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Incorporating an iterative energy restraint for the Surface Energy Balance System (SEBS)

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ABSTRACT

The Surface Energy Balance System (SEBS) has proven itself as an effective remotely sensed estimator of actual evapotranspiration (ET_a). However, it has several vulnerabilities associated with the partitioning of the available energy (*AE*) at the land surface. We introduce a two stage energy restraint process into the SEBS algorithm (SEBS-ER) to overcome these vulnerabilities. The first offsets the remotely sensed surface temperature to ensure the surface to air temperature difference reflects *AE*, while the second stage uses a domain based image search process to identify and adjust the proportions of sensible (*H*) and latent (λE) heat flux with respect to *AE*. We effectively implemented SEBS-ER over 61 acquisitions over two Landsat tiles (path 90 row 84 and path 91 row 85) in south-eastern Australia that feature heterogeneous land covers. Across the two areas we showed that the SEBS-ER algorithm has: greater resilience to perturbed errors in surface energy balance algorithm inputs; significantly improved accuracy ($p < 0.05$) at two eddy covariance flux towers in heavily forested (RMSE 62.3 W m^{-2}, R^2 0.879) and sub-alpine grassland (RMSE 33.2 W m^{-2}, R^2 0.939) land covers; and greater temporal stability across 52 daily actual evapotranspiration (ET_a) estimates compared to a temporally stable and independent ET_a dataset. The energy restraint within SEBS-ER has reduced exposure to the complex errors and uncertainties within remotely sensed, meteorological, and land type SEBS inputs, providing more reliable and accurate spatially distributed ET_a products.

1. Introduction

Evapotranspiration (*ET*) is a critical process for water accounting in catchment areas (Glenn et al., 2011), driving current and future water yields for urban populations (Chiew and McMahon, 2002; McVicar et al., 2012). It represents complex interactions involving moisture availability and transpiration, influenced by wind, temperature, heat fluxes, and surface roughness (Kalma et al., 2008). Estimating actual evapotranspiration (ET_a) and understanding how it varies spatially and temporally is essential for quantifying water loss across complex heterogeneous catchments (Glenn et al., 2011). Water planning authorities often rely on ET_a measurements from a few isolated ground flux towers or calculations of potential evapotranspiration (ET_o) (Monteith, 1965; Priestley and Taylor, 1972) or reference evapotranspiration (ET_r) (Allen et al., 1998) from one or more nearby meteorological ground stations. Estimations of catchment evaporative water loss and water yield are also complicated by patchy or non existent stream flow records (Winsemius et al., 2009), arising from substantial infrastructure costs or logistical difficulties. So, water accounting through hydrological models is often limited by the reliance on incomplete datasets (Merz et al., 2011; Winsemius et al., 2009), including relatively poor estimation of ET_a and ET_o. Satellite remote sensing techniques can reduce uncertainty within these inputs in hydrological models (Immerzeel and Droogers, 2008; Yin et al., 2016) through estimations of fine scale spatially explicit ET_a throughout catchments, improving water accounting for urban populations.

Remotely sensed thermal imagery and its estimation of surface temperature (T_S, K) is a critical component in surface energy balance (SEB) algorithms (Evett et al., 2012; Kalma et al., 2008) for the calculation of spatially explicit ET_a at landscape (≈30 m) or regional (250 m–1 km) scales. While spaceborne instruments like the Advanced Very High Resolution Radiometer (AVHRR) and the Moderate Resolution Imaging Spectrometer (MODIS) can provide high temporal frequency ET_a assessments at regional, continental, or global scales (Kalma et al., 2008; Mu et al., 2011), significant ET_a variability is often present in agricultural or forested landscapes at a few hundred meters or less (Anderson et al., 2012). Landsat data are an obvious choice to obtain moderate spatial resolution (30 m–120 m) SEB ET_a

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estimates, given continued investment in the Landsat program (Roy et al., 2014) combined with access to processed and freely available historical archives of thermal, near infrared and visible imagery (Masek et al., 2006). Moving forwards, Landsat 8 (Feb 2013 onwards, Roy et al., 2014) and Sentinel 3 (Feb 2016 onwards, Donlon et al., 2012) data will provide the basis for current and future moderate spatial resolution (10 m–90 m) cost-free SEB applications.

