International Journal of Applied Earth Observation and Geoinformation 13 (2011) 934–941

Contents lists available at ScienceDirect

International Journal of Applied Earth Observation and Geoinformation

journal homepage: www.elsevier.com/locate/jag

The potential of multitemporal Aqua and Terra MODIS apparent thermal inertia as a soil moisture indicator

Jasper Van doninck[a,*], Jan Peters[b], Bernard De Baets[b], Eva M. De Clercq[c], Els Ducheyne[c], Niko E.C. Verhoest[a]

[a] Laboratory of Hydrology and Water Management, Ghent University, Coupure links 653, Ghent, Belgium
[b] Department of Applied Mathematics, Biometrics and Process Control, Ghent University, Coupure links 653, Ghent, Belgium
[c] Avia-GIS, Risschotlei 33, Zoersel, Belgium

ARTICLE INFO

Article history:
Received 10 November 2010
Accepted 18 July 2011

Keywords:
Apparent thermal inertia
Soil moisture
Thermal infrared
MODIS
AMSR-E
Multitemporal analysis

ABSTRACT

Variations in surface thermal inertia—the resistance to temperature variations—can be indicative for variations in soil moisture. In this paper, we present a flexible multitemporal approach to derive an approximation of thermal inertia, called apparent thermal inertia (*ATI*), from daily Aqua and Terra MODIS observations. In a first step, a varying number of land surface temperature measurements were, together with the time of observation, fit to a sinusoidal function to obtain diurnal surface temperature amplitudes. These were subsequently combined with surface albedo to derive *ATI*. This was done for the southern part of the African continent for the year 2009. Apparent thermal inertia was compared both spatially and temporally to AMSR-E soil moisture, generated by the algorithm developed by the Vrije Universiteit Amsterdam and NASA. The temporal behaviour of apparent thermal inertia, derived using MODIS data only, showed a strong correspondence to that of AMSR-E soil moisture, especially in arid and semi-arid environments. The approach showed some limitations for vegetated terrains. Further post-processing is required to filter meteorologically induced noise and to transform *ATI* to actual soil moisture content.

1. Introduction

The water held in the top few centimeters of the soil is a key variable in many hydrological, climatological and ecological processes. Models describing these processes often need spatially distributed soil moisture information as input. These data are difficult and costly to acquire through in situ measurements, especially at high temporal frequencies. This justifies the amount of research invested in the derivation of soil moisture related information from remote sensing. Different types of remote sensing systems are currently used to infer soil moisture at different spatial and temporal scales, each with its specific characteristics and limitations. While coarse resolution microwave radiometers and scatterometers are today considered the only satellite systems able to routinely measure soil moisture at global scale (Wagner et al., 2007), their spatial resolution is too low for many local applications. Synthetic aperture radars (SAR) can reach a much higher spatial resolution. This, combined with the sensitivity of the backscatter signal to surface soil moisture and with the atmospheric permeability to microwave radiation, makes approaches using SAR attractive for applications on watershed and field scale. Strong perturbation of the backscatter signal by surface roughness and vegetation cover, however, strongly hampers the applicability of these approaches when ancillary ground reference data is not available (Verhoest et al., 2008). Optical sensors complemented with thermal infrared channels have, in spite of the strong atmospheric attenuation and the limited penetration depth of the used signal, received much attention as a source of information on soil moisture content and surface evaporation (Kalma et al., 2008; Verstraeten et al., 2008). This is mainly due to the wide range of spatial resolutions covered by this group of sensors and the observed relation between surface temperature and surface soil moisture content. One group of methods combining optical and thermal information is based on the concept of thermal inertia.

The thermal inertia of a material or surface determines its resistance to temperature variations and is function of the material's bulk density, specific heat capacity and thermal conductivity. As these three properties are material-specific, different materials can be distinguished by their thermal inertia, offering numerous applications in terrestrial and planetary geology (Cracknell and Xue, 1996). Furthermore, since the thermal conductivity of soils changes with fluctuating moisture level (Minacapilli et al., 2009), thermal inertia can be used as a soil moisture indicator, given all other soil properties constant over space or time. Unfortunately, bulk density,

* Corresponding author. Tel.: +32 9 264 61 40; fax: +32 9 264 62 36.
E-mail address: Jasper.Vandoninck@UGent.be (J. Van doninck).

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doi:10.1016/j.jag.2011.07.003

specific heat capacity and thermal conductivity cannot be derived from remote sensing, thus mapping of thermal inertia through remote sensing requires alternative approaches.

For several decades, thermal inertia has been approximated using land surface temperature differences as acquired by infrared thermometers. As materials with higher thermal inertia will experience smaller temperature changes than materials with low thermal inertia, given identical external driving forces, the night/day or pre-sunrise/midday temperature differences in remote sensing images can be used to discriminate between materials or soil moisture levels. The first physically based models to derive thermal inertia for geologic mapping of the Earth's surface including remote sensing data originate from the early and mid 70s (Kahle et al., 1976; Watson, 1973). More formulations for the computation of thermal inertia were suggested in the subsequent years (Idso et al., 1976; Price, 1977, 1980; Pratt et al., 1980; Abdellaoui et al., 1986). However, these all assume the availability of meteorological and/or other ancillary data, and are thus limited in use.

