Available online at www.sciencedirect.com
ScienceDirect
Remote Sensing of Environment 112 (2008) 1268–1281
Remote Sensing of Environment
www.elsevier.com/locate/rse

Monitoring root-zone soil moisture through the assimilation of a thermal remote sensing-based soil moisture proxy into a water balance model

Wade T. Crow [a,*], William P. Kustas [a], John H. Prueger [b]

[a] USDA ARS, Hydrology and Remote Sensing Laboratory, Beltsville, MD, United States
[b] USDA ARS, National Soil Tilth Laboratory, Ames, IA, United States

Received 28 July 2006; received in revised form 17 November 2006; accepted 22 November 2006

Abstract

Two types of Soil Vegetation Atmosphere Transfer (SVAT) modeling approaches can be applied to monitor root-zone soil moisture in agricultural landscapes. Water and Energy Balance (WEB) SVAT modeling is based on forcing a prognostic root-zone water balance model with observed rainfall and predicted evapotranspiration. In contrast, thermal Remote Sensing (RS) observations of surface radiometric temperature (T_R) are integrated into purely diagnostic RS-SVAT models to predict the onset of vegetation water stress. While RS-SVAT models do not explicitly monitor soil moisture, they can be used in the calculation of thermal-based proxy variables for the availability of soil water in the root zone. Using four growing seasons (2001 to 2004) of profile soil moisture, micro-meteorology, and surface radiometric temperature measurements at the United States Department of Agriculture (USDA) Optimizing Production Inputs for Economic and Environmental Enhancements (OPE^3) study site in Beltsville, MD, prospects for improving WEB-SVAT root-zone soil water predictions via the assimilation of diagnostic RS-SVAT soil moisture proxy information are examined. Results illustrate the potential advantages of such an assimilation approach relative to the competing approach of directly assimilating T_R measurements. Since T_R measurements used in the analysis are tower-based (and not obtained from a remote platform), a sensitivity analysis demonstrates the potential impact of remote sensing limitations on the value of the RS-SVAT proxy. Overall, results support a potential role for RS-SVAT modeling strategies in improving WEB-SVAT model characterization of root-zone soil moisture.
Published by Elsevier Inc.

Keywords: Thermal remote sensing; Soil moisture; Data assimilation; Surface radiometric temperature

1. Introduction

The development of modeling techniques to estimate soil moisture availability beyond the near-surface has been an area of extensive research during the past decade. Currently, the most advanced approaches are based on the assimilation of remote sensing observations into soil-vegetation-atmosphere transfer (SVAT) models. Following Crow et al. (2005a), these models can be conceptually divided into thermal remote sensing (RS) and water and energy balance (WEB) approaches.

In RS-SVAT approaches, T_R is derived from thermal remote sensing on cloud- free days and combined with vegetation information obtained at visible and near-infrared wavelengths in order to solve the surface energy balance. By accurately interpreting thermal signals from vegetation, these approaches can detect the increase in surface temperature – due to a reduction in evapotranspiration – occurring in canopies at the onset of water stress. Detection of these stress signals typically requires accurate ancillary vegetation cover information to distinguish between stressed vegetation and warm soil/substrate backgrounds (see e.g. Moran, 2003). RS-SVAT approaches are generally diagnostic in nature and make instantaneous predictions only for times at which remote surface T_R retrievals are available.

In contrast, WEB-SVAT approaches typically neglect T_R observations and obtain energy flux predictions by parameterizing components of the surface energy balance as a function of surface aerodynamic temperature and numerically solving the balance equation. These flux predictions are then combined with rainfall observations and vertical modeling of the soil column in order to continually track soil moisture. Soil water stress is diagnosed when predicted root-zone soil moisture falls

* Corresponding author.
E-mail address: wcrow@hydrolab.arsusda.gov (W.T. Crow).

0034-4257/$ - see front matter. Published by Elsevier Inc.
doi:10.1016/j.rse.2006.11.033

below a predefined level and triggers an increase in vegetation stomatal resistance. If available, T_R observations can be used to constrain WEB-SVAT predictions through data assimilation. A number of past studies have developed techniques to directly assimilate T_R observations into WEB-SVAT models with the goal of improving surface energy flux and profile soil moisture estimates (Jones et al., 1998; Lakshmi, 2000; van den Hurk et al., 1997). Additional work has also focused on the assimilation of surface (0–5 cm) soil moisture retrievals obtained from microwave remote sensing (Houser et al., 1998; Margulis et al., 2002; Reichle et al., 2002; Walker et al., 1999).

