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# Environmental factors affecting the accuracy of surface fluxes from a two-source model in Mediterranean drylands: Upscaling instantaneous to daytime estimates

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ABSTRACT

The temperature-based two-source model (TSM) of Norman et al. (1995) has not been properly evaluated under the water stress conditions that are typical in natural Mediterranean drylands. In such areas, the asynchrony between precipitation and energy supply strongly reduces evapotranspiration, *E* (or latent heat flux, *LE*, if expressed in energy terms), making sensible heat flux (*H*) the dominant turbulent heat flux. In this study, we present a detailed analysis of the main environmental factors affecting the TSM effectiveness under such challenging conditions. The accuracy of the TSM, evaluated via errors in 15-min *H* estimates, was shown to have a diurnal variation. Accuracy was clearly reduced for solar elevation angles lower than 25° and during marginal hours of daytime, before 10 am and after 3 pm. The surface to air temperature difference ($T_R - T_a$) and the wind speed were the two environmental factors showing the strongest effect on the TSM accuracy. In contrast with results observed in other ecosystems, in this Mediterranean tussock grassland the TSM accuracy was not clearly reduced by cloudiness and it was improved under highly stressed vegetation conditions. The parallel resistances scheme of the TSM ($TSM_P$) showed overall lower errors and a lower tendency to underestimate at high *H* values, but the series resistances scheme of the TSM ($TSM_S$) increased the model accuracy under some specific circumstances such as low energy supply and atmospheric neutral conditions.

Finally, two extrapolation methods to obtain daytime ($Rn > 55\,\mathrm{W\,m^{-2}}$) turbulent fluxes from the 15-min estimates of TSM were compared: (i) assuming the self-preservation of the evaporative and the non-evaporative fraction (*EF* and *NEF method*) and (ii) averaging the total daytime instantaneous fluxes (*Averaging method*). Despite the assumption of daytime self-preservation of *EF* and *NEF* was showed consistent, this method retrieved less accurate daytime estimates of *H*, and *E* than the *Averaging method* as a result of inaccuracies affecting estimates of *EF* and *NEF* from the TSM at our site. Moreover, better daytime estimates of *H* and *E* were obtained when using instantaneous fluxes from the $TSM_P$ than from the $TSM_S$. Thus, reliable daytime estimates of *H* were obtained from the $TSM_P$ in a Mediterranean dryland, with mean errors of 20% and high correlations ($R^2 = 0.85$). However, daytime *E* was strongly overestimated (125%) using the TSM by both methods, although a good correlation with eddy covariance measurements was found ($R^2 = 0.84$).



## 1. Introduction

A two-source energy balance model (TSM) was proposed by Norman et al. (1995) for modelling the surface energy fluxes over sparse vegetated areas consisting of a more realistic and physically sound design than one-source models (OSM) (French et al., 2005; Timmermans et al., 2007). The TSM model considers the surface to air temperature gradient as the key driver of the

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turbulent fluxes coming from soil and vegetation surfaces. The TSM, under a multilayer perspective, models the land surface as a resistance network between energy sources from soil, vegetation and the overlying atmosphere (French et al., 2005). Depending on the coupling assumed between temperatures and fluxes from canopy and soil, the resistance network of the TSM can be considered *in series* ($TSM_S$), when interaction between canopy and soil temperatures is assumed or, *in parallel* ($TSM_P$) assuming that no thermal interaction exists between both layers (Kustas and Norman, 1999b). To account for the partitioning of turbulent fluxes between soil and canopy layers by the TSM, radiometric temperatures from soil ($T_s$) and canopy ($T_c$) are necessary. However, the spatial resolution of most of the surface temperature ($T_R$) data provided by remote sensing is commonly too coarse to distinguish between them. The TSM faces this issue applying an iterative procedure based on two main assumptions. First, a simple linear contribution of the soil and canopy emitted radiances, proportional to vegetation cover, to the remotely sensed radiance measured by the sensor is assumed (see the Appendix A). The second assumption considers an initial canopy latent heat flux ($LE_c$) responding to a potential rate estimated by the Priestley–Taylor equation (Priestley and Taylor, 1972). This initial $LE_c$ value is iteratively reduced when necessary until the surface energy balance equation is met on both, soil and canopy layers, assuming that soil is fully dry before any stress on vegetation occurs, and that during daytime hours condensation is very unlikely to occur. Thus, the TSM retrieves *H* and *LE* of soil and canopy layers using single measurements of $T_R$, meteorological variables (air temperature, vapor pressure deficit, wind speed and solar irradiance) and ancillary information about the vegetation (leaf area index, vegetation height and cover fraction) (Colaizzi et al., 2012b). A detailed description of the TSM formulation can be found in the Appendix A.

