Utility of Coupling Microwave-derived Soil Moisture and Radiometric Surface Temperature in an Energy Balance Modeling Scheme

William P. Kustas, Rajat Bindlish, Andrew N. French and Tom J. Schmugge
USDA-ARS Hydrology and Remote Sensing Lab Bldg 007 BARC-West, Beltsville, MD, 20705-2350

Abstract—Over the last several years a Two-Source (soil + vegetation) Energy Balance (TSEB) modeling scheme has been developed and tested using either microwave-derived near-surface soil moisture (TSEB_SM) or radiometric surface temperature (TSEB_TR) as the key surface boundary condition. Output of the surface heat fluxes from both schemes are compared using microwave and radiometric surface temperature observations collected during the 1997 Southern Great Plains experiment (SGP97) conducted in Oklahoma, USA. Results from the heat flux comparisons and simulated versus observed surface temperatures suggest revisions to the TSEB_SM scheme are needed to better constrain flux predictions from the soil and vegetation in order to accommodate a wider range of environmental conditions. The revisions involve an adjustment to the soil evaporation algorithm for 'decoupling' effects and assimilation of the Priestley-Taylor coefficient estimated from the TSEB_TR model.

I. INTRODUCTION

Both the TSEB_TR and the TSEB_SM models have been applied to remotely sensed data collected during SGP97 and have been validated using tower and aircraft-based flux observations. For TSEB_TR, TIMS (Thermal Infrared Multi-spectral Scanner) data at high resolution (~12 m pixel) have been used by [1], while for TSEB_SM, the L-band ESTAR (Electronically Scanned Thinned Array Radiometer) near-surface soil moisture (~0.5 cm layer) product at 800 m pixel resolution has been applied in [2]. Results of the comparisons with flux observations suggest the models provide acceptable estimates. However, tower-based fluxes represent a very small fraction of the land surface, while aircraft-based fluxes represent regional averages. Hence it is nearly impossible to validate the spatial patterns in heat fluxes produced by such models.

For one day, (Day 183, July 2, 1997) both TIMS and ESTAR data were collected during the same midmorning period (~1630 UTC) over the El Reno study site. This provided a unique opportunity to compare output from both two-source models for the same region on a pixel-by-pixel basis, with the TIMS radiometric surface temperature, $T_A$, aggregated to the same 800 m pixel resolution as the ESTAR data. In addition, since TSEB_SM also simulates an effective surface temperature, $T_{\text{est}}$, these estimates could be compared to $T_A$ observed from TIMS, providing additional information for evaluating TSEB_SM parameterizations.

II. METHODOLOGY

Both the TSEB_TR and the TSEB_SM models use the land surface transfer scheme developed by [3]. A resistance network for the vegetation and soil components is utilized based on the approximation that the radiometric and effective surface temperature is comprised of mean canopy, $T_C$, and soil, $T_S$, component temperatures,

$$T_{av} \approx T_A \approx \left( f_c \cdot T_C + (1-f_c) \cdot T_S \right)^{1/4} \quad (1)$$

where the fractional vegetation cover, $f_c$, is estimated from a "normalized" Normalized-Difference-Vegetation-Index (NDVI) as derived by [4]. The sensible heat flux from the canopy, $H_c$, and soil, $H_s$, are initially estimated using the following relations,

$$H_c = \rho C_p \frac{T_C - T_{\text{est}}}{R_g} = \left( 1 - f_c \alpha_{\text{g}} \right) \frac{\Delta}{\Delta + \gamma} R_{\text{ec}}$$

$$H_s = \rho C_p \frac{T_S - T_{\text{est}}}{R_s}$$

$$H = H_c + H_s = \rho C_p \frac{T_C - T_{\text{est}}}{R_g} + \frac{T_S - T_{\text{est}}}{R_s}$$

