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Revisiting the paper "Using radiometric surface temperature for surface energy flux estimation in Mediterranean drylands from a two-source perspective"

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ABSTRACT

The recent paper by Morillas et al. [Morillas, L. et al. Using radiometric surface temperature for surface energy flux estimation in Mediterranean drylands from a two-source perspective, Remote Sens. Environ. 136, 234–246, 2013] evaluates the two-source model (TSM) of Norman et al. (1995) with revisions by Kustas and Norman (1999) over a semiarid tussock grassland site in southeastern Spain. The TSM - in its current incarnation, the two-source energy balance model (TSEB) - was applied to this landscape using ground-based infrared radiometer sensors to estimate both the composite surface radiometric temperature and component soil and canopy temperatures. Morillas et al. (2013) found the TSEB model substantially underestimated the sensible *H* (and overestimated the latent heat *LE*) fluxes. Using the same data set from Morillas et al. (2013), we were able to confirm their results. We also found energy transport and exchange behavior derived from primarily the observations themselves to differ significantly from a number of prior studies using land surface temperature for estimating heat fluxes with one-source modeling approaches in semi-arid landscapes. However, revisions to key vegetation inputs to TSEB and the soil resistance formulation resulted in a significant reduction in the bias and root mean square error (RMSE) between model output of *H* and *LE* and the measurements compared to the prior results from Morillas et al. (2013). These included more representative ground-based vegetation greenness and local leaf area index values as well as modifications to the coefficients of the soil resistance formulation to account for the very rough (rocky) soil surface conditions with a clumped canopy. This indicates that both limitations in remote estimates of biophysical indicators of the canopy at the site and the lack of adjustment in soil resistance formulation to account for site specific characteristics, contributed to the earlier findings of Morillas et al. (2013). This suggests further studies need to be conducted to reduce the uncertainties in the vegetation and land surface temperature input data in order to more accurately assess the effects of the transport exchange processes of this Mediterranean landscape on TSEB formulations.

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1. Introduction

Reporting errors in the modeled latent heat flux (*LE*) of approximately 90% mostly due to a significant underestimate of the sensible heat flux (*H*) (70 W m^{-2}), the recent study by Morillas et al. (2013) suggests that the two-source energy balance (TSEB) model, which has been successfully applied to a wide variety of landscapes and climates (Kustas and Anderson, 2009), could not produce reliable estimates of *LE* in a semiarid Mediterranean tussock grassland site in southeast Spain (Balsa Blanca). The Balsa Blanca site is representative of arid regions which cover ~25% of the Earth's land surface (Fensholt et al., 2012) and are characterized by having low *LE* fluxes resulting in *H* being the dominant turbulent flux during most of the year (Ryu et al., 2008). To better understand the factors adversely affecting the utility of the TSEB model in this very heterogeneous semiarid environment,

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where the average daytime LE was about 115 W m^{-2}, an analysis of the local flux-gradient relationship was conducted using a combination of the measurements from the eddy covariance flux tower and the observed surface-air temperature differences. In addition, based on other observations from the Balsa Blanca site suggesting modification of TSEB resistance and canopy transpiration formulations from the standard, the TSEB results are re-analyzed. Reaffirming an earlier study by Villagarcía et al. (2007) that suggested that this landscape has some unique aerodynamic characteristics, the results of the analysis presented here indicate that the flux-gradient behavior observed at the Balsa Blanca site is quite different from what has been observed in prior studies over semiarid areas using surface-air temperature differences to estimate surface fluxes (e.g., Stewart et al., 1994; Troufleau et al., 1997; Verhoef et al., 1997). However, using local observations of vegetation cover conditions in combination with revisions to some of the TSEB formulations, the unique flux-exchange characteristics suggested by the observations can be accommodated by the model and the bias in the H and LE greatly reduced.

In this investigation, the measurements from the Balsa Blanca flux tower are used to compute the effective resistances to the transport of sensible heat, following the single-source approach with radiometric surface temperature as the boundary condition (Stewart et al., 1994). By examining values of the ratio of roughness lengths for momentum (z_{om}) and heat (z_{oh}) exchange with the single-source approach, which is indicative of the relative efficiency of momentum versus heat transport, we found that the ratio of roughness lengths at this site departs significantly from that at many other semi-arid sites analyzed by Stewart et al. (1994) among others. This difference in momentum versus heat transport in many past studies is quantified in terms of the variable kB^{-1} [$=\ln(z_{om}/z_{oh})$], which is discussed below, and its magnitude for the Balsa Blanca is found to be similar to values derived theoretically and from observations for fully vegetated surfaces (Brutsaert, 1982; Massman, 1999). Consequently, any current thermally-based single-source technique using the measurements from Morillas et al. (2013) would likely produce large errors in H and LE without a priori calibration of kB^{-1}.

