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.

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 Wm^{-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, 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 Villagarcia 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.

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).

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:

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

$$R_{AM} = \frac{\left[ln\left(\frac{(z-d)}{z_{om}}\right) - \psi_m\right]\left[ln\left(\frac{(z-d)}{z_{om}}\right) - \psi_m\right]}{uk^2} \tag{2b}$$

where z is the measurement height of mean wind speed, u, and air temperature, T_A, d is the displacement height, z_{om} is the aerodynamic roughness length (momentum roughness length), k is von Karman's constant ($k = 0.4$), ψ_m is the surface layer stability correction function for wind, and ψ_h is the stability correction function for temperature. Since the friction velocity (u_*) is defined as $u_* = uk\{ln[(z-d)/z_{om}] - \psi_m\}^{-1}$, R_{AM} can be computed directly from the measurements of u and u_* collected via a three-dimensional sonic anemometer according to

$R_{AM} = u/u_*^2$. To calculate R_A, the roughness parameters were estimated from canopy height (h_c) using well-established empirical relationships, namely $z_{om} = 0.13h_c$ and $d=0.6h_c$ (Brutsaert, 1982), and the stability correction functions proposed by Brutsaert (1992).

As discussed by Stewart et al. (1994), among others, a single resistance (R_{AH}) formulation that relates to the aerodynamic surface temperature T_{AEROH} to the heat flux-temperature gradient relationship (see Fig. 1a) has often historically been defined as follows:

$$R_{AH} = \frac{ln\left(\frac{(z-d)}{z_{om}}\right)-\psi_h}{u_* k} + \frac{ln\left(\frac{z_{om}}{z_{oh}}\right)}{u_* k} \quad (3)$$

which then gives the following one-source formulation for sensible heat flux exchange:

$$H = \rho C_p \frac{T_{AEROH}-T_A}{R_{AH}} \quad (4)$$

where R_{AERO} is represented in Eq. (3) by the first RHS term and R_H is represented by the second RHS term ($R_{AH} = R_{AERO} + R_H$). The R_H term is often expressed as the inverse of the Stanton number, B^{-1}, which is defined as $B^{-1} = k^{-1}\ \ln(z_{om}/z_{oh})$ (Owen and Thompson, 1963), normalized by u_*. Further, the product, kB^{-1} [= $\ln(z_{om}/z_{oh})$], characterizes the difference in the efficiency of heat and momentum transport. As mentioned above, others do not make a distinction between the roughness length for heat and momentum and only relate the sensible heat exchange to the aerodynamic resistance R_{AERO}, so that in Eq. (4) T_{AEROM} defines the aerodynamic surface temperature (see Fig. 1). However this often results in even greater discrepancies between aerodynamic surface temperature computed via Eq. (4) and radiometric (remotely-sensed) surface temperature (Kustas et al., 2007).

Two-source formulation:

Within the TSEB scheme, there is flexibility to evaluate alternative formulations for the resistances from soil (R_S) and canopy (R_X) and sensitivities to uncertainties in resistance coefficients (McNaughton and van den Hurk, 1995; Choudhury and Monteith, 1988; Kustas and Norman, 1999; Cammalleri et al., 2010) as well as different methods to parameterize the canopy transpiration in order to obtain a solution based on the partitioning of radiometric temperature and energy balance between soil and canopy elements (e.g., Colaizzi et al., 2014). Using the standard TSEB parameterizations for R_S and R_X, we have the following

$$R_S = \frac{1}{c(T_{SOIL} - T_{CANOPY})^{1/3} + bu_S} \quad (5)$$

and

$$R_X = \frac{C'}{LAI}\sqrt{\left(\frac{l_W}{u_{d+z_{OM}}}\right)} \quad (6)$$

In the formulation for R_S, u_S is wind speed near soil surface (~0.05 m), T_{SOIL} and T_{CANOPY} are radiometric temperatures and default values are c = 0.0024 (m s^{-1} $K^{-1/3}$) and b = 0.012 for moderately rough soil surfaces (Kustas and Norman 1999). However, values up to c ~ 0.0038 m s^{-1} $K^{-1/3}$ and b ranging from 0.034 to 0.087 are proposed in the literature (Kondo and Ishida 1997; Sauer et al. 1995) for rough soil and partially vegetated surfaces. This is the case in the Balsa Blanca, where there is considerable rock content on the soil surface and strongly clumped vegetation. For R_X , l_W is the leaf size/width, and u_{d+zom} the wind speed at the level of effective momentum absorption by the canopy. A value for C'=130 $s^{1/2}\,m^{-1}$ was suggested by McNaughton and van den Hurk (1995), in comparison with the 90 $s^{1/2}\,m^{-1}$ adopted by Norman et al. (1995). In the original version of the TSEB, an initial solution for the canopy transpiration component, LE_C, is obtained using the Priestley-Taylor formulation,

$$LE_C = \propto_{PTC} f_G \frac{\Delta}{\Delta+\gamma} R_{NC} \quad (7)$$

where α_{PTC} ~1.3 , Δ is the slope of the temperature-saturation vapor pressure curve, γ is the psychrometric constant, R_{NC} is the canopy net radiation, and f_G is the green vegetation fraction. Recent ground-based observations from the Balsa Blanca site indicate f_G was significantly lower than what was derived from the MODIS data and used in the Morillas study.

Results with One-Source Model: Evaluating kB^{-1} Parameter

In most studies evaluating one-source modeling approaches, no distinction is made between R_{EX} and R_H and the value of kB^{-1} is parameterized so that T_{COMP} and T_{AEROH} agree. Studies by Stewart et al. (1994), Verhoef et al. (1997), and Troufleau et al. (1997) evaluated kB^{-1} using Eq. (1) with R_{EX} approximated as $kB^{-1}/(u_* \, k)$ (based on $R_{EX} \approx R_H$ assumption) for several semiarid and arid sites. Since R_{AERO} computed using R_A and R_{AM} yielded similar results for the Balsa Blanca field site, the former was used in Eq. (1) to estimate kB^{-1} at this site for consistency with these previous studies.