As a result of their structural differences, RS- and WEB-SVAT models use fundamentally different approaches to predict surface energy fluxes and diagnose the availability of root-zone soil moisture. Crow et al. (2005a) demonstrate that, even when forced with consistent meteorological and vegetation information, the structural differences between WEB- and RS-SVAT modeling approaches are profound enough that errors in surface energy flux estimates produced by both models are statistically independent. Such independence can be exploited using data assimilation or integration approaches designed to filter errors in continuous WEB-SVAT state predictions based on the consideration of instantaneous RS-SVAT retrievals. A small number of past studies have exploited this potential by inserting RS-SVAT evapotranspiration predictions directly into a water balance model (Meijerink et al., 2005), using RS-SVAT energy flux predictions to constrain WEB-SVAT model parameter selection (Franks & Beven, 1999), or employing simple data assimilation techniques to update WEB-SVAT soil moisture predictions using RS-SVAT evapotranspiration predictions (Schuurmans et al., 2003).

Despite these advances, little is currently known about the potential for improving WEB-SVAT soil moisture estimates via the assimilation of RS-SVAT retrievals. As noted above, the direct assimilation of T_R observations offers an alternative approach for the integration of thermal remote sensing observations into a WEB-SVAT model. Therefore, a key unresolved issue is whether any rationale exists for processing T_R observations through a RS-SVAT model prior to their assimilation. Here we use a four-year soil moisture and T_R data set within an agricultural site to evaluate the accuracy of a RS-SVAT-based root-zone soil moisture proxy and the potential for improving root-zone soil moisture predictions through the assimilation of this proxy into a WEB-SVAT model. Assimilation results are compared to the competing approach of directly assimilating T_R observations. The modeling and Ensemble Kalman filter (EnKF) data assimilation strategy used in the analysis will be presented in Section 2. Modeling and data assimilation results are discussed in Section 3, and Section 4 describes a sensitivity analysis aimed at quantifying the impact of limitations in satellite-based T_R retrievals on results.

2. Approach

Both RS- and WEB-SVAT modeling strategies are based on the partitioning of net radiation (R_N) into sensible heating (H), latent heating (LE), and ground heat flux (G) components via solution of separate surface energy balance equations for the vegetation canopy (C) and soil surface (S)

$$R_{N,C} = H_C + LE_C \tag{1}$$

$$R_{N,S} = H_S + LE_S + G_S. \tag{2}$$

Observations of downward solar ($S_\downarrow$) and longwave radiation ($L_\downarrow$) at the top of the vegetation canopy are decomposed into incident canopy and soil radiation components based on the radiative transfer model of Campbell and Norman (1998). These components are then used to calculated $R_{N,C}$ and $R_{N,S}$ as

$$R_{N,C} = (1-\tau_{longwave})(L_\downarrow + \varepsilon_S\sigma T_S^4 - 2\varepsilon_C\sigma T_C^4) + (1-\tau_{solar})(1-\alpha_C)S_\downarrow \tag{3}$$

$$R_{N,S} = \tau_{longwave}L_\downarrow + (1-\tau_{longwave})\varepsilon_C\sigma T_C^4 - \varepsilon_S\sigma T_S^4 + \tau_{longwave}(1-\alpha_S)S_\downarrow \tag{4}$$

where ε, τ, and α refer to emissivity, canopy transmissivity and albedo parameters, respectively, and σ is the Stephen-Boltzman constant. Total surface flux quantities are obtaining by summing canopy and surface components (e.g., $LE=LE_C+LE_S$). Subsequent differences in RS- and WEB-SVAT modeling approaches are described below.

2.1. RS-SVAT modeling

The RS-SVAT modeling approach employed here is based on the parallel version of the two-source model (TSM) methodology originally described in Norman et al. (1995). The TSM parameterizes sensible heating from the vegetation canopy and soil surface as

$$H_C = \rho C_p \frac{T_C - T_A}{R_A} \tag{5}$$

$$H_S = \rho C_p \frac{T_S - T_A}{R_A + R_{A,S}} \tag{6}$$

where ρ is the density of air, C_p the specific heat of air, R_A the above canopy aerodynamic resistance term, $R_{A,S}$ the within canopy aerodynamic resistance, T_A the air temperature, T_S the soil temperature, and T_C the canopy temperature. The parameterization of R_A and $R_{A,S}$ is based on assumed surface roughness lengths, wind speed, and stability considerations presented for the parallel version of the TSM in Norman et al. (1995). A more complicated series resistance formulation was also developed by Norman et al. (1995) allowing more complete interaction between soil and canopy components. However, differences in flux predictions from the parallel and series formulations are minor in most cases (Li et al., 2005; Norman et al., 1995). Neglecting emissivity differences between the canopy and the soil (Kustas & Norman, 1997),