It is important for the reader to understand that kB^{-1} originally accounted for the higher efficiency of momentum versus heat transport from soil and vegetated surfaces, which comes from the fact that very close to the surface elements heat transfer occurs by diffusion while momentum transfer occurs by both viscous and pressure forces (Thom, 1972). With the use of radiometric surface temperature in single-source approaches there is added complexity in defining a kB^{-1} to account not only for key factors affecting aerodynamic transport of heat versus momentum but also surface properties (notably fractional vegetation cover) and sensor viewing angle affecting radiometric surface temperature observations (see discussion below).

We also find with TSEB that using ground-based local estimates of leaf area index (LAI) and local green vegetation fraction (f_G), as opposed to using MODIS-derived estimates of local LAI and f_G as in the Morillas study, there is a significant reduction in bias between TSEB model and measured fluxes. In addition, adjustments to the empirical coefficients in the TSEB soil resistance formulation based on visual inspection of the site indicating a rocky rough soil surface further improved agreement between measured and modeled fluxes. This result indicates that modifications to model inputs as well as some of the algorithms for modeling the turbulent exchange are required in order to markedly improve model-measurement agreement at this semi-arid flux site.

2. Methodology

As shown in Fig. 1a, single-source or bulk transfer schemes for modeling sensible heat flux (H) often employ an additional resistance term (R_H) because heat transport is less efficient than momentum transport from land surface (see e.g., Garratt and Hicks, 1973). However, in applications of remotely sensed land surface temperature, an additional radiative resistance term is added (represented by R_R) so that the total excess resistance (R_{EX}) is defined, namely $R_{EX}=R_H+R_R$ and accounts for the numerous factors that cause differences between the remotely-sensed surface temperature and the aerodynamic surface temperature, most notably sensor view angle and vegetation cover effects. The aerodynamic surface temperature is defined in Fig. 1 as either T_{AEROH} or T_{AEROM}, which is physically coupled to the sensible heat exchange and associated aerodynamic resistance R_{AERO}. If it is assumed there is no difference in the efficiency in heat and momentum transport ($z_{oh}=z_{om}$ or $kB^{-1}=0$) then T_{AEROM} is associated with R_{AERO} while assuming additional resistance to heat exchange results in computing T_{AEROH} from R_{AH} ($=R_{AERO}+R_H$), requiring $z_{oh}<z_{om}$ or $kB^{-1}>0$ (Kustas et al., 2007).

Due to the difficulty in parameterizing R_{EX} robustly and parsimoniously in the application of the one-source scheme for different landscapes, climates, and observational configurations, the two-source modeling approach was developed. Because it considers vegetation and soil layers separately (Fig. 1b), this approach can accommodate the major factors that influence differences between radiometric or remotely-sensed surface temperature and the aerodynamic surface temperature which is explicitly defined in the two-source formulation (Kustas, 1990; Norman et al., 1995). The different roles of soil and vegetation in the convective and radiometric processes can be represented in a simplified form by a two-source model, such as TSEB, without requiring any additional input information beyond that needed by single-source models using more sophisticated kB^{-1} parameterizations (Norman et al., 1995; Kustas and Norman, 1999).

2.1. Single-source formulation

According to Merlin and Chebhouni (2004) one-source model formulations can provide reliable fluxes, if the excess resistance term, R_{EX}, is calibrated for a given site. The problem is that applying the R_{EX} formulation to another landscape often leads to poor results, indicating a lack of generality to the relationships (e.g., Verhoef et al., 1997). On the other hand, there have been several formulations derived from applying more complex soil-vegetation-atmosphere-transfer (SVAT) models for estimating R_{EX} or kB^{-1} based on vegetation cover conditions and radiometer viewing angle (Boulet et al., 2012; Lhomme et al., 2000; Matsushima, 2005) yielding satisfactory results using a single-source approach. Such attempts to relate R_{EX} to vegetation and surface properties are shown to mainly affect the value of R_R (Kustas et al., 2007). However, regardless of whether or not R_{EX} values appropriate for a particular landscape can be estimated from SVAT-derived formulations, computing R_{EX} from the remotely sensed surface temperature and heat flux measurements does provide a metric quantifying the efficiency of heat exchange from the observations, themselves. In the context of the one-source model, H can be expressed as:

$$H=\rho C_p\frac{T_{COMP}-T_A}{R_{AERO}+R_{EX}} \tag{1}$$

where ρC_p is the volumetric heat capacity of air, T_{COMP} is the “composite radiometric (remotely-sensed) land surface temperature”, T_A is the air temperature in the surface layer, and R_{AERO} is the aerodynamic resistance (Verma, 1989). Given measurements of T_{COMP} and T_A, H and estimates of R_{AERO}, which can have several forms as described by Verma (1989; see also e.g., Stewart et al., 1994; Verhoef et al., 1997), the value of the excess resistance term, R_{EX}, can be computed via Eq. (1). Two commonly used forms for estimating R_{AERO}, which differ in the stability correction functions applied to the logarithmic expressions, are:

$$R_A=\frac{\left[\ln\left(\frac{(z-d)}{z_{om}}\right)-\psi_m\right]\left[\ln\left(\frac{(z-d)}{z_{om}}\right)-\psi_h\right]}{uk^2} \tag{2a}$$