where $\rho$ is the air density, $C_p$ is the heat capacity of air, $\alpha_{\text{g}}$ is the Priestley-Taylor parameter set equal to 1.3 [5] for the green part of the canopy, $\Delta$ is the slope of the saturation vapor pressure-temperature curve at $T_C$, $\gamma$ is the psychrometric constant, and $f_c$ is the fraction of canopy that is "green" or actively transpiring , which may be obtained from knowledge of the phenology of the vegetation. The net radiation of the canopy, $R_{\text{RCO}}$, is estimated from a radiation extinction model evaluating shortwave and longwave exchanges within the canopy layer [6]. The resistances $R_g$, $R_s$ and $R_{\text{a}}$ are the total boundary layer resistance of the complete canopy of leaves, the soil surface resistance and the aerodynamic resistance to heat transfer from canopy air space temperature, $T_{\text{ACO}}$, to the surface layer temperature, $T_A$, respectively; formulas are described in [3]. The Priestley-Taylor formulation only provides an initial calculation, and it can be overridden to accommodate a wider range of environmental conditions [3]. An iteration procedure has been recently developed by [7] and [8] which will adjust the $\alpha_{\text{g}}$ value until $T_C$ and $T_S$ estimates used in Eq. (1) agree with the measured $T_A$.

For TSEB_SM a similar set of expressions are used, except the soil surface latent heat flux is solved directly from the expression,
where the resistance $R_{soil}$ represents the soil resistance to water vapor transfer within the soil layer and is estimated from an exponential expression relating $R_{soil}$ to the ratio of actual to saturated soil water content of the near-surface (0-5 cm layer) [9]. The parameter $e_s(T_s)$ is the saturation vapor pressure at soil surface temperature $T_s$, $e_{ac}$ is the vapor pressure in the canopy air space, and $h_s$ is the relative humidity of the soil layer computed from the surface soil water content using the method described by [10]. With the expression for $H_s$ in (2) and taking soil heat flux as a fraction of net radiation at the soil surface (i.e., $G = 0.3 R_{ns}$) the soil surface energy balance (viz., $R_{ns} - LE_s = 0$) can be satisfied yielding $T_s$. Then with $T_s$ derived from the Priestley-Taylor formulation, this is used in deriving the effective surface temperature $T_{surf}$ using (1) and the vapor pressure of the canopy surface, $e_c$, required to achieve energy balance for the canopy layer (i.e., $R_{ns} - LE_c = 0$) where

$$LE_s = \frac{\rho C_v h_s e_s(T_s) - e_{ac}}{R_{soil} + R_s}$$

Unfortunately, adjusting $e_{wp}$ for a wider range of environmental conditions is not as straightforward with the TSEB$_{sm}$ scheme since (1) cannot be used to restrict the component temperatures. However, the model will not permit non-physical solutions, such as $LE_s < 0$ or condensation during the daytime. In this case, the Priestley-Taylor approximation is dropped, and several approximations are used [2].

III. RESULTS

Both the TSEB$_{sm}$ and TSEB$_{tr}$ schemes were run using half-hourly averaged meteorological data from the Mesonet network. From the same aircraft supporting TIMS, the Thematic Mapper Simulator (TMS) instrument provided similar resolution visible-near infrared imagery for creating an NDVI map for the area. Overlapping coverage for ESTAR and TIMS/TMS comprised an area approximately 6 km north-south by 20 km east-west, which was primarily composed of harvested winter wheat fields and grasslands used for grazing cattle. For more details concerning the processing of TIMS/TMS data see [1]. Both NDVI and $T_R$ were aggregated to 800 m pixel resolution of ESTAR to allow pixel-by-pixel comparisons of output from TSEB$_{tr}$ and TSEB$_{sm}$ models.

Since the most significant discrepancies are with the turbulent fluxes, $H$ and $LE$, these results will only be presented here. A pixel-by-pixel comparison of $H$ and $LE$ in Fig. 1 shows a fair amount of scatter having Root-Mean-Square-Difference (RMSD) of $\approx 60$ W m$^{-2}$ for $H$ and $LE$. The area-average $<H>$ from TSEB$_{sm}$ $\approx 40$ W m$^{-2}$ lower and $<LE>$ $\approx 25$ W m$^{-2}$ higher than estimated by TSEB$_{tr}$ (Table 1). A comparison of $T_{surf}$ from TSEB$_{sm}$ with $T_R$ from TIMS shows (Fig. 2) a bias ($\approx 2$ K, see Table 1), with a RMSD $\approx 3$ K.

Previous studies, [2] and [11], comparing $T_{surf}$ simulated by TSEB$_{sm}$ with $T_R$ show similar scatter, albeit without a significant bias. The fact that $<T_{surf}>$ is less than $<T_R>$ is not surprising since $T_R$ is affected by surface moisture conditions whereas the TSEB$_{sm}$ formulation uses an integrated soil moisture value for
the 0-5 cm depth. In fact, [12] using a soil profile model show a significant “decoupling” between surface soil moisture (0.5 cm) and the moisture at 5 cm as the soil dries suggesting that the soil surface energy balance becomes more strongly coupled to surface moisture conditions than at deeper layers as the soil dries.