Over about 30 years of development (Carlson, 1986), different SEB algorithms now exist, such as the Surface Energy Balance System (SEBS) (Su, 2002), the Simplified Surface Energy Balance Index (S-SEBI) (Roerink et al., 2000), the Hybrid Dual-Source Scheme and Trapezoid Framework-Based Evapotranspiration Model (HTEM) (Yang and Shang, 2013), Mapping Evapotranspiration at High Resolution with Internalised Calibration (METRIC) (Allen et al., 2007), and others (Kustas and Norman, 1997; Long and Singh, 2012; Wang et al., 2014). Commonly, each algorithm employs a mechanism to constrain or reference sensible heat flux (H, W m^{-2}) and latent heat flux (λE, W m^{-2}) to the energy available at the land surface (AE); Net Radiation (R_N, W m^{-2}) minus Soil Heat Flux (G, W m^{-2}). While the instantaneous sum of sensible and latent heat fluxes is not necessarily equal to AE due to regional advection effects, its imbalance can be mitigated when ET_a is quantified over daily time scales or longer (Allen et al., 2011a).

Within SEB models, the scaling or calibration of H and λE is critical to ensure the surface energy balance can be satisfied (Kalma et al., 2008), for individual remotely sensed land units. Triangular (Gampe et al., 2016; Knipper et al., 2016; Petropoulos et al., 2009a) or trapezoidal (Long and Singh, 2012) techniques are distinct in their approach for the constraint and partitioning of H and λE within SEB algorithms. They generally exploit the relationship between T_S and a measure or index of vegetation (T_S-VI) (Carlson, 2007; Long et al., 2012; Price, 1990) to define boundaries or vertices associated with theoretical conditions of the surface energy balance. They have considerable utility and applicability over different environments and landscape scales, particularly those with limited ground reference data where there are often water management challenges (Gampe et al., 2016; Long et al., 2012).

Approaches vary for the choice of the vegetative axis, with most using the Normalized Difference Vegetation Index ($NDVI$) (Han et al., 2006; Sun, 2016; Yang and Shang, 2013), the fractional vegetation cover (Carlson, 2007), or the Leaf Area Index (LAI) (Han et al., 2006), while use of T_S among existing ET triangle methods remains similar, apart from incorporating the difference to air temperature (T_A, °C) (Long and Singh, 2012). Automated detection or definition of triangle/trapezoidal boundaries and vertices is a crucial requirement for the fast and objective production of ET_a, particularly for deriving estimates over large areas (Elhaddad and Garcia, 2014) and dense time series.

T_S-VI triangle and trapezoidal models have performed well when compared to other forms of energy restraint (Lian and Huang, 2016; Long and Singh, 2013) and when validated against Large Aperture Scintillometers (LAS) (Tang et al., 2010) or eddy covariance flux towers (Long and Singh, 2012; Long et al., 2012). However, T_S-VI techniques are often limited to heterogeneous areas that exhibit different vegetation conditions, varying across a range of water availabilities (Long et al., 2012). Also, as the domain size and land unit resolution changes, T_S-VI boundaries or vertices may vary (Long et al., 2012) and questions remain as to whether a triangle or a trapezoidal theoretical structure better encompasses the complete range of T_S-VI values (Long et al., 2012), and at what areal scale triangle techniques can be successfully implemented (Long et al., 2012).