Compared to the values of kB^{-1} from these earlier studies, the data from Balsa Blanca site yield values that are atypically low (Table 1). The values of kB^{-1} at the Balsa Blanca site, which averaged near 2, are more typical of those observed when the heat exchange occurs primarily with permeable vegetative roughness elements (Brutsaert, 1982, Fig. 4.24) that make up fully-vegetated surfaces (Garratt and Hicks, 1973). Based on both field observations (e.g., Kustas, 1990; Stewart et al., 1994) and modeling studies using a two-source model based on Lagrangian theory (McNaughton and van den Hurk; 1995), the value of kB^{-1} can be as much as a factor of ten larger when the soil surface also contributes significantly to heat exchange. The increase in the value of kB^{-1} is due to the lower relative efficiency of heat exchange from the soil compared to the exchange from the canopy elements that results from the greatly diminished winds near the soil surface. Stated differently, larger kB^{-1} values reflect a reduction in the overall coupling between the surface and the atmosphere, a behavior which is typically observed in semi-arid sparsely vegetated landscapes. However, with a kB^{-1} ~2 this does not appear to be the case for the Balsa Blanca site. Apart from the fractional cover and structural characteristics of the vegetation, kB^{-1} values are also strongly affected by plant stress levels and micrometeorological conditions causing kB^{-1} to change by a factor of 10 during the course of a day at the same site (Lhomme et al., 1997). The uniqueness of this dataset is further demonstrated in Figure 2, showing a histogram of kB^{-1} values derived from the Balsa Blanca data along with the mean and standard deviations of the kB^{-1} values for all the sites listed in Table 1. A Z-test at the 95% confidence level indicates the mean kB^{-1} value from Balsa Blanca data does not come from the population of samples that generated the mean kB^{-1} values from the other sites in Table 1. In other words, the mean kB^{-1}=2.2 falls outside the likely range of mean values observed at the other semi-arid and arid sites.

The data set can also be visualized in terms of the implied ratio of the roughness lengths for heat and momentum, z_{oh}/z_{om}. As can be seen in Figure 3, this ratio from the Balsa Blanca site is an order of magnitude larger than the ratio observed for nearly all of the other sites. This suggests the relative efficiency of heat exchange is much greater than has been typically observed for sparsely-vegetated arid sites, if the radiometric temperature observations are indeed representative of the entire site composite surface.

The "aerodynamic surface temperature", T_{AEROH}, can be computed by inverting Eq. (4) and using an *a priori* formulation for R_H (i.e., $R_H = kB^{-1}/u_* k$) according to:

$$T_{AEROH} = T_A + \frac{HR_{AH}}{\rho C_p} \quad (8)$$

Using the observed values of H, T_A and u_* along with estimates of R_{AERO} using Eq. (2a), and assuming kB^{-1} has a value of either 2, indicative of vegetated surfaces (Brutsaert, 1982), or 7, an average from the semi-arid sites analyzed in Stewart et al. (1994), T_{AEROH} was calculated via Eq. (8) . As one would expect with kB^{-1} equaling ~2, the derived T_{AEROH} is approximately equal to T_{COMP} since for the Balsa Blanca site the average value of kB^{-1} equals 2.2, with T_{AEROH} values falling slightly above and below the 1:1 line (Fig. 4a). However, when kB^{-1} is set equal to 7, T_{AEROH} is significantly greater than T_{COMP} (Fig. 4b). This would suggest an unusual case where the effective emitting surface temperature is *hotter* than the observed surface temperature during the daytime hours.

At the Balsa Blanca site, having perennial grasses, the vegetation fractional cover remains fairly constant, f_C ~0.6 (Morillas et al., 2013), hence midday soil - canopy temperature differences (T_{SOIL}-T_{CANOPY}), by assuming $T_{COMP} = [f_c T_{CANOPY}{}^4 + (1 - f_c) T_{SOIL}{}^4]^{\frac{1}{4}}$, ranged from 2 °C to 12 °C over the growing season. This range in temperature difference between T_{SOIL} and T_{CANOPY} is relatively small compared to soil - canopy temperature differences typically observed in semi-arid environments, often exceeding 20 °C (e.g., Chebhouni et al., 2001; Humes et al., 1994; Kustas et al., 2004). This is likely due in large part to the fact that plant green-up coincides with the wet season in many semi-arid environments whereas in Mediterranean ecosystems, the rainy period tends to be over the winter months while green-up of the vegetation happens during the dry season. This leads to the vegetation generally having higher stress conditions resulting in relatively higher values of T_{CANOPY} (Were et al., 2007; Verhoef et al., 1996).

Applying Lhomme et al. (2000) expression for estimating B^{-1} with LAI adjusted for clumped vegetation yields a kB^{-1}value of ~3.7 which results in a z_{oh}/z_{om} ratio of ~1/40 whereas kB^{-1} from the observations yields a z_{oh}/z_{om} ratio of ~1/9. This again points to other measurement factors and/or landscape features at Balsa Blanca that is affecting the efficiency of heat transport from its surface. In a recent single-source model application using remotely sensed surface temperature, modification to the soil resistance or the kB^{-1} expression for bare soil heat transfer was required to improve heat flux predictions in the semi-arid Tibetan Plateau region (Chen et al., 2013). Indeed, the single-source expression for heat transfer over bare soil surfaces derived theoretically by Brutsaert (1975) shows a strong dependency of kB^{-1} on roughness Reynolds number, and has been validated using remotely sensed surface temperature and sensible heat flux observations (Cahill et al., 1997; Yang et. al., 2008).

Results from TSEB --Before and After Modifications of Inputs: LAI and f_G and R_S

Morillas et al. (2013) used the effective values of LAI from MODIS LAI/fAPAR (fAPAR: fraction of absorbed photosynthetically active radiation) estimates (average between the Terra MOD15A and Aqua MYD15A products), with a f_C = 0.6 from site measurements. The value of f_G was estimated based on the empirical approach of Fischer et al (2008), with fAPAR defined as well from MODIS LAI/fAPAR data.

Using recent observations made in the Balsa Blanca study site from a different year but similar weather conditions, estimates of local green LAI were derived from monthly NDVI data measured using a multi-spectral camera and field LAI sampling at the study site. The one-sided leaf area index (LAI) was estimated for Stipa tenacissima from reflectance measurements with a Tetracam ADC camera (Tetracam, Inc., Gainesville, FL, USA[1]). This camera records images with 2048×1536 pixels using an 8 mm lens and 8 mm focal length. The pictures were taken at a height of 2 m to cover all the surface of the plants in one or two images. The plant canopy reflectance was divided in red, green and NIR band of wavelengths by the optical filters of the camera. The images were processed with the specific software delivered with the camera (PixelWrench II) that allows adjust the factory calibration to the spectral balance of the ambient light selecting in the picture a training area (a White Teflon Calibration Plate located near each plant, also provided with the camera) and calculate NDVI or other vegetation indices. After this correction, the pictures with the NDVI index were exported to the ESRI ArcMap software in TIFF format to select only the pixels that represented the plant canopy, thereby eliminating the noise caused by the surrounding soil. In our study, LAI values were calculated from an NDVI-LAI relationship obtained by correlating NDVI values from the Tetracam ADC camera with LAI values from destructive sampling.

