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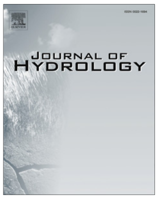

Comparisons of satellite-based models for estimating evapotranspiration fluxes

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SUMMARY

Two different types of remote sensing-based techniques were applied to assess the mass and energy exchange process within the continuum soil–plant-atmosphere of a typical Mediterranean crop. The first approach computes a surface energy balance using the radiometric surface temperature (T_s) for estimating the sensible heat flux (H), and obtaining the evapotranspiration fluxes (ET) as a residual of the energy balance. In the paper, the performance of two different surface energy balance approaches (i.e. one-source and two-source (soil + vegetation)) was compared. The second approach uses vegetation indices ($\mathrm{VI_s}$), derived from the canopy reflectance, within the FAO-based soil water balance approach to estimate basal crop coefficients to adjust reference $\mathrm{ET_0}$ and compute crop ET. Outputs from these models were compared to fluxes of sensible (H) and latent (LE) heat directly measured by the Eddy Covariance method, through a long micrometeorological monitoring campaign carried out in the area of interest.

The two-source (2S) model gave the best performance in terms of surface energy fluxes and ET rate estimation, although the overall performance of the three approaches was appreciable. The reflectance-based crop coefficient model has the advantages to do not require any upscaling of the instantaneous ET fluxes from the energy balance models to daily integrated ET. However, its results may be less sensitive to detect crop water stress conditions respect to approaches based on the radiometric surface temperature detection.

1. Introduction

Evapotranspiration (ET) has been recognized as the most important process playing an essential role in determining exchanges of energy and mass between the hydrosphere, atmosphere and biosphere (Sellers et al., 1992). In agriculture, being it the major consumptive use of irrigation water and precipitation, any attempt to improve water use efficiency must be based on reliable ET estimates. ET varies regionally and seasonally, depending on weather and wind conditions and the comprehension of these variations is essential for water resources planning and management in arid and semi-arid regions (Consoli et al., 2006; Gowda et al., 2008; Consoli and Barbagallo, 2012).

At field scale, ET can be measured using conventional energy balance techniques, such as Eddy Covariance (EC), Bowen ratio-energy balance (BREB), or by weighing lysimetry. However, some of these systems do not provide spatial distribution at wide spatial scale (i.e. regional), especially in regions with advective climatic conditions.

The integration of remotely sensed data into ET models may facilitate the estimation of water consumption in agricultural areas. In particular, the operation of remote sensing-based ET models to hydrology and agriculture has increased in the last few years (Gonzalez-Dugo et al., 2009).

Two general types of remote sensing approaches for estimating crop ET have been successfully applied in agricultural water use studies. The first approach is based on the land surface energy balance (EB), that uses remotely sensed surface reflectance in the visible (VIS) and near-infrared (NIR) portion of the electromagnetic spectrum and the radiometric surface temperature (T_s), derived from thermal band imagery (Kustas and Norman, 1996; Bastiaanssen et al., 1998; Barbagallo et al., 2009; Gonzalez-Dugo et al., 2010). Remote sensing based EB models convert satellite sensed radiances into land surface characteristics such as albedo, leaf area index, vegetation indices, surface emissivity and surface temperature to estimate ET as a residual of the land surface energy balance equation.

A second approach relies on the ability of vegetation indices ($\mathrm{VI_s}$) derived from surface reflectance data to trace the crop growth and estimate the basal crop coefficient (K_{cb}). This second method determines spatially distributed values of K_{cb} that capture

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field-specific crop development and are used to adjust reference ET (ET_0) daily estimated from local weather station data. The main advantage of the VI-based methods is that satellite imagery in the reflective bands are more readily available than the thermal band data, and generally at higher spatial resolution. However, unless coupled to a soil water balance, this method cannot account for soil evaporation or crop transpiration rate changes due to water stress conditions. In contrast, surface temperature-based methods can readily capture stress effects without requiring ancillary rainfall data and soil hydraulic and texture properties (Anderson et al., 2007).

This paper compares the performance of a semi-empirical one-source (1S) energy balance model, a two-source (2S) energy balance model for estimating sensible and latent heat fluxes from soil and canopy elements, and the vegetation index-basal crop coefficient (VI-FAO) approach for estimating daily crop ET. Remote sensing-based models were compared with *in situ* micrometeorological measures of ET by the Eddy Covariance (EC) technique.

The experiment was conducted over an irrigated orange orchard in Sicily (south Italy) during 2012.

2. Methodology

2.1. Experimental field and in situ measurements

Accurate and precise ground-based measurements are essential to define and verify satellite-based estimates, as well to support specialized research. To fill this niche, a micrometerological long monitoring program was established in 2009 through the support of the Sicilian Region administration. Its primary objective was to support agro-meterological research with accurate continuous, long-term measurements pertaining to the surface energy balance within the continuum soil–plant-atmosphere system.

