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Estimation of daily evapotranspiration over Africa using MODIS/Terra and SEVIRI/MSG data

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ABSTRACT

Most existing remote sensing-based evapotranspiration (ET) algorithms rely exclusively on polar-orbiting satellites with thermal infrared sensors, and therefore the resulting ET values represent only "instantaneous or snapshot" values. However, daily ET is more meaningful and useful in applications. In this study, daily ET estimates are obtained by combining data from the MODIS sensor aboard the polar-orbiting Terra satellite and the SEVIRI sensor aboard the geostationary-orbiting MSG satellite. The procedure consists of estimating the instantaneous evaporative fraction (EF) based on the MODIS/Terra land data products, and estimating the daily net radiation and daily available energy based on the 30-min SEVIRI/MSG data products. Assuming constant EF during the daytime, daily ET is estimated as the product of the SEVIRI/MSG-based daily available energy and MODIS/Terra-based instantaneous EF. The daily ET estimates are evaluated against flux tower measurements at four validation sites in Africa. Results indicate that the synergistic use of SEVIRI/MSG and MODIS/Terra has the potential to provide reliable estimates of daily ET during wet periods when daily ET exceeds 1 mm/day. The satellite-based daily ET estimates however tend to underestimate ET by 13% to 35%. The daily ET estimation algorithm can further be improved by incorporating a temporal data-filling interpolation technique to estimate the unavailable net radiation information during cloudy sky conditions, and by improving the accuracy of the instantaneous EF. The assumption of constant evaporative fraction during the daytime is reasonable, and does not result in substantial errors in the daily ET estimates.

1. Introduction

Regional evapotranspiration (ET) from land surface is essential to understand water cycle, and to estimate surface runoff and groundwater (Idso et al., 1975; Shukla and Mintz, 1982). Routine high quality data from satellite remote sensing has allowed capturing continuous ET maps on a wide range of spatio-temporal scales (*e.g.*, Nagler et al., 2005; Mu et al., 2007; Leuning et al., 2008). Most existing remote sensing-based ET algorithms rely exclusively on polar-orbiting satellites with thermal infrared sensors, and therefore the resulting ET values represent only "instantaneous or snapshot" values (*e.g.*, Wang et al., 2007; Venturim et al., 2008). However, daily ET is more meaningful and useful in applications.

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The typical approach of estimating daily evapotranspiration (ET) from satellite data involves two steps.

First, "instantaneous" ET estimates are obtained from polar-orbiting satellite data in the visible, near infrared and thermal infrared bands (Gebremichael et al., 2010). The MODerate resolution Imaging Spectroradiometer (MODIS) sensor on board Terra and Aqua polar-orbiting satellites has long been recognized for its potential to produce frequent instantaneous ET maps across the globe (*e.g.*, Mu et al., 2007).

Second, the instantaneous ET estimates are scaled up to daily using ground-based measurements of daily radiation. Three methods currently exist to scale up instantaneous ET values to daily: sine function (SF) method, evaporation fraction (EF) method, and reference-crop ET fraction (ETrF) method. The SF method (Jackson et al., 1983) assumes that the diurnal variability of ET closely follows that of the incident solar radiation, which can be characterized by a sine function during cloud-free days. The EF method (Sugita and Brutsaert, 1991) assumes that the evaporative fraction (the ratio of latent heat flux to available energy) is constant during the daytime and this fraction can be used with daily total radiation, typically estimated using ground-based solar radiation measurements, to scale up instantaneous ET to daily. The ETrF method (Allen et al., 2007) assumes that the ratio of instantaneous ET to instantaneous reference-crop ET (defined in Allen et al., 1998) remains constant during the daytime and this ratio can be used with daily reference-crop ET, typically estimated using ground-based meteorological measurements, to scale up instantaneous ET to daily. Among these methods, only the EF and ETrF methods work in all weather conditions. However, these methods require daily data that cannot be achieved from once or twice a day MODIS snapshots.