Assuming total (green+dead) LAI is a constant value of ~1.75 over the growing season (study period), which appears reasonable based on visual observations of the site (Fig. 5c), we derived new values of f_G (Fig. 6) based on Tetracam ADC camera derived green LAI (Fig. 6b).

[1] The mention of trade names of commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the US Department of Agriculture.

Here, f_G was allowed to vary from 0, if the green LAI reached 0, up to 0.7 when green LAI reached its maximum value, considering that there are always dead/senescent material in the tussock grass over all seasons (Fig. 5b and 5c). The results of changing the LAI and f_G inputs in TSEB from those used originally in the TSEB model run by Morillas et al. (2013) are illustrated in Figure 7. There is a considerable reduction in the bias and RMSE for *H* and *LE* estimates using the new LAI and f_G inputs in TSEB, which highlights the limitations of using MODIS derived values of LAI and f_G at this site and the need of ground-based biophysical measurements at the same spatial resolution as the radiometric surface temperature measurements for evaluating TSEB model performance under such conditions.

Modifications to the empirical parameters *c* and *b* used to estimate soil resistance, R_S, were also made to better capture a more efficient heat exchange due to the rough soil surface and greater intensity in the turbulence based on the significant rock content of the soil surface and clumpiness of the vegetation (see Fig. 5). The values used in Eq.5 were $c = 0.0038$ (Kondo and Ishida, 1997) and b=0.065 (average of the range in value reported by Sauer et al., 1995 for small and developing canopies). This modification in R_S resulted in a further significant reduction in *H* and *LE* bias, with TSEB estimates much closer to the 1:1 line, and considerably lower RMSE for both fluxes (Fig. 7e and f). However for *LE* it resulted in a lower R^2 as a result of an increase in scatter in *H* estimates. Using a larger resistance to heat exchange from the canopy with C'=130 instead of 90 in Eq. (6) as proposed by McNaughton and van den Hurk (1995) had little effect on TSEB output of *H* and *LE* (results not shown). The implication of these results is that while the bulk heat transport expressed in terms of the kB^{-1} parameter at the Balsa Blanca differs significantly from earlier findings over most other semi-arid and arid surfaces using one-source modeling approaches, the TSEB indicates that there are physical factors related to soil and vegetation properties that largely contribute to this result. By using local observations of LAI and f_G as inputs to TSEB and changing the soil resistance coefficients to be more representative of the surface characteristics, the TSEB model achieves good agreement with *H* and *LE* measurements.

Conclusions

While there can be limitations in applying TSEB in complex heterogeneous water-limited environments having natural vegetation without modifications to the canopy transpiration formulations (Agam et al., 2010; Guzinski et al., 2013; Chirouze et al., 2014), caution needs to be exercised interpreting and using measurements made over such surfaces. In the case of the Morillas et al. (2013) paper, the relationship of the radiometric surface temperature-air temperature differences and heat flux exchange differ significantly from other semiarid areas with partial vegetation cover as defined by the kB^{-1} variable used in single-source modeling approaches.

For example, applying a mean value of kB^{-1} =7, typical for semi-arid sparsely vegetated surfaces derived by Stewart et al (1994), Stewart (1995) showed significant improvement in heat flux estimation using T_{COMP} for a sparsely vegetated grassland site with LAI ~0.5 and fractional vegetation cover ~75% in the in the Konza Prairie, Kansas, USA. However, the Konza Prairie site is not strongly clumped as the Mediterranean tussock grassland in the Balsa Blanca nor has as dry a climate.

Obviously, this same value for kB^{-1} would not be appropriate for the Balsa Blanca and is indicative of the fact that while one-source modeling approaches using radiometric surface temperature can provide a diagnostic tool for evaluating the efficiency of heat exchange, they are not reliable in general for heat flux estimation without *a priori* calibration, particularly for heterogeneous sites. However, their utility for heat flux estimation has improved through the development of kB^{-1} formulations that account for fractional vegetation cover or LAI (Su et al., 2001; Lhomme et al., 2000; Boulet et al., 2012) and variation in kB^{-1} for bare soil heat transport (e.g., Chen et al., 2013).

The current findings require flux-gradient parameterization that is not typically observed in any other previously studied semi-arid and arid sites, and with modifications to the TSEB soil resistance parameters for a very rough soil surface and more efficient heat exchange as well as modifications to the LAI and estimate of f_G based on ground observations, the significant underestimate of H and overestimate of LE is greatly reduced. These revisions to both soil resistance parameterizations and input data emphasize the need for detailed local measurements to better understand model limitations and/or refinements necessary for different land cover types.

While regional to global scale application of TSEB land surface scheme using a modeling system based on coarse resolution satellite data called the Atmosphere Land Exchange Inverse (ALEXI) model, which also has a Disaggregation scheme (DisALEXI) when using higher resolution imagery (Anderson et al., 2011) is currently producing continental scale flux fields, studies like the current one suggest this model is not applicable with a single set of resistance parameterizations for all landscapes. On the other hand, results of such local studies can be entered into a land use data base at satellite resolutions to refine model parameterizations for certain regions found to be especially challenging.

This study also cautions on the use of local observations (radiometric surface temperature) with non-local or larger scale estimates of other key inputs which are not necessarily representative of local conditions (i.e., leaf area index, green fraction). Clearly, additional measurements and analyses for this landscape are needed to confirm that these modifications to TSEB resistances are warranted, which in addition should include more ground-based infrared radiometer measurements as well as simultaneous local observations of LAI and f_G. At the same time, application with satellite data for all model inputs should also be performed to evaluate the limitations of remote sensing algorithms used in defining key model inputs (e.g., Guzinski et al., 2013).

Finally, other two-source resistance formulations from Choudhury and Monteith (1988) and McNaughton and van den Hurk (1995) should be evaluated to see if there is a consistency in results using different two-source resistance formulations, which may help better understand the observations and findings of Morillas et al. (2013).

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List of Figure Captions

Figure 1. Schematic diagram of one-source and two-source thermal-based models of sensible heat flux. See text for definition of the symbols used in the one-source model formulations. For the two-source model (TSEB), T_{SOIL} is the soil surface temperature with associated soil surface aerodynamic resistance (R_S) and heat flux from the soil (H_S) and T_{CANOPY} is the vegetation canopy temperature with associated aerodynamic canopy resistance (R_X) and heat flux from the canopy (H_C) . T_{SOIL} and T_{CANOPY} are derived from T_{COMP} and an estimate of fraction vegetation cover with an initial assumption of canopy transpiration and T_{AC} is the temperature in the canopy air space which is related to the surface aerodynamic temperature via the surface layer aerodynamic resistance (R_{AERO}) For details of the TSEB formulations see Norman et al. (1995).

