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Thermal-based techniques for land cover change detection using a new dynamic MODIS multispectral emissivity product (MOD21)

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ABSTRACT

Land Surface Temperature and Emissivity (LST&E) data determine the amount of net longwave radiation emitted from the Earth's surface and are therefore critical variables for studying a variety of surface–atmosphere processes over land such as evapotranspiration, land cover change, and surface composition. Because emissivity is an intrinsic property of the surface, multispectral thermal infrared emissivity data have the potential for enhancing our ability to monitor landscape changes in environmentally sensitive zones beyond what is currently possible from standard practices used today. The most common of these practices is the use of visible to shortwave infrared data, in particular the Normalized Difference Vegetation Index (NDVI). Two algorithms are currently used to generate the LST&E products from MODIS data, but studies have identified several issues with both these algorithms that limit their usefulness for land cover change detection. These issues have been recently addressed by applying the ASTER Temperature Emissivity Separation (TES) algorithm to MODIS thermal infrared data to generate LST and a dynamically varying multispectral emissivity product for bands 29, 31, and 32 at 1-km resolution. The new product (MOD21) will be released with MODIS Collection 6 during fall 2013. This study demonstrates the utility of the dynamic MOD21 multispectral emissivity product to detect land cover changes over a broad range of different Earth surface domains including land degradation in dryland regions, snow melt characteristics on glaciers and ice sheets, extreme ecosystem disturbances, and agricultural activities. The MOD21 spectral emissivity provided increased sensitivity to land cover change in a more consistent manner than is currently possible with other emissivity products and, depending on the application, standard visible to near infrared (VNIR) data. The results suggest that synergistic use of thermal and VNIR data will help us to better identify and understand changes in the Earth surface system, and reduