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Effect of remote sensing spatial resolution on interpreting tower-based flux observations

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Abstract

Validation comparisons between satellite-based surface energy balance models and tower-based flux measurements over heterogeneous landscapes can be strongly influenced by the spatial resolution of the remote sensing inputs. In this paper, a two-source energy balance model developed to use thermal and visible /near-infrared remotely sensed data is applied to Landsat imagery collected during the 2004 Soil Moisture Experiment (SMEX04) conducted in southern Arizona. Using a two dimensional flux-footprint algorithm, modeled surface fluxes are compared to tower measurements at three locations in the SMEX04 study area: two upland sites, and one riparian site. The effect of pixel resolution on evaluating the performance of the land surface model and interpreting spatial variations of land surface fluxes over these heterogeneous areas is evaluated. Three Landsat scenes were examined, one representing the dry season and the other two representing the relatively wet monsoon season. The model was run at three resolution scales: namely the Landsat visible/near-infrared band resolution (30 m), the Landsat 5 thermal band resolution (120 m), and 960 m, which is nominally the MODIS thermal resolution at near-nadir. Comparisons between modeled and measured fluxes at the three tower sites showed good agreement at the 30 m and 120 m resolutions — pixel scales at which the source area influencing the tower measurement (~100 m) is reasonably resolved. At 960 m, the agreement is relatively poor, especially for the latent heat flux, due to sub-pixel heterogeneity in land surface conditions at scales exceeding the tower footprint. Therefore in this particular landscape, thermal data at 1-km resolution are not useful in assessing the intrinsic accuracy of the land-surface model in comparison with tower fluxes. Furthermore, important spatial patterns in the landscape are lost at this resolution. Currently, there are no definite plans supporting high resolution thermal data with regular global coverage below ~700 m after Landsat 5 and ASTER fail. This will be a serious problem for the application and validation of thermal-based land-surface models over heterogeneous landscapes.
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Keywords: Remote sensing; Spatial resolution; Land surface flux; Footprint

1. Introduction

Remote sensing-based land surface models have demonstrated ability to provide spatially distributed estimates of energy fluxes/evapotranspiration (ET) over large areas (e.g., Diak et al., 2004). However, the ability to capture the full range of variability in the fluxes is dependent on the resolution of the remote sensing data. For example, in a relatively homogeneous cropping region in Iowa where over 90% of vegetation cover is either corn or soybean, Kustas et al. (2004a) found that when the resolution is >500 m, fluxes from the two crops could not be easily distinguished. Clearly, for landscapes with significant variability in vegetation cover, type/architecture, and moisture, the spatial resolution of the remote sensing data is crucial for discriminating fluxes for the different land cover types and hence avoiding significant errors due to application of a land surface model to a mixed pixel containing large contrasts in surface temperature and vegetation cover (Kustas & Norman, 2000a; Moran et al., 1997).

Operationally, many applications in the western U.S. require assessment of ET variability at high spatial resolutions of 10^2 m and finer. To accurately characterize ET or moisture stress for even a single relatively large agricultural field (~500×500 m),

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for example, there needs to be several within-field pixels to allow averaging and to clearly distinguish contributions from adjacent fields. Water managers must account for evaporative losses along canals and riparian corridors ($\sim 10^1$–10^2 m wide) in planning for water distribution within irrigation districts. Moreover, to properly validate remote sensing land surface models, the model grid must resolve the surface footprint of the flux measurement device, which is typically a tower-based eddy covariance system with a source-area/flux-footprint of a few 100 m or less. For grids coarser than the measurement footprint, model-measurement differences over heterogeneous landscapes will not necessarily be representative of the intrinsic model accuracy (Anderson et al., 2004).

Current operational thermal sensors are at relatively coarse resolution (~ 1 km for MODIS — Moderate Resolution Imaging Spectroradiometer), making it difficult to account for the spatial variation in fluxes for many landscapes. Unfortunately, it also is not certain whether future Landsat programs will support a high resolution (~ 100 m) thermal band sensor. The main objective of this paper is to determine if and how restriction to MODIS-resolution thermal data will limit our ability to apply and validate remote-sensing-based energy balance models over heterogeneous surfaces.