In particular, micrometeorological fluxes and ground-based measurements were collected within a 20-hectare plot planted with 15–25-year-old orange trees (*Citrus sinensis*, cv Tarocco Ippolito). The experimental field is located in Lentini (Eastern Sicily, Lat. 37°16′N, Long. 14°53′E), in a Mediterranean semi-arid environment (Fig. 1). The site presented conditions of crop homogeneity (i.e. fairly monoculture farming system, high percentage of ground cover by vegetation), flat slope, dominant wind speed and fetch that are ideal for micrometeorological measurements. The planting layout was 4.0 × 5.5 m and the trees were drip irrigated with 4 on-line drippers per plant with a discharge rate of 4 l h^{-1}; the crop was well-watered by irrigation supplied every day during the warm months (May–October), with irrigation timing of 5 h d^{-1}. The study area had a mean leaf area index (LAI) of 4 $m^2\ m^{-2}$, measured by a LAI-2000 digital analyser (Li-COR, Lincoln, Nebraska, USA). The instrument was programmed to calculate a mean reading from 18 measurements (2 above and 16 below the canopy). LAI data were collected with about 25 replications at selected ground sites and the percentage ground cover was estimated from the tree size relative to tree spacing in the orchards. The mean PAR light interception was 80% within rows and 50% between rows; the canopy height (h_c) was 3.7 m (Castellví et al., 2012; Consoli and Papa, 2012; Consoli and Papa, 2013).

The experimental site was equipped with Eddy Covariance (EC) systems mounted on a micrometeorological fluxes tower (Fig. 2). Continuous energy balance measurements were made from the year 2009. Net radiation (R_n, W m^{-2}) was measured with two CNR 1 Kipp&Zonen (Campbell Scientific Ltd.) net radiometers at a height of 8 m. Soil heat flux density (G, W m^{-2}) was measured with three soil heat flux plates (HFP01, Campbell Scientific Ltd.) placed horizontally 0.05 m below the soil surface. Three different measurements of G were selected: in the trunk row (shaded area), at 1/3 of the distance to the adjacent row, and at 2/3 of the distance to the adjacent row. The soil heat flux was measured as the mean output of three soil heat flux plates. Data from the soil heat flux plates was corrected for heat storage in the soil above the plates. The heat storage (ΔS) was quantified in the upper layer by measuring the rate of temperature change. The net storage of energy (ΔS) in the soil column was determined from the temperature profile taken above each soil heat flux plate. Three probes (TCAV, Campbell Scientific Ltd.) were placed in the soil to sample soil temperature. The sensors were placed 0.01–0.04 m (z) below the surface; the volumetric heat capacity of the soil C_v was estimated from

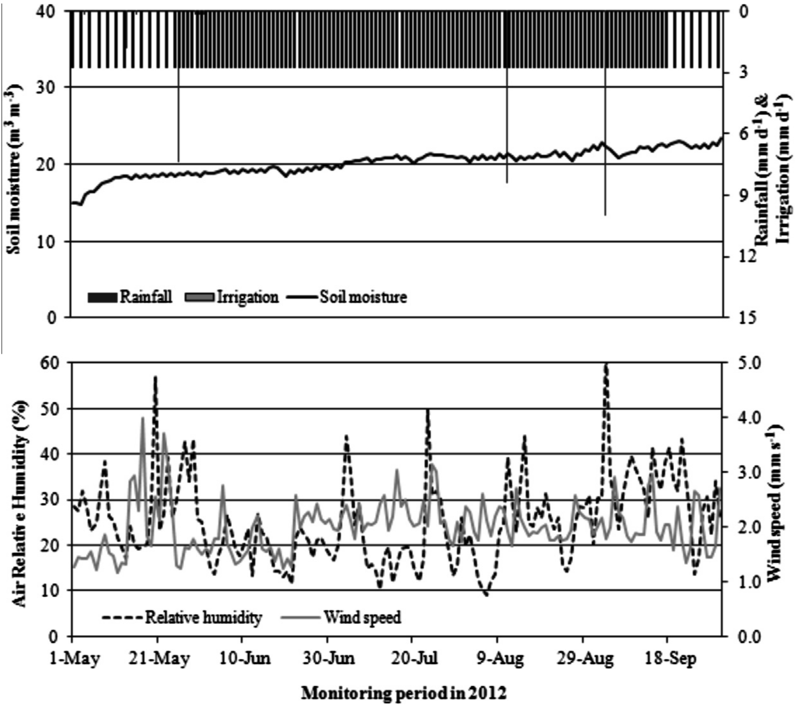

Fig. 1. Daily value of weather variables, irrigation rates and soil moisture content in the study periods.