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Spatial-scale effect on the SEBAL model for evapotranspiration estimation using remote sensing data

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ABSTRACT

The Surface Energy Balance Algorithm for Land (SEBAL) has been successfully applied to remote sensing data to estimate surface evapotranspiration (ET) at different spatial and temporal resolutions in more than 30 countries. However, the selection of dry and wet pixels over the area of interest (AOI) makes the SEBAL-estimated ET subject to the sizes of the AOI and the satellite pixels. This paper investigates the effect of the sizes of the AOI and satellite pixels on SEBAL-derived surface energy components by proposing generalized analytical equations. These equations demonstrate how the variations in the intermediate variables, the AOI, and the pixel size affect the resulting surface energy components and under which circumstances the sensible heat flux will be misestimated, without needing to run the SEBAL model. These analytical equations were verified through application to 23 clear-sky MODIS overpasses that cover different soil water contents and crop growth stages from January 2010 to late October 2011. The spatial effects of increasing the size of the AOI for SEBAL can be summarized as follows: (1) if the locations of dry and wet pixels do not vary, the pixel-by-pixel sensible heat flux (H_{LA}) calculated using the larger AOI is equal to that of the smaller AOI (H_{SA}, with $H_{LA}/H_{SA} = 1$), (2) if only the surface temperatures of wet pixels do not vary, the relative variation in H is equal to the relative variation of the slope (a) of the linear equation between the near-surface air temperature difference and the surface temperature ($H_{LA}/H_{SA} = 1 + \delta H_{SA}/H_{SA} = 1 + \delta a/a$), and (3) under other circumstances, H_{LA}/H_{SA} decreases with surface temperatures at a slowing pace from $\sim\infty$ at the temperature of the wet pixel ($T_{s,wet}$) to a certain value at the temperature of the dry pixel ($T_{s,dry}$) (both temperatures are for the small AOI). Analogously, a general analytical equation—a function of the coefficients of the linear equation between the near-surface air temperature difference and surface temperature at the high-resolution, the effective temperature, and the effective momentum roughness length—could be used to quantify the spatial-scale effect of the satellite pixel size. The findings from this study may help determine suitable sizes of the AOIs and the satellite pixels and aid in quantifying uncertainties in the SEBAL-derived surface energy components.

1. Introduction

Land surface evapotranspiration (ET) consumes 60% of the annual land precipitation in the global hydrological cycle (Oki and Kanae, 2006). Quantifying the distribution of the land surface ET at different temporal and spatial scales is critical to meteorology, hydrology, global climate change, and almost all other water-related scientific fields. There are more than 140 sites on five continents in the Fluxnet network that currently measure the exchanges of energy, water, and carbon dioxide between the land surface and the atmosphere (Baldocchi et al., 2001). However, these sparsely distributed tower sites are insufficient for local, regional, and global ET studies due to the heterogeneity of the earth's surface. Remote sensing provides a potential method to estimate ET at various scales.

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Over the past two decades, various remote sensing-based ET models, roughly classified as the end-member-based single-source models and the soil and vegetation energy/temperature separation two-source models, have been developed. These models include the Surface Energy Balance Algorithm for Land (Bastiaanssen, 1995; Bastiaanssen et al., 1998), surface temperature versus vegetation index triangle/trapezoid space (Price, 1990; Moran et al., 1994; Jiang and Islam, 1999; Tang et al., 2010), Simplified Surface Energy Balance Index (Roerink et al., 2000), Surface Energy Balance System (Su, 2002), Mapping Evapotranspiration with Internalized Calibration (Allen et al., 2007), the two-source N95 model (Norman et al., 1995), and the Atmosphere-Land Exchange Inverse model (Anderson et al., 1997). Li et al. (2009), among others, provides an overview of the limitations, advantages, and uncertainties of these commonly used ET models. The Surface Energy Balance Algorithm for Land (SEBAL), proposed by Bastiaanssen (1995) and Bastiaanssen et al. (1998), assumes a linear relationship between near-surface air temperature difference and surface temperature. It has been used to estimate the surface sensible heat flux and latent heat flux at different spatial and temporal resolutions in more than 30 countries (Bastiaanssen et al., 2005; Timmermans et al., 2007; Singh et al., 2008; Teixeira et al., 2009). Typical accuracies of the estimated ET in the SEBAL model are 85%, 95%, and 96% at daily, seasonal, and annual scales, respectively. The SEBAL model has several advantages over other approaches in estimating surface-energy fluxes from remote sensing data, including: (1) it uses minimal ground-based data, (2) the near-surface air temperature is not mandatory, unlike in many other bulk transfer models, and (3) a self-calibration process is automated in each region of interest through the identification of dry and wet pixels and the determination of the near-surface air temperature difference. The most current version of the SEBAL model (SEBAL2008) has incorporated three major refinements: (1) the effect of the land-surface slope and aspect in mountainous areas, (2) a correction of the advection effect, and (3) improved estimates of surface albedo and soil heat flux (Bastiaanssen et al., 2010).