An attempt to account for the effect of decoupling in the soil evaporation formulation (3) was made by adjusting the relative humidity in the pore space, $h_r$, since $h_r \sim 1$ until the moisture is well below field capacity [10]. The adjustment was simply to multiply $h_r$ in (3) by the ratio of the ESTAR-derived soil moisture, $W_s$, to the field capacity, $W_{FC}$, based on soil texture information following [13]. In addition, since the TSEB_{SM} scheme cannot easily adjust $\alpha_{p}$, the TSEB_{TR} estimate of $\alpha_{p}$ for each pixel was used (i.e., assimilated) by TSEB_{SM}.

The effect of these two revisions in the TSEB_{SM} output of the fluxes and $T_{surf}$ is significant (Fig. 3 and 4). The agreement between the two model estimates has improved (Fig. 3) with RMSD for $H$ reduced to $\approx 40$ W m$^{-2}$; RMSD remains at $\approx 60$ W m$^{-2}$ for $LE$, but there is better overall agreement between the two model estimates (Fig. 3).

Fig. 3. Comparison of $H$ and $LE$ between the revised TSEB_{SM} model and the TSEB_{TR} scheme.

On an area-average basis, $<H>$ from the revised TSEB_{SM} is within 10 W m$^{-2}$ of the TSEB_{TR} estimate and $<LE>$ is within $\approx 20$ W m$^{-2}$ of the TSEB_{TR} value (Table 1). In addition, the pixel-by-pixel comparison of $T_{surf}$ simulated by TSEB_{SM} with $T_s$ from TIMS shows virtually no bias (Table 1) and a RMSD $= 3$ K (Fig. 4).

The results only revising (3) to address the effects of “decoupling” in the TSEB_{SM} scheme yielded a similar comparison between simulated $T_{surf}$ and $T_s$ from TIMS. However, there were larger discrepancies in the heat fluxes between the two models; RMSD for $H$ and $LE$ were higher at $\approx 55$ W m$^{-2}$ and $\approx 70$ W m$^{-2}$, respectively.

Fig. 4. Comparison of $T_{surf}$ from the revised TSEB_{SM} formulation versus $T_s$ from TIMS.

The spatial patterns of $H$ and $LE$ from TSEB_{SM} and TSEB_{TR} models are illustrated in Fig. 5. There is general agreement in the spatial distributions of the heat fluxes, except for an area located near the center of the image, which has significantly lower $H$ and higher $LE$ estimated by TSEB_{SM}. Factors contributing to this discrepancy are under investigation.

Fig. 5. Spatial patterns of $H$ and $LE$ from the revised TSEB_{SM} model and the TSEB_{TR} scheme.

IV. CONCLUSIONS

This preliminary analysis comparing output on a spatially distributed manner from two land-atmosphere transfer schemes (TSEB) linked to different remotely sensed boundary conditions provided a unique
opportunity to evaluate uncertainty in model flux estimates on a pixel-by-pixel basis. Moreover the TSEB$_{sm}$ scheme, which is less able to consider a wider range of environmental conditions compared to the TSEB$_{sr}$ formulation using radiometric surface temperature, is revised based on comparisons made with TSEB$_{ts}$ output of the heat fluxes, and comparisons between the effective surface temperature $T_{eff}$ simulated by TSEB$_{sm}$ and $T_s$ observations from TIMS. This lead to the implementation of two revisions; one to the soil evaporation formulation (3) and the other to adopting $a_{soil}$ values predicted by TSEB$_{sr}$. With both revisions being implemented, there is closer agreement in heat fluxes computed by the two models and better agreement between TSEB$_{sm}$ simulated and radiometric surface temperature observations.

ACKNOWLEDGEMENT

This work was supported by the NASA EOS and Land Surface Hydrology Programs. In particular funding under NASA NRA 98-OES-11 (Proposal order number S-10202-X) supported this research investigation. We are indebted to Dr. Tom Jackson for organizing and coordinating the The Southern Great Plains 1997 Hydrology Experiment and Dr. Ming Ying Wei of NASA Headquarters whose guidance and support made this project of greater value than its individual components.

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