Figure 2. Histogram (grey bars) of kB^{-1} values computed for the Balsa Blanca site using $R_{AERO} = R_A$. Also plotted are the mean (filled circles) and standard deviation (horizontal bars) of the kB^{-1} values listed in Table 1 staggered in the vertical with the Balsa Blanca identified with the solid star symbol.

Figure 3. The ratio of z_{oh}/ z_{om} by inverting the kB^{-1} expression, namely, $z_{oh} /z_{om}=\exp(-kB^{-1})$ for all the kB^{-1} values listed in Table 1.

Figure 4. The composite radiometric temperature measured by the thermal infrared radiometer, T_{COMP} versus the surface aerodynamic temperature T_{AEROH} computed from Eq. (5) using measurements of H, and u_* and estimates of R_{AH} from Eq. (3) with a) kB^{-1} = 2.2 derived for the Balsa Blanca site (see Table 1) and b) kB^{-1}= 7, an average value from the semi-arid sites analyzed by Stewart et al. (1987). Line is 1:1 relationship with T_{COMP} .

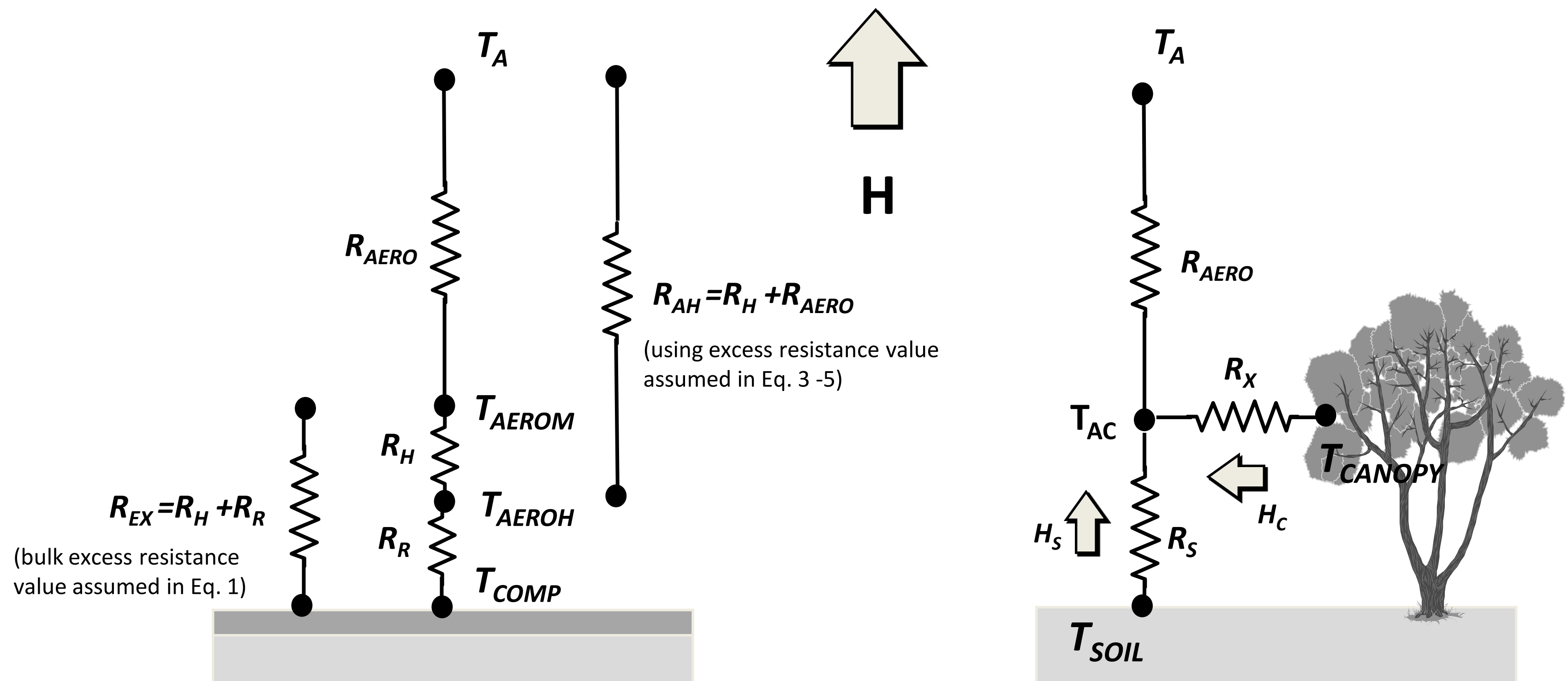
Figure 5. Photos of a) typical rock cover in non-canopy covered soil surface at the Balsa Blanca site and b) photo illustrating the strongly clumped nature of the semiarid Mediterranean tussock grassland in southeast Spain during green-up and c) at senescence in late September.

Figure 6. Estimated Leaf area index (LAI) and fraction of green LAI (Green LAI) versus Day of Year (DOY) a) from Morillas et al. (2013) using MODIS LAI/fAPAR and a green vegetation fraction, f_G, derived from Fisher et al. (2008);and b) produced using monthly NDVI data from multi-spectral camera and destructive sampling performed at the site between 2009 and 2010.