Thermal and other sensors aboard geostationary satellites provide diurnal variation of radiation at a temporal resolution of 15 to 30 min, which may be used to scale up instantaneous ET values to the daily timescale. Literature review reveals that there are only a few studies that attempted to combine geostationary-orbit satellite data with polar-orbit satellite data to estimate ET (Anderson et al., 2011; Shu et al., 2011). Anderson et al. (2011) estimated daily ET at 5–10 km resolution from geostationary satellite data using the Atmospheric-Land Exchange Inverse (ALEXI) model, and then used polar orbiting satellite data for downscaling the ET estimates to finer resolutions through the DisALEXI algorithm. In their approach, the advantages of polar orbiting satellite data (more accurate, and finer spatial and spectral resolutions) do not directly contribute to ET estimates. Shu et al. (2011) estimated ET by combining the 5-km MODIS vegetation index (VI) data with the surface temperature (Ts) data from the Chinese geostationary satellite, Fengyun-2C. Limitations of their approach include difficulty of locating the required vertices of the VI − △Ts (surface temperature difference) diagram based on 5-km pixel sizes, and unrealistic assumption of homogeneous atmospheric forcing in the VI − △Ts space over a wide spatial range of 400 to 500 km, as described by Sun et al. (2011).

The main purpose of this study is to assess the value of combining the polar orbiting (MODIS/Terra) and new geostationary (SEVIRI/MSG) satellite datasets to estimate daily ET. Results are evaluated based on flux tower measurements at four sites in Africa. The remainder of this paper is organized as follows. Section 2 describes the data used. Section 3 presents the methodology used to estimate daily ET from the MODIS/Terra and SEVIRI/MSG datasets. The resulting ET estimates are evaluated against flux tower measurements in Section 4. Possible sources of errors in the satellite-based daily ET estimates, and limitation of the flux tower measurements are discussed in Section 5. Conclusions are drawn in Section 6.

2. Data

2.1. MODIS Data

MODIS sensor onboard the Terra and Aqua polar-orbiting satellites has 36 spectral bands over a wide range at moderate resolutions (250, 500, and 1000 m) with almost daily coverage of the Earth (http://modis.gsfc.nasa.gov). In this study, we used three quality-flagged MODIS/Terra land data products: 8-day land surface temperature (MOD11A2) (http://modis-land.gsfc.nasa.gov/temp.htm), yearly International Geosphere-Biosphere Programme (IGBP) land cover map (MOD12Q1) (http://modis-land.gsfc.nasa.gov/landcover.htm), and 16-day Normalized Difference Vegetation Index (NDVI) (MOD13A2) (http://modis-land.gsfc.nasa.gov/vi.htm).

2.2. SEVIRI Data

The Spinning Enhanced Visible InfraRed Imager (SEVIRI) sensor onboard the Meteorological Second Generation (MSG) geostationary-orbiting satellite provides 30/15-min observations of land surface and the atmosphere in 12 spectral bands for Europe, South America, and Africa at 3.1 km spatial resolution at nadir (http://www.esa.int/SPECIALS/MSG/). In this study, we used four SEVIRI/MSG data products: 30-min downwelling shortwave radiation flux (LSA-SAF, 2008a), 30-min downwelling longwave radiation flux (LSA-SAF, 2009), 15-min land surface temperature (LSA-SAF, 2008b), and daily vegetation cover fraction (LSA-SAF, 2008c).

2.3. Ground measurements

We obtained ground measurements of quality-controlled 30-min net radiation, soil heat flux, sensible and latent heat fluxes from four sites of the CarboAfrica flux tower network in Africa (see Papale et al., 2006 and the CarboAfrica website at http://gaia.agraria.unitus.it/database/carboafrica/ for the details about the ground measurements). Fig. 1 shows site locations; Table 1 provides the site salient features and the period of data availability. The sites are located in different parts of Africa (Sudan, Congo, Zambia and South Africa), and represent the dominant climate and land surface conditions of Africa.

3. Methodology

The proposed methodology for the estimation of daily actual ET is illustrated with a flow chart in Fig. 2. Here, we discuss the algorithms involved.