SEBS uniquely applies the Penman-Monteith combination equation (Monteith, 1965) to determine the residual H (H_{wet}, W m^{-2}) for conditions where λE reaches the upper potential rate (λE_{wet}, W m^{-2}) (Su, 2002), different to most SEB algorithms (Kalma et al., 2008). This removes a common evaporative energy control at the cold and wet limit common among many SEB algorithms, that λE_{wet} is equivalent to AE (Bastiaanssen et al., 1998; Long and Singh, 2012; Yang and Shang, 2013). The METRIC algorithm also applies a similar evaporative control (Allen et al., 2007), however, it relies on the identification of representative land units relevant to ET_r surface conditions (Allen et al., 2013). Comparatively, the determination of $H_{wet}/\lambda E_{wet}$ by SEBS is spatially explicit and is not restricted by the need to identify specific land units. This makes SEBS more applicable to the estimation of ET_a over non-agricultural land types, where the composition of plant and tree species can be heterogeneous and is often largely unknown.

McCabe and Wood (2006) reported consistent flux estimates between different satellite platforms and at different spatial scales, indicating SEBS has good utility to create multi-scale high spatial and temporal resolution ET_a datasets, useful for hydrological accounting. When SEBS has been compared to other SEB algorithms it has been show to perform well. Tang et al. (2011) found comparable performance to the Two-Source Energy Balance (TSEB) model and improved performance to a T_S-VI triangle technique over wheat and corn agricultural land types. Yang and Shang (2013) obtained a root mean squared error (RMSE) for SEBS slightly larger than that for HTEM in wheat and corn, and Webster et al. (2016) showed SEBS had lower RMSE compared to S-SEBI and HTEM in forested and sub-alpine grassland land types. Furthermore, the current implementation of SEBS contains some structural limitations that if addressed may further improve its performance and applicability across different land types.

SEBS's constraint of H is different from other SEB algorithms; the initial unbounded estimates of H and H_{wet} are used directly to calculate evaporative fraction (Λ) (Su, 2002). While H_{wet} cannot exceed AE, there is no current control to enforce H to be greater than H_{wet} or less than AE (Su, 2002). This makes SEBS vulnerable to errors and bias within input variables related to the determination of H and H_{wet} (Liaqat and Choi, 2015). These error sources include: the interpolative uncertainty in the calculation of T_A, wind speed (U_x, m s^{-1}), vapour pressure (P_{vap}, kPa), and solar exposure (δ, MJ day^{-1}) (Elhag, 2016; Webster et al., 2016); errors and bias in T_S associated with the atmospheric correction for atmospheric transmissivity (τ), upwelling path radiance (R_{path}) and downwelling sky radiance (R_{sky}) (Allen et al., 2011a); landscape heterogeneity (Gibson et al., 2011; Rwasoka et al., 2011); and the uncertainty in Vegetation Fraction and σ_s given the absence of accurate land type classifications (Gibson et al., 2011). For example, SEBS was significantly more sensitive to errors in T_S and Leaf Area Index (LAI) inputs compared to TSEB (Tang et al., 2011). Furthermore, Timmermans et al. (2013) used the Soil Canopy Observation, Photochemistry and Energy fluxes (SCOPE) model to evaluate and validate SEBS by simulation of remote sensing input variables. They identified large uncertainties in SEBS G and H driven primarily by the original parametrisation for the roughness height for heat transfer (Z_{OH}, m) (Su, 2002), which was not suitable for tall canopies such as maize (Timmermans et al., 2013). After improving Z_{OH} using LAI to account for tall vegetation, H was still underestimated and λE overestimated (Timmermans et al., 2013). Also acknowledging the limitation in Z_{OH}, Gokmen et al. (2012) utilised microwave soil moisture measurements to account for increased water stress for Z_{OH} in the semi-arid Konya basin Turkey, improving estimations of SEBS flux components. Unfortunately, availability of supplementary microwave soil moisture measurements is often scarce in remote or heterogeneous environments (Daly, 2006).

The overall goal of this research was straightforward; to evaluate the effectiveness of adding a two dimensional (EVI-H) energy restraint process into the SEBS algorithm (SEBS-ER) to improve its operation, accuracy and temporal stability. Given the development task and the three performance aspects for algorithm improvement, we separated our research into four specific aims: a) to effectively integrate an energy restraint component into the original SEBS