Many studies have tested the utility of the TSM and subsequent improvements over a broad range of vegetation cover and climate conditions (see a summary in Wang and Dickinson, 2012). Nonetheless, the TSM model has been particularly recommended for clear sky conditions, high thermal difference between soil and canopy (Wang and Dickinson, 2012) and no presence of senescent vegetation (Norman et al., 1995; Colaizzi et al., 2012a). Kustas and Anderson (2009) evaluated the TSM performance (in comparison with OSM) under extreme scenarios simulated by the Cupid model, a complex soil–vegetation–atmosphere transfer (SVAT) model, and they did not found special limitations for their water stressed vegetation scenario. However, model performance has not been properly in situ evaluated under strong water limited conditions where *H* represents a significantly greater proportion of the available energy, as it occurs in Mediterranean drylands (García et al., 2007). In Morillas et al. (2013a) the TSM performance under the water-limited conditions characterizing natural Mediterranean drylands was tested during an extensive time period (5 months including the growing season) for the first time in studies on TSM. Morillas et al. (2013a) showed that similar results were found from both resistance approaches of the model, $TSM_S$ and $TSM_P$, under such conditions with reliable estimates of the dominant turbulent flux *H* (mean errors around 30%), although significant variability was still found ($R^2$ = 0.75–0.78) mainly attributed to uncertainties affecting surface temperature measurements. However, a poor accuracy was found for the *LE* flux, with errors up to ~90%, as a result of the limitations that the residual estimation of *LE* presents in areas with such reduced *LE* magnitudes (see detailed discussion in Morillas et al., 2013a). These results highlighted the need for clarifying the environmental conditions that reduce the TSM effectiveness in natural arid and semiarid areas. This is a prior step before further model development and improvement in those natural ecosystems can be undertaken.

The TSM was originally designed to estimate the surface energy fluxes using instantaneous surface temperature retrievals from remote sensing sensors (Norman et al., 1995). The model is designed to be applied during daytime conditions and is based on parameterizations optimized for a period encompassing few hours around solar noon (Kustas and Anderson, 2009). Even though, when continuous $T_R$ measurements have been available, the TSM has been applied for the complete daytime period (Colaizzi et al., 2012b; Norman et al., 2000; Sánchez et al., 2008). Nonetheless, the diurnal behaviour of the TSM has not been discussed yet despite of the fact that other temperature-based models have shown weakness during marginal hours of daytime period (i.e., early morning and late afternoon) (Su, 2002). This has important practical implications for potential users of the TSM, especially when data from sun synchronous satellites, limited to the time of the satellite overpass, are used for model running.

The majority of studies in relation to the TSM have analyzed model accuracy just for instantaneous fluxes (Norman et al., 1995; Kustas and Norman, 1999a; French et al., 2007; Timmermans et al., 2007). However, daily or daytime estimates of turbulent fluxes are required for water resources monitoring and ecological management purposes (Glenn et al., 2007; Kalma et al., 2008). Some recent papers have shown acceptable results estimating daily *E* using the TSM in irrigated agricultural areas (French et al., 2007; Gonzalez-Dugo et al., 2009; Colaizzi et al., 2012a,b). Nevertheless, no references exist in the bibliography about the possibilities for obtaining daytime turbulent fluxes using the TSM in Mediterranean semiarid natural areas where it is expected a reduced daily *LE* and an increased daytime *H* fluxes (Domingo et al., 2011).

The objective of this work is to clarify some of the issues previously described regarding TSM performance under Mediterranean natural semiarid conditions. Specifically, three issues have been evaluated in the present work: (i) the diurnal behaviour of the TSM to estimate the dominant *H* flux, (ii) the main environmental factors affecting model accuracy for estimating *H* and (iii) the capacity of the TSM to obtain daytime values of *H* and *E*. To perform these analyses we used a dataset including in situ Eddy Covariance (EC) flux measurements and 15-min TSM model outputs from both series and parallel schemes obtained from Morillas et al. (2013a). The analysis performed here should provide new insights on the effectiveness and sensitivity of the two resistance schemes of the TSM under a wide range of environmental conditions and set the basis for estimating diurnal surface fluxes from instantaneous estimates from satellite images in Mediterranean semiarid grasslands.

## 2. Experimental dataset and field site measurements

This study was performed in a Mediterranean semiarid field site called Balsa Blanca located in Southeast Spain (36°56′24.17″ N; 2°1′59.55″ W). The vegetation of the site is sparse and it is dominated by the perennial tussock grass *Stipa tenacissima* (L.) showing a cover fraction (*fc*) estimated on the field of 0.6. The climate is Mediterranean semiarid with a mean annual rainfall of 200 mm and a mean annual temperature of 18 °C. More detailed information about the site can be found in Rey et al. (2012).

This field site was equipped with an EC system located at 3.5 m height for measuring *H* and *LE* fluxes from a homogeneous and representative area (further details in Rey et al., 2012). From the EC, measurements of *H* were recorded every 15 min in a CR-3000 datalogger (Campbell Scientific Inc., USA) and considered here as instantaneous fluxes. In order to ensure the energy closure of our EC derived measurements, which presented an imbalance of ~20%, the *residual-LE* closure method was applied (Twine et al., 2000) as previous authors suggested (Alfieri et al., 2012; Li et al., 2005) to obtain 15-min *LE* data.