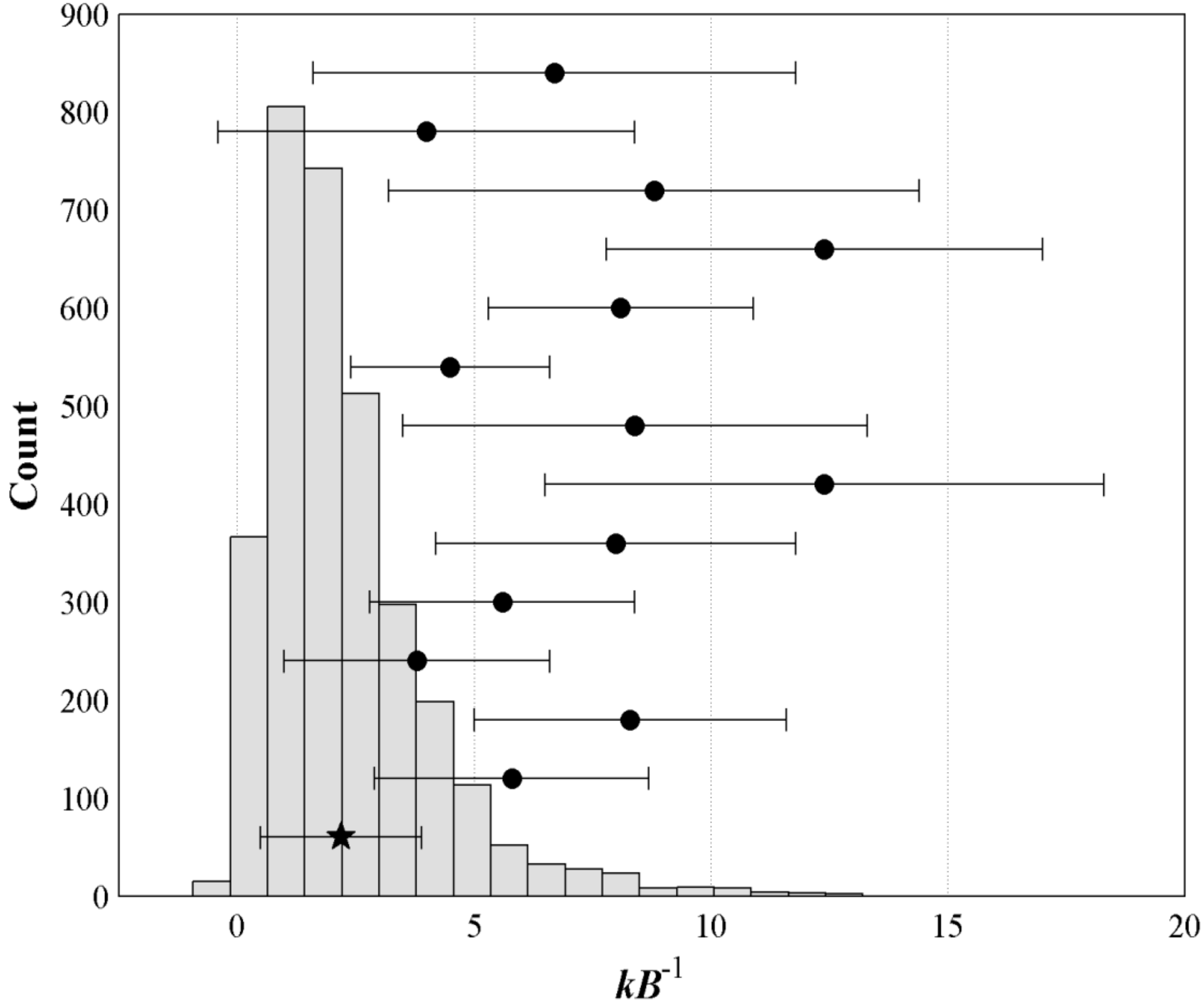
Figure 7. Sensitivity in the output from TSEB for a) H and b) LE using original LAI and f_G inputs from Morillas et al (2013) and with the standard soil resistance formulation coefficients c and b (c=0.0024, b=0.012), with c) H and d) LE computed using modifications to LAI (LAI~1.75) and green LAI (f_G * LAI) inputs (see Figs. 5 and 6) based on ground observations and with the standard soil resistance formulation coefficients c and b, and with e) H and f) LE computed using modfied LAI and green LAI inputs along with assuming a rough soil surface with clumped vegetation which resulted in revising the values of the soil resistance coefficients c and b (c=0.0038, b=0.0605). See text for more details.

Table 1. Average (avg) and standard deviation (σ) of the kB^{-1} variable based on Eq. (1) and R_{EX} ~ B^{-1}/u_* using the Balsa Blanca site from Morillas et al (2013) and study sites from Stewart et al. (1994), Troufleu et al. (1997) and Verhoef et al. (1997) having vegetation cover (not bare soil). Where available measurements or indirect estimates (*) from the literature of leaf area index (LAI), canopy height (h_C), fractional canopy cover (f_C) are provided from the lieterature as well as number of data point (n) in the statistics. The symbol NO indicates the authors found no observations or estimates provided.

Project	Surface type	LAI (-)	h_C (m)	f_C (-)	n	KB^{-1} avg	KB^{-1} σ
Balsa Blanca	Tussock grass	1.75	0.7	0.6	4803	2.2	1.7
SEBEX	Fallow Savannah	0.2→0.7 (grass) 0.1→0.6 (shrub)	0.6 (grass) 2.5 (shrub)	0.3* 0.2*	507	5.8	2.9
SEBEX	Open forest	1.3*	4.5	0.3	1142	8.3	3.3
MONSOON 90	Grassland	0.8	0.1	0.35	95	3.8	2.8
MONSOON 90	Shrubland	0.5	0.5	0.26	98	5.6	2.8
Owens Valley	Shrubland	0.48	1	0.25	22	8.0	3.8
Smith Creek Valley	Shrubland	1*	0.75	0.25	69	12.4	5.9
Smoke Creek Desert	Shrubland	NO	0.5*	0.30	79	8.4	4.9
La Crau	Stone/grass	NO	0.1*	0.05	40	4.5	2.1
EFEDA	Vineyard	0.4	1	0.10	246	8.1	2.8
HAPEX-Sahel	Savannah	NO (shrub) NO (grass)	2→2.5 (shrub) 0.5< (grass)	0.2 (shrub) NO (grass)	285	12.4	4.6
HAPEX-Sahel	Fallow Savannah	0.5 (shrub) NO (grass)	3.5 (shrub) 0.2→0.6 (grass)	0.2* (shrub) NO (grass)	1229	8.8	5.6
HAPEX-Sahel	Millet 1992	0.41→2.81	0.76→2.53	0.19→0.56	1011	4	4.4
HAPEX-Sahel	Millet 1991	1.9→2.8	0.72→2.2	0.20→0.30	648	6.7	5.1