In contrast to these earlier models, Xue and Cracknell (1995) developed a methodology that required only a single ground measurement, being the time of maximum surface temperature in the daytime. For operational use, they suggest to replace this parameter by the time of maximum air temperature. This meteorological information may however not always be available. Furthermore, the time of maximum air temperature can differ from the time of maximum surface temperature. Sobrino and El Kharraz (1999a) therefore adapted this methodology by obtaining the time of maximum surface temperature from the remote sensing data itself. As such, a method to derive thermal inertia requiring only remotely sensed surface temperature and albedo was obtained.

A very basic approximation of thermal inertia, solely requiring surface albedo and a night-day surface temperature pair, was obtained by simplification of the Price (1977) model. This approximation was originally applied on Heat Capacity Mapping Mission (HCMM) data and named apparent thermal inertia (Short and Stuart, 1982). Apparent thermal inertia was initially found to be of limited use in areas with strong evapotranspiration (Price, 1985). Wet surfaces allow considerable evaporation and/or transpiration during the daytime, thus reducing daytime surface temperatures through evaporative cooling and introducing errors in apparent thermal inertia. Nevertheless, apparent thermal inertia recently received renewed interest for mapping of both geology (Mitra and Majumdar, 2004) and soil moisture (Tramutoli et al., 2000; Verstraeten et al., 2006) because of its simple formulation requiring remote sensing data only.

The coupling between apparent thermal inertia and soil moisture is not straightforward. True thermal inertia can be converted to soil moisture when soil properties are known (Lu et al., 2009; Minacapilli et al., 2009). Apparent thermal inertia might be directly related to soil moisture for areas with limited extent so that only a single soil and land cover type are present (e.g. individual fields). Over areas with varying geology or land use, however, soil moisture can only be extracted using a multitemporal approach (Tramutoli et al., 2000; Verstraeten et al., 2006). Since geology and soil composition in general change only over very long time scales, short-term changes in (apparent) thermal inertia can be linked to changes in soil moisture.

Sensors on sun-synchronous polar orbiting satellites such as NOAA/AVHRR or Aqua and Terra MODIS provide day- and night-time land surface temperature measurements on a near-daily basis at approximately 1 km resolution, which allows for the derivation of time series of daily apparent thermal inertia. However, these sensors suffer from the disadvantage, compared to lower resolution geostationary sensors, that the time of observation of a position on the ground may differ between two consecutive days. Aqua's equatorial crossing time, for example, is approximately 1:30 pm in ascending mode and 1:30 am in descending mode. Due to the wide swath width of the MODIS instrument (2330 km), however, the local solar time of observation at a particular point at the Earth's surface can be considerably earlier or later than the time at nadir, resulting in possibly large differences in time of observation for two consecutive days. Additional heating or cooling will occur during this time span, hampering meaningful comparison of apparent thermal inertia images of different dates. A second limitation of most (apparent) thermal inertia methods up to present is that they use only two surface temperature observations as (approximations of) the diurnal temperature range, except for the method of Sobrino and El Kharraz (1999a) which requires four daily measurements. When one of these observations is lacking—due to cloud cover or because the area of interest lies between sensor swaths, which is common in regions near the equator—the (apparent) thermal inertia for that day can obviously not be derived.

Here we propose a methodology to derive apparent thermal inertia by a multitemporal approach, using Aqua and Terra MODIS data of a full year. The method is based on a sinusoidal approximation of the diurnal surface temperature curve, where a sinusoid is fitted to either four, three or two MODIS land surface temperature observations, depending on the number of available observations. The methodology allows for a certain flexibility and exploits the full amount of information gathered by the MODIS instrument. The method is applied on a sub-continental scale for the year 2009, the derived apparent thermal inertia is validated using coarse resolution passive microwave data.

2. Methodology

In this study, the diurnal temperature cycle is approximated as a sinusoid defined by:

$$T(t_i) = \bar{T} + \frac{A}{2}\cos(\omega t_i - \psi). \tag{1}$$

In Eq. (1): $T(t_i)$ is the surface temperature at time t_i [K]; $\bar{T}$ the diurnal average surface temperature [K]; A the amplitude of diurnal temperature cycle [K]; ω the angular velocity of rotation of Earth [rad s^{-1}]; t_i the time of day [s]; ψ is the phase angle [rad].

Considering the phase ψ known, e.g. from in situ measurements, then Eq. (1) contains two unknowns: $\bar{T}$ and A. The amplitude and average temperature can thus be derived for each pixel for each day with two observations $(t_i, T(t_i))$ or with more (n) observations using a least squares approach. The solutions for A and $\bar{T}$ then become, denoting $T_i \equiv T(t_i)$:

$$\frac{A}{2} = \frac{n\sum_{i=1}^{n}\cos(\omega t_i - \psi)T_i - \sum_{i=1}^{n}\cos(\omega t_i - \psi)\sum_{i=1}^{n}T_i}{n\sum_{i=1}^{n}\cos^2(\omega t_i - \psi) - \left(\sum_{i=1}^{n}\cos(\omega t_i - \psi)\right)^2} \tag{2}$$

and

$$\bar{T} = \frac{\sum_{i=1}^{n}T_i - (A/2)\sum_{i=1}^{n}\cos(\omega t_i - \psi)}{n}. \tag{3}$$

With $n = 2$, the exact solution for the diurnal amplitude is:

$$\frac{A}{2} = \frac{T_1 - T_2}{\cos(\omega t_1 - \psi) - \cos(\omega t_2 - \psi)}. \tag{4}$$

The MODIS sensor onboard Aqua and Terra can provide up to four land surface temperature observations each day. A maximum number of observations can be used to derive the diurnal temperature amplitude from Eqs. (2) or (4). In the case of only two