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Combining the triangle method with thermal inertia to estimate regional evapotranspiration — Applied to MSG-SEVIRI data in the Senegal River basin

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Abstract

Spatially distributed estimates of evaporative fraction and actual evapotranspiration are pursued using a simple remote sensing technique based on a remotely sensed vegetation index (NDVI) and diurnal changes in land surface temperature. The technique, known as the triangle method, is improved by utilizing the high temporal resolution of the geostationary MSG-SEVIRI sensor. With 15 min acquisition intervals, the MSG-SEVIRI data allow for a precise estimation of the morning rise in land surface temperature which is a strong proxy for total daytime sensible heat fluxes. Combining the diurnal change in surface temperature, $\mathrm{d}T_\mathrm{s}$ with an interpretation of the triangular shaped $\mathrm{d}T_\mathrm{s}-$NDVI space allows for a direct estimation of evaporative fraction. The mean daytime energy available for evapotranspiration ($R_\mathrm{n}-G$) is estimated using several remote sensors and limited ancillary data. Finally regional estimates of actual evapotranspiration are made by combining evaporative fraction and available energy estimates. The estimated evaporative fraction (EF) and actual evapotranspiration (ET) for the Senegal River basin have been validated against field observations for the rainy season 2005. The validation results showed low biases and RMSE and R^2 of 0.13 [−] and 0.63 for EF and RMSE of 41.45 W m^{-2} and R^2 of 0.66 for ET.

Keywords: MSG SEVIRI; Remote sensing; Evaporative fraction; Evapotranspiration; Surface temperature; NDVI; Thermal inertia; Triangle method

1. Introduction

Evapotranspiration (ET) is a fundamental variable in the hydrological cycle and in any investigation of water and energy balances at the surface of the Earth. The rate of evapotranspiration is mainly controlled by the available energy, the availability of water, the humidity gradient away from the surface and the wind speed at the surface.

Evapotranspiration varies in time and space and is difficult to estimate as it depends on many interacting processes. At the local scale ET may be accurately estimated from detailed ground observations. At the regional scale sufficient ground observations will never be available and instead spatially distributed remote sensing data can be used as proxies for important controlling variables. Hence, information on the spatial distribution of ET require remote sensing observations and a number of simplifying assumptions due to under parameterization at the regional scale.

The residual methods utilize remote sensing data in combination with ancillary data to estimate sensible heat flux H and through that ET (Bastiaanssen et al., 1998; Boegh & Soegaard, 2004; Boegh et al., 2002; Kustas et al., 1994; Li & Lyons, 1999; Moran et al., 1994b; Norman et al., 2003). These methods vary in complexity, but usually estimate surface resistances from radiometric surface temperatures, e.g. through the estimation of the excess resistance term kB^{-1} (Kustas et al., 1989). One approach referred to as the "simplified method" is based on an empirical relation between sensible heat flux expressed as ($R_\mathrm{n}-$ET) and surface-air temperature difference ($T_\mathrm{s}-T_\mathrm{a}$) (Seguin & Itier, 1983). The relation can be formulated as $R_\mathrm{n}-\mathrm{ET}=a+b(T_\mathrm{s}-T_\mathrm{a})$, where the constants a and b are

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estimated empirically and are considered time and site specific. This method was further improved by Sandholt and Andersen (1993) who incorporated land cover information, by letting b vary as a function of NDVI.

Other models combine remote sensing data with meteorological data (Anderson et al., 1997) or utilize remote sensing data through data assimilation schemes (Caparrini et al., 2004; Margulis et al., 2005). Still, these methods are dependant on key parameters like wind speed and air temperature which usually are not available on a regional scale or from remote sensing data.

Another simple remote sensing method, not dependant on ancillary data, is the contextual method based on the surface temperature–vegetation index space (T_s-NDVI). This method, known as "the triangle" method, has been applied successfully in certain applications for estimation of both evapotranspiration (Gillies et al., 1997; Jiang & Islam, 2001; Nemani & Running, 1989; Nishida et al., 2003; Price, 1990; Roerink et al., 2000) and soil moisture (Carlson et al., 1995b; Sandholt et al., 2002).

Other studies have focused on the thermal inertia as a proxy for energy exchanges at the surface or combined thermal inertia with the above mentioned methods (Abdellaoui et al., 1986; Anderson et al., 1997; Wang et al., 2006).