a) One-source model b) Two-source model



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500
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300
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100
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Count
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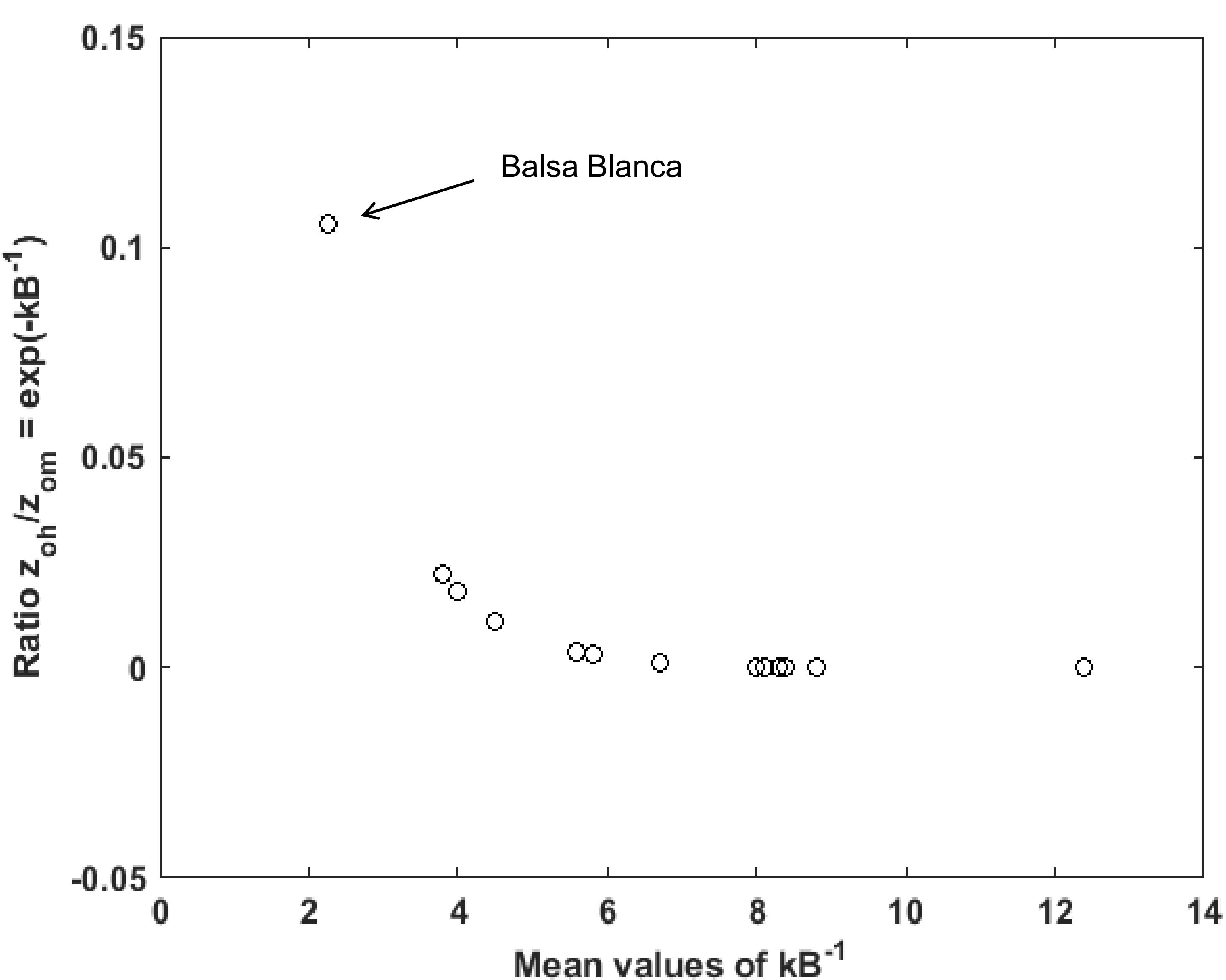
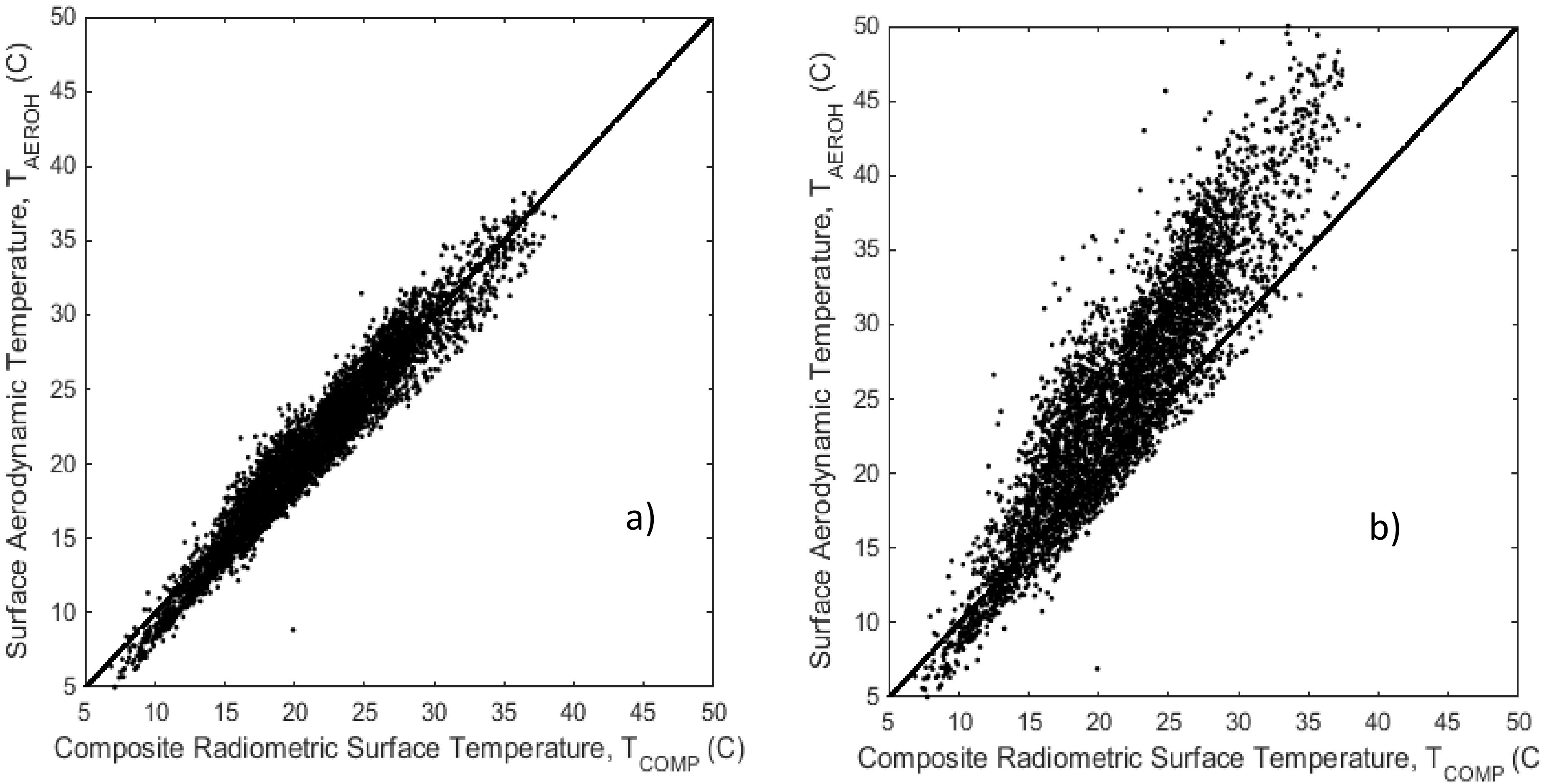
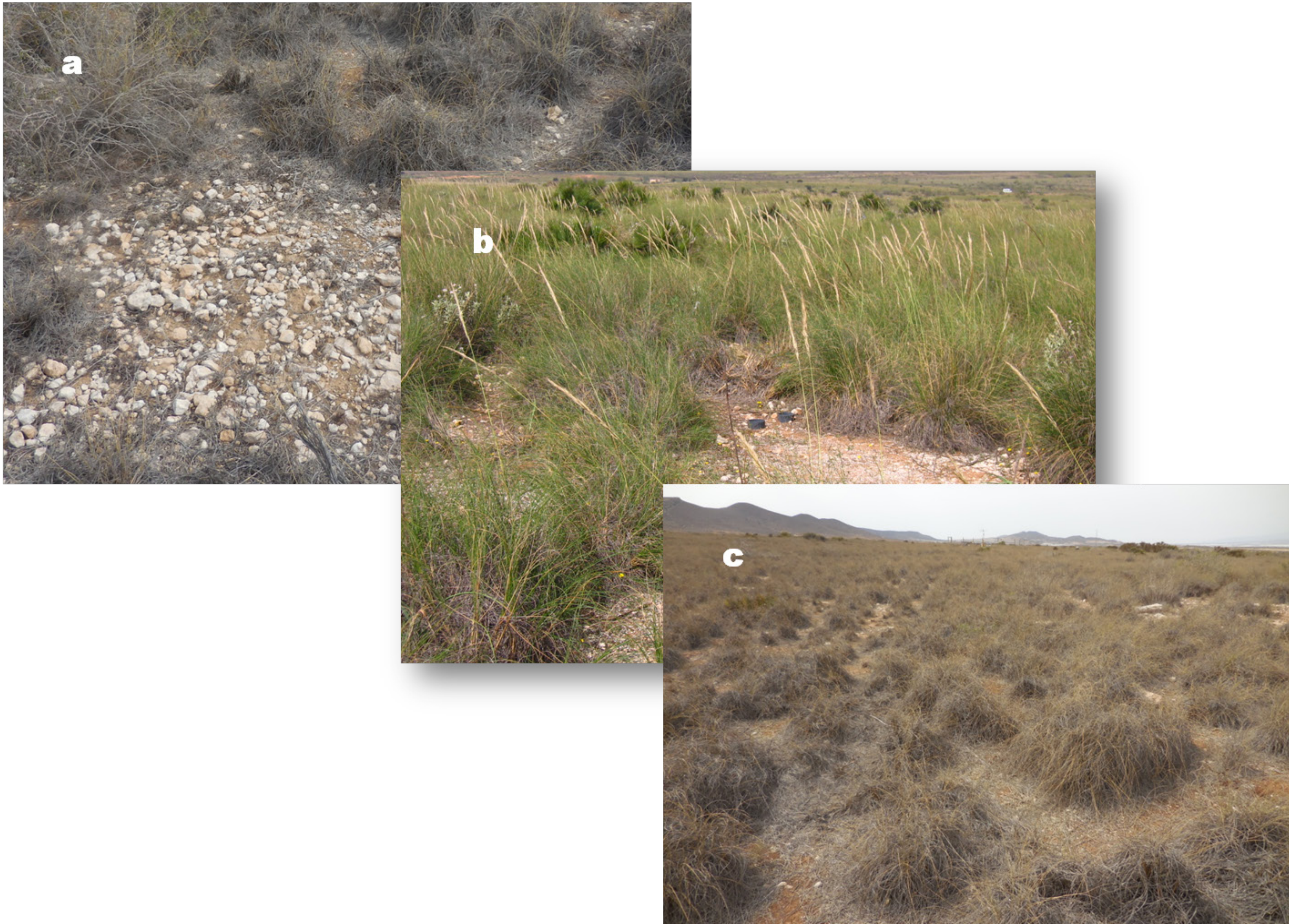
5
10
15
20
kB-1