To investigate the impact of model/remote sensing resolution on flux estimation, three Landsat 5 Thematic Mapper (TM) scenes collected during the 2004 Soil Moisture Experiment (SMEX04) conducted in southern Arizona and Mexico were combined with local meteorological measurements to drive simulations from a remote sensing-based land surface model during the dry and wet/monsoon seasons. We focus on three landscapes featuring different types of spatial structure: two upland sites, one with grass cover and patches of shrubs correlated with the terrain and the other with relatively uniform sparse shrubland cover; and a riparian site near the San Pedro River. The impact of resolution on variability in model land surface fluxes is examined for these semiarid heterogeneous landscapes, where 1-km pixels may represent a mixture of

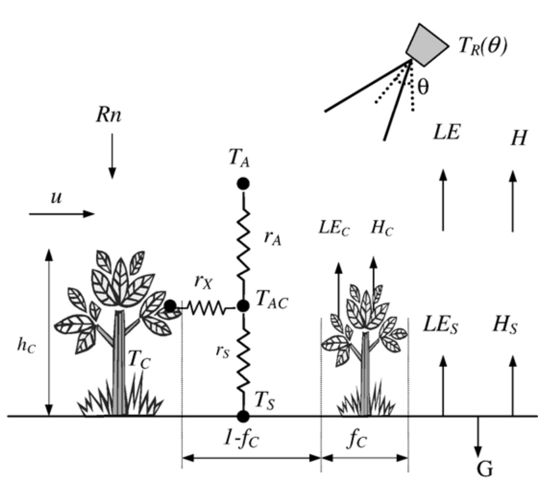

Fig. 1. Schematic diagram illustrating the resistance network for the TSM. Also shown are the flux partitioning between soil (subscript S) and canopy (subscript C) and key model inputs. Symbols are defined in the text.

relatively low evapotranspiration for the upland areas and high values from the riparian corridor.

2. The model

The model used in this study is the series version of the Two-Source-Model (TSM) developed by Norman et al. (1995). The formulations presently used in the TSM are described in Kustas and Norman (1999), and more recently in Li et al. (2005), with the resistance network and modeling framework illustrated in Fig. 1. In the TSM, the key remotely sensed variables are radiometric surface temperature (T_R) and vegetation cover fraction (f_C). The model partitions T_R between the vegetation and soil components within the scene, weighted by f_C:

$$T_R(\theta) \approx [f_C(\theta)T_C^4 + (1 - f_C(\theta))T_S^4]^{1/4} \tag{1}$$

where T_C is canopy temperature, T_S is soil temperature and $f_C(\theta)$ is the fractional vegetation cover at the thermal sensor view angle θ.

The sensible heat flux (H) is also partitioned between the vegetated canopy (H_C) and soil (H_S):

$$H = H_C + H_S = \rho C_P \frac{T_{AC} - T_A}{r_A} \tag{2}$$

$$H_C = \rho C_P \frac{T_C - T_{AC}}{r_X} \tag{3}$$

$$H_S = \rho C_P \frac{T_S - T_{AC}}{r_S} \tag{4}$$

where ρC_P is the volumetric heat capacity of air (Jm^{-3} K^{-1}), T_{AC} is the air temperature in canopy-air space, T_A is the air temperature, r_A is the aerodynamic resistance to heat transfer across the canopy-surface layer interface (Kustas & Norman, 1999), r_X is the total boundary layer resistance of the complete canopy of leaves (see Kustas & Norman, 1999) and r_S is the resistance to heat flow in the boundary layer immediately above the soil surface (see Kustas & Norman, 1999). In the current application of the model, both T_A and $T_R(\theta)$ are from the observations (i.e., T_A from the on-site flux tower and $T_R(\theta)$ from Landsat thermal observations), whereas T_S, T_C and T_{AC} are computed by the TSM. The resistance terms r_X, r_A and r_S are largely influenced by vegetation properties, wind speed and atmospheric stability (see Kustas & Norman, 1999; Kustas et al., 2004b; Norman et al., 1995).

The latent heat flux from the vegetated canopy ($\mathrm{LE_C}$) is initially computed from the Priestley–Taylor formulation:

$$\mathrm{LE_C} = \alpha_{PT} f_G \frac{\Delta}{\Delta + \gamma} \mathrm{Rn_C} \tag{5}$$

where γ is the psychrometric constant ($\approx$67 PaK^{-1}), Δ is the slope of the saturation vapor pressure verses temperature curve, α_{PT} is Priestley–Taylor parameter (~ 1.3), f_G is the fraction of the leaf area index (LAI) that is green, and $\mathrm{Rn_C}$ is divergence of net radiation within the vegetative canopy layer is described by Kustas and Norman (1999, 2000b).