In this study we have developed a method for estimating surface fluxes that is based entirely on remote sensing data. We combine the triangle method developed by Jiang and Islam (2001) with thermal inertia information obtained from the geostationary MSG-SEVIRI sensor to estimate regional evaporative fraction (EF). Additionally, remote sensing data are used for estimating daily available energy (R_n-G) which in combination with EF return the daily actual evapotranspiration. The method is applied to the Senegal River basin in West Africa and estimations are validated against field observations from a site in Dahra, Northern Senegal, for the rainy season 2005.

2. Methodology — the triangle method

Numerous studies have documented and interpreted the triangular (or trapezoidal) shape of the T_s-NDVI space that emerges from a scatter plot of remotely sensed surface temperature against the normalized difference vegetation index (Carlson et al., 1995a; Gillies et al., 1997; Goward & Hope, 1989; Jiang & Islam, 2001; Moran et al., 1994a; Nemani & Running, 1989; Price, 1990; Roerink et al., 2000; Sandholt et al., 2002). Detailed discussions on the T_s-NDVI relation are found in e.g. Gillies et al. (1997), Sandholt et al. (2002), Moran et al. (1994a).

Theoretically it can be argued that the temperature axis of the T_s-NDVI scatter should represent the surface-air temperature gradient (T_s-T_a) to capture the exchange in energy at the surface. The gradient in temperature between the surface and the atmosphere is what drives the sensible heat flux, which expresses the part of the available energy at the surface not consumed by evapotranspiration. For reasons of data availability T_s-T_a is however often replaced by T_s in remote sensing applications, e.g. Jiang and Islam (2001), Nishida et al. (2003), Sandholt et al. (2002). In this study T_s-T_a is replaced by two different temperature measures; one is a simple instantaneous T_s defined as T_s at 12:00 UTC and the second is a change in surface temperature over time dT_s, defined as the difference between T_s at 12:00 and 8:00 UTC. In the subsequent detailed description of our interpretation of the T_s-NDVI parameter space, the notation T_s will be assigned to the temperature variable, although the theory can be applied to both T_s, T_s-T_a and dT_s data.

2.1. Parameterization of the Priestly–Taylor parameter ϕ

Various methods using the T_s-NDVI space have been proposed for the estimation of surface evaporation and soil moisture. In this study we use the T_s-NDVI space method to parameterize the Priestly–Taylor parameter ϕ (Priestley & Taylor, 1972). This approach has also been applied by Jiang and Islam (2001) for estimation of surface evaporation over the Southern Great Plains using NOAA-AVHRR data.

The Priestly–Taylor equation is developed from Penman–Monteith's equation (Monteith, 1965) by assuming that the aerodynamic term can be represented by a parameter ϕ leading to the following simplified form for predicting ET:

$$\mathrm{ET} = \phi\left[(R_n - G)\frac{\Delta}{\Delta + \gamma}\right] \tag{1}$$

where ET is evapotranspiration (W m^{-2}), R_n is net radiation (W m^{-2}), G is soil heat flux (W m^{-2}), Δ is the slope of the saturated vapour pressure curve [kPa K^{-1}] and γ is the psychrometric constant [kPa K^{-1}] (Table 1). The Priestly–Taylor parameter ϕ is a substitute for the Priestly–Taylor constant α_{PT} applied for wet surface equilibrium conditions and generally agreed upon to be $\alpha_{PT}=1.26$ (Eichinger et al., 1996). ϕ, which represents an effective surface resistance to evapotranspiration, is not related to a single surface attribute (Jiang & Islam, 1999).

The estimation of available energy (R_n-G) by remote sensing will be treated separately and it is therefore convenient

Table 1
List of symbols

Symbol	Unit	Description
σ	W m^{-2}K^{-4}	The Bolzman constant
EF	W m^{-2}	Evaporative fraction
ET	W m^{-2}	Actual evapotranspiration
G	W m^{-2}	Ground heat flux
$R_{L,down}$	W m^{-2}	Incoming longwave radiation
$R_{L,up}$	W m^{-2}	Outgoing longwave radiation
R_n	W m^{-2}	Net radiation
R_s	W m^{-2}	Incoming shortwave radiation
R_{s0}	W m^{-2}	Clear sky incoming shortwave radiation
γ	kPa K^{-1}	Psychrometric constant
Δ	kPa K^{-1}	Slope of the saturated vapour pressure curve
dT_s	K	Difference in T_s over time
T_a	K	Air temperature
T_s	K	Land surface temperature
ε	–	Surface emissivity
α	–	Surface albedo
α_{PT}	–	Priestly–Taylor constant (1.26)
k	–	Clearness index
kB^{-1}	–	Surface resistance term
n	–	Cloud cover index
ϕ	–	Priestly–Taylor parameter