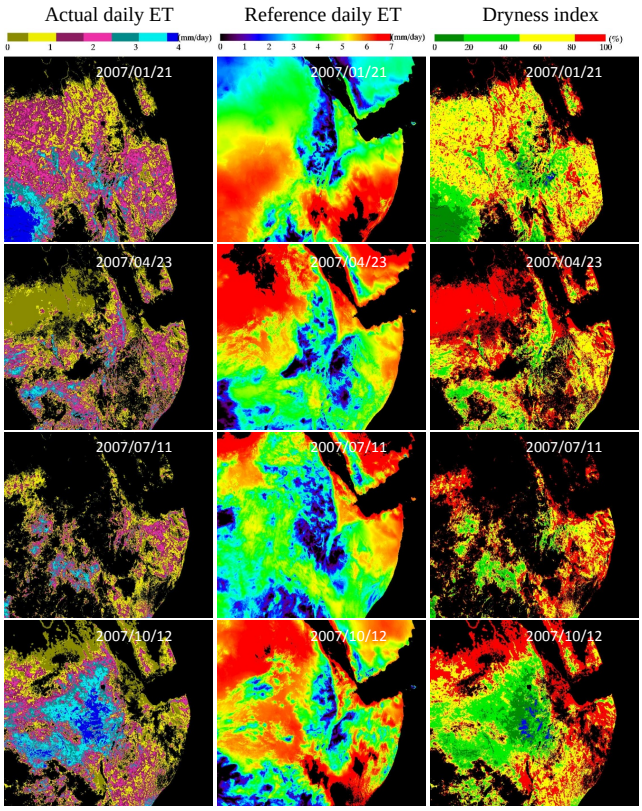

Fig. 3. Sample maps of (left panel) actual daily ET, (middle panel) daily reference ET, and (right panel) daily dryness index in different seasons in the study region.

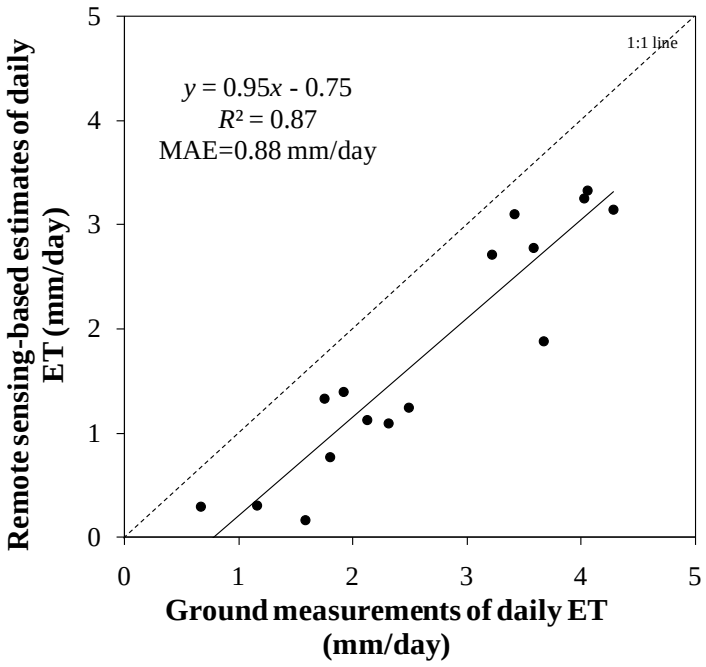

Fig. 4. Comparison of satellite-based daily actual ET estimates and eddy covariance measurements of daily actual ET at the SD-Dem site.

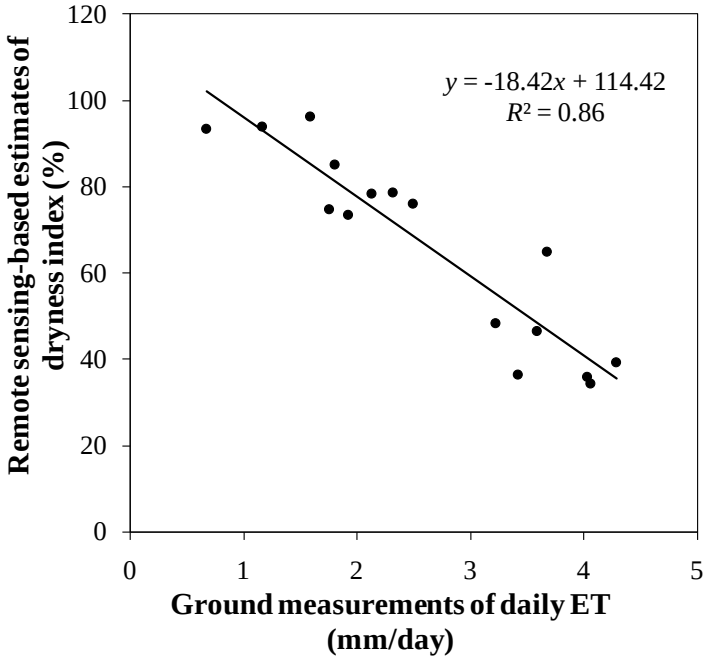

Fig. 5. Satellite-based daily dryness index estimates versus eddy covariance measurements of daily actual ET at the SD-Dem site.