A basic premise associated with the SEBAL model, in general, is that under the given atmospheric conditions, the area of interest exhibits an extreme contrast in surface hydrological condition so that the dry and wet pixels where sensible heat flux (H_{dry} and H_{wet}) and latent heat flux (LE_{dry} and LE_{wet}) are known a priori could coexist. Bastiaanssen et al. (2005) have suggested that the wet pixel can be identified in open water bodies or in well-irrigated agricultural fields whereas the dry bare soil surface may be a good candidate for the dry pixel when no other knowledge can be used for calibration. After determining the locations of the dry and wet pixels, a linear relationship between the near-surface air temperature difference (dT_s) and surface radiometric temperature (T_s) constructed by fitting data to the dry and wet pixels is further applied to estimate the pixel-by-pixel dT_s under intermediate hydrologic/surface temperature conditions (Fig. 1).

When SEBAL and other end-member-based models are used to estimate surface energy components, a concern is how large the area of interest (AOI) should be. A lack of general agreement on this issue brings about some uncertainties when the size of the AOI is varied, as the slope and intercept of the linear line between dT_s and T_s may have changed. To the best of our knowledge, there have been few studies dedicated to the effect of the size of the AOI on the sensible heat flux and latent heat flux derived using the SEBAL. Long et al. (2011) noted this heat flux difference by comparing the pixel-by-pixel sensible heat fluxes calculated for three different-sized sub-watersheds within the Baiyangdian watersheds in North China, and they concluded that the discrepancies in the sensible heat fluxes using the SEBAL are systematic for given atmospheric conditions when the AOI is expanded. However, it is unclear under which circumstances and how the sensible heat flux will change. Determining the mechanism of this change in the SEBAL-derived surface energy fluxes is important for understanding the uncertainties that result from the selection of dry and wet pixels for given atmospheric conditions within a given AOI.

For a given AOI, the SEBAL model is also affected by the pixel size of the satellite data. In most cases, extremely dry or wet pixels may not exist in the low-resolution satellite view of the area of interest due to areas that contain both soil and vegetation. Compared with the low-resolution data, high-resolution satellite data are better able to capture the spatial variability of the surface, and therefore, the extremely dry and wet pixels are more readily identified. The SEBAL-derived surface energy components (surface net radiation, soil heat flux, sensible heat flux, and latent heat flux) may differ over an area when the satellite surface temperature at one scale is changed to a different scale. In previous studies (Long et al., 2011; Gebremichael et al., 2010; Hong et al., 2009; Compaoré et al., 2008), the uncertainty that results from the variation of pixel size in the SEBAL has generally been evaluated by comparing the ET estimated at a targeted lower resolution (e.g., MODIS) and the spatially averaged value derived by aggregating either output (output up-scaling) or input (input up-scaling) of the SEBAL with high-resolution data (e.g., TM/ETM+ or ASTER). Long et al. (2011), among others, have demonstrated the significant differences of the SEBAL-estimated sensible heat flux and latent heat flux using satellite data with different pixel sizes. They attributed the heat flux discrepancy to the difference in the range and magnitude of surface temperatures acquired at the different spatial resolutions. When the satellite pixel size is changed, estimates of the sensible heat flux and latent heat flux are influenced by a number of other factors, including variations in surface albedo, emissivity, and aerodynamic resistance (surface roughness length), in addition to the variation in surface temperature. Those inconclusive evaluations are far from an all-around apprehension of the mechanism implicit in the scaling transfer of the sensible and latent heat fluxes when the satellite pixel is coarsened.

The objective of this paper is to comprehensively quantify the spatial-scale effect of the SEBAL model caused by variation in the sizes of the AOI and satellite pixel on estimating the regional sensible heat flux and latent heat flux by proposing generalized analytical equations and through model application. We examine under which circumstances the sensible heat flux is overestimated/underestimated/unaltered in the SEBAL model when the size of the AOI is increased. We also investigate how the sensible and latent heat fluxes vary when high-spatial-resolution satellite data are aggregated with or replaced by low-resolution data. This study differs from previous studies primarily in two aspects: (1) the data cover a broad range of vegetation growth stages under a full range of vegetation cover and soil wetness conditions from January 2010 to late October 2011, allowing the inclusion of a variety of meteorological, surface vegetation, and soil moisture conditions; and (2) analytical equations are proposed to reveal the mechanism of the scaling transfer of the SEBAL model, which is different from previous studies that evaluate the spatial-scale effect of the SEBAL model by simple comparison and make inconsistent conclusions that depend on the meteorological, soil, and vegetation conditions. Moreover, these equations can help understand how uncertainties in the intermediate variables in the SEBAL model propagate to the resulting surface energy components due to the alteration of dry and wet pixels when the size of the AOI is changed or when using satellite data with different spatial resolutions. Section 2 presents the study area used as the AOI, the MODIS dataset, the SEBAL model theory, the spatial scaling theory, and how the simulations are carried out. In Section 3, the spatial-scale effect of the AOI size and satellite pixel size on the SEBAL model are presented and the proposed analytical equations are verified by comparing the pixel-by-pixel sensible (latent) heat flux with that estimated by directly