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Modelling surface energy fluxes over maize using a two-source patch model and radiometric soil and canopy temperature observations

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Abstract

Models estimating surface energy fluxes over partial canopy cover with thermal remote sensing must account for significant differences between the radiometric temperatures and turbulent exchange rates associated with the soil and canopy components of the thermal pixel scene. Recent progress in separating soil and canopy temperatures from dual angle composite radiometric temperature measurements has encouraged the development of two-source (soil and canopy) approaches to estimating surface energy fluxes given observations of component soil and canopy temperatures. A Simplified Two-Source Energy Balance (STSEB) model has been developed using a "patch" treatment of the surface flux sources, which does not allow interaction between the soil and vegetation canopy components. A simple algorithm to predict the net radiation partitioning between the soil and vegetation is introduced as part of the STSEB patch modelling scheme. The feasibility of the STSEB approach under a full range in fractional vegetation cover conditions is explored using data collected over a maize (corn) crop in Beltsville Maryland, USA during the 2004 summer growing season. Measurements of soil and canopy component temperatures as well as the effective composite temperature were collected over the course of the growing season from crop emergence to cob development. Comparison with tower flux measurements yielded root-mean-square-difference values between 15 and 50 W m^{-2} for the retrieval of the net radiation, soil, sensible and latent heat fluxes. A detailed sensitivity analysis of the STSEB approach to typical uncertainties in the required inputs was also conducted indicating greatest model sensitivity to soil and canopy temperature uncertainties with relative errors reaching ~30% in latent heat flux estimates. With algorithms proposed to infer component temperatures from bi-angular satellite observations, the STSEB model has the capability of being applied operationally.

Keywords: STSEB; Soil temperature; Canopy temperature; Sensible heat flux; Latent heat flux

1. Introduction

The estimation of surface energy fluxes using remote sensing techniques has been widely studied in recent years. Despite some early criticisms suggesting that thermal infrared satellite observations are not sufficiently accurate for energy balance modelling (eg., Hall et al., 1992; Sellers et al., 1995), a wide variety of field experiments and associated studies have clearly shown the feasibility of using thermal remote sensing in the retrieval of surface fluxes (Anderson et al., 1997).

The development of two-source (soil+vegetation) layer models to accommodate partial canopy cover conditions considers energy exchange between soil and canopy components, and hence interaction between soil and canopy elements (Choudhury & Monteith, 1988; Shuttleworth & Wallace, 1985). Another type of two-source model formulation is the so-called patch model where it is assumed that all the fluxes act vertically and that there is no interaction between soil and canopy components (i.e., a complete energy balance between the atmosphere and each element; Blyth & Harding, 1995; Lhomme & Chehbouni, 1999).

Norman et al. (1995) introduced a remote sensing-based two-source layer modelling framework for computing surface fluxes using directional brightness temperature observations. The Two-Source Energy Balance model (TSEB) was developed to require minimal inputs, similar to single-source models. Since typically only composite brightness temperature observations

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are available, an additional assumption is required for obtaining initial estimates of soil and vegetation canopy component temperatures and energy fluxes. For the TSEB scheme, the Priestley–Taylor (PT) equation applied to the vegetated canopy is used to obtain an initial solution. Although the TSEB uses the Priestley–Taylor approximation as an initial estimate for the canopy transpiration flux, the model has a built-in mechanism for throttling the PT coefficient, α_{PT}, back from its potential value (~1.3) when conditions of vegetation stress are detected (Kustas et al., 2004). The TSEB model has been widely applied, validated and modified to deal with unique landscapes over the past several years (French et al., 2003, 2005; Kustas & Norman, 1999a, 2000; Li et al., 2005; Schmugge et al., 1998).

Alternatively, if the partitioning of composite land-surface temperature into soil and canopy temperatures is known a priori, e.g., through dual angle Thermal InfraRed (TIR) decomposition (e.g., François, 2002; Otterman et al., 1992), the soil and canopy latent heat rates can be computed directly as a residual to the component energy budgets. In this case, the PT formulation is no longer required in the TSEB scheme (Kustas & Norman, 1997, 1999b).