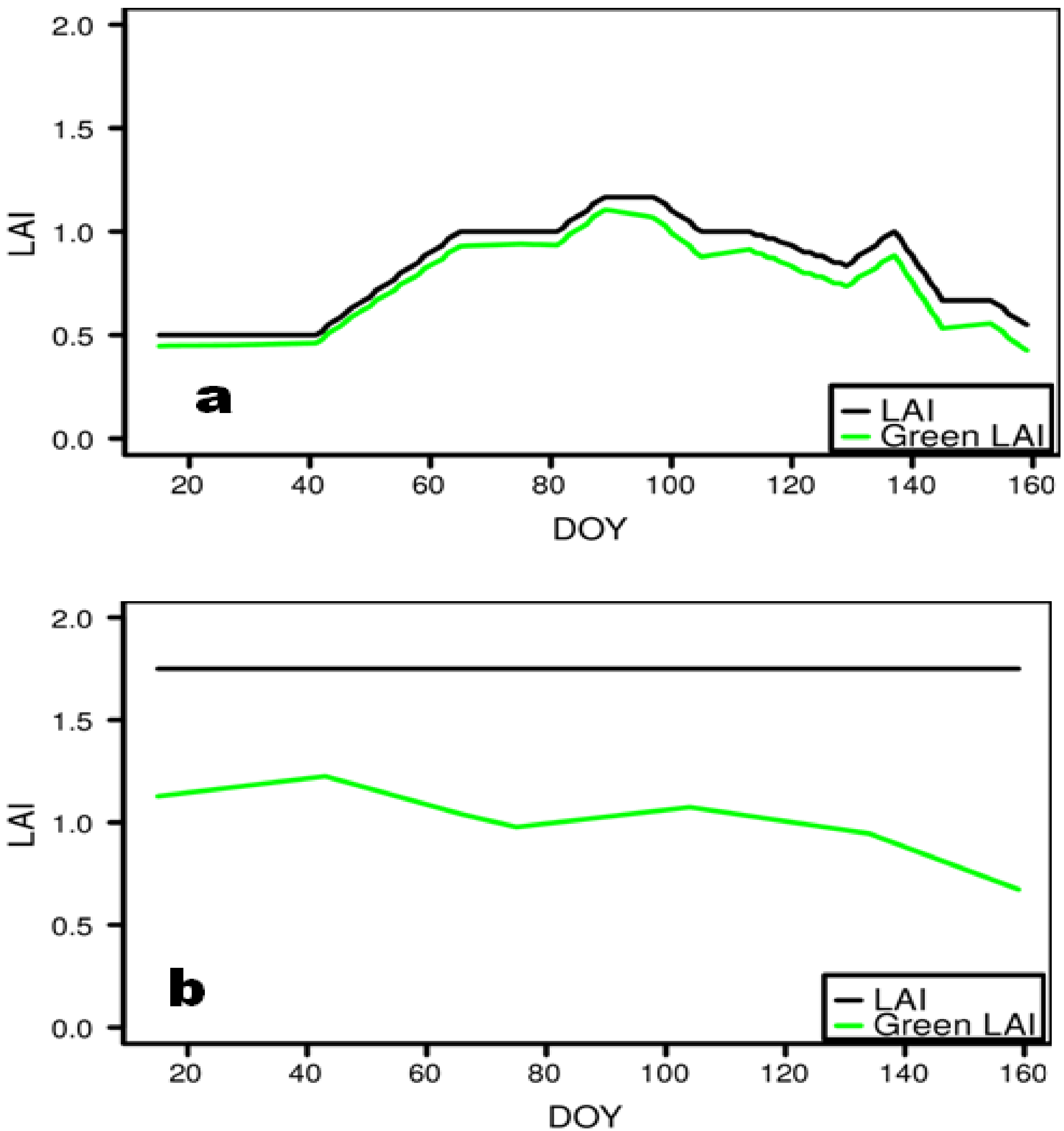


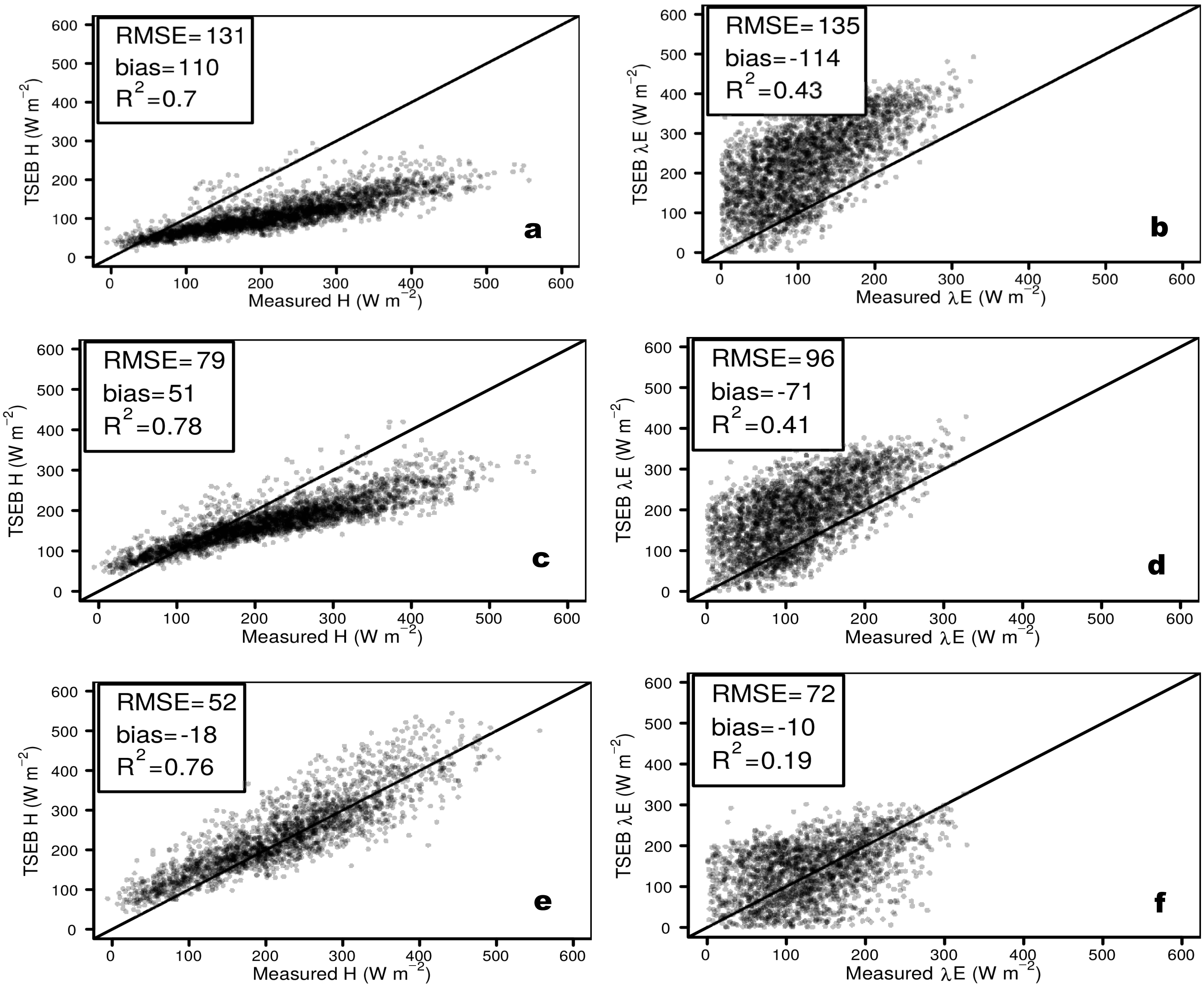
Balsa Blanca
Ratio $z_{oh}/z_{om} = \exp(-kB^{-1})$
Mean values of kB^{-1}
0.15
0.1
0.05
0
-0.05
0
2
4
6
8
10
12
14



Surface Aerodynamic Temperature, T_{AEROH} (C)
Composite Radiometric Surface Temperature, T_{COMP} (C)
a)
Surface Aerodynamic Temperature, T_{AEROH} (C)
Composite Radiometric Surface Temperature, T_{COMP} (C)
b)


a
b
c


2.0
1.5
1.0
0.5
0.0
LAI
a
LAI
Green LAI
20
40
60
80
100
120
140
160
DOY
b
LAI
Green LAI
DOY



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bias=110
R^2=0.7
a
TSEB H (W m^{-2})
Measured H (W m^{-2})
RMSE=135
bias=-114
R^2=0.43
b
TSEB λE (W m^{-2})
Measured λE (W m^{-2})
RMSE=79
bias=51
R^2=0.78
c
TSEB H (W m^{-2})
Measured H (W m^{-2})
RMSE=96
bias=-71
R^2=0.41
d
TSEB λE (W m^{-2})
Measured λE (W m^{-2})
RMSE=52
bias=-18
R^2=0.76
e
TSEB H (W m^{-2})
Measured H (W m^{-2})
RMSE=72
bias=-10
R^2=0.19
f
TSEB λE (W m^{-2})
Measured λE (W m^{-2})