In this paper a Simplified Two-Source Energy Balance (STSEB) model is developed, based on a patch representation of the energy exchange from soil and canopy, which permits estimation of surface fluxes under partial canopy cover conditions directly from component soil and canopy temperatures. A simple algorithm to predict the net radiation partitioning between soil and vegetation is also developed as part of the STSEB model.

Reliable measurements of the soil and canopy temperatures are required as inputs in the STSEB. These temperatures are not readily available from most satellite systems. Otterman et al. (1992) proposed one of the first models for inferring canopy and underlying soil temperatures from multi-directional measurements. Further studies on the angular effects on the brightness surface temperature for a variety of canopies (e.g., Chehbouni et al., 2001a; Lagouarde et al., 1995, 2000) were followed by new models to obtain soil and canopy temperatures from dual angle radiometric temperatures (François, 2002; François et al., 1997). Experiments using these dual angle observations of radiative surface temperature, in conjunction with energy balance models, to derive heat fluxes over partially vegetated surfaces have been conducted with varying degrees of success (Chehbouni et al., 2001b; Jia et al., 2003a; Kustas & Norman, 1997, 1999b; Merlin & Chehbouni, 2004). The Advanced Along-Track Scanning Radiometer (AATSR) on board the EOS-Terra satellite is currently able to provide quasi-simultaneous multispectral measurements at two view angles (approximately 0° and 53° at surface). Jia et al. (2003b) developed an operational algorithm to retrieve soil and canopy temperature over heterogeneous land surface based on the analysis of dual-angle and multi-channels observations made by the previous version of the AATSR, the second Along-Track Scanning Radiometer (ATSR-2).

The limitations and uncertainties in retrieving these component temperatures from the ATSR-2 observations indicate that the algorithm for retrieving the soil and canopy component temperatures, required as inputs in the STSEB model, may be acceptable for operational applications using satellite observations. Kimes (1983) presented a strategy for obtaining component temperatures in a cotton row crop using multi-angle TIR measurements. He obtained root mean square deviation (RMSD) values of 1 °C for the vegetation temperature and of 2 °C for the soil temperature with respect to observed component temperatures. Chehbouni et al. (2001a,b) measured radiative temperature, over a grassland site, at two viewing angles mimicking nadir and forward observations of the AATSR. These authors concluded that an error of 1 °C in measured directional radiative temperature leads to an error of about 1 °C in the inverted component temperatures. Similar errors were obtained by Merlin and Chehbouni (2004). These authors inverted soil and canopy temperatures from simulations of directional temperature observations, yielding estimation errors in the range 1–2 °C.

The objective of this paper is to validate the STSEB model under conditions of variable vegetation cover, as well as to explore its sensitivity to the input uncertainties likely to typically occur at regional scales. Ground and tower-based remote sensing, vegetation cover and micrometeorological data from maize (corn) crop in an experimental field site in Beltsville Maryland, USA during the 2004 summer growing season were used.

This paper is organized as follows. Section 2 provides the framework and details of the proposed STSEB model. A description of the study site and data used in this study are described in Section 3. An analysis of the radiometric temperatures and the energy balance measurements are given in Section 4. In Section 5, the results of a comparison between the surface energy balance components from the STSEB model and the observations as well as a STSEB–TSEB model intercomparison are discussed. In addition, a sensitivity analysis of the STSEB model to uncertainties in key inputs is provided and the dependence on the fractional vegetation cover is also presented. Finally, conclusions are given in Section 6.

2. Model description

The net energy balance of soil–canopy–atmosphere system is given by (neglecting photosynthesis and advection):

$$R_n = H + LE + G + F \tag{1}$$

where R_n is the net radiation flux (W m^{-2}), H is the sensible heat flux (W m^{-2}), G is the soil heat flux (W m^{-2}), and F is the rate of change of heat storage in the canopy layer (W m^{-2}). For short canopies, F can be neglected since its contribution to energy balance is usually quite small and difficult to reliably estimate with standard micrometeorological measurements (Meyers & Hollinger, 2004; Wilson et al., 2002). The effective radiometric surface temperature in the same system, T_R (K), can be obtained as a weighted composite of the soil temperature, T_s (K), and the canopy temperature, T_c (K):

$$T_R = \left[\frac{P_v(\theta)\varepsilon_c T_c^4 + (1 - P_v(\theta))\varepsilon_s T_s^4}{\varepsilon}\right]^{1/4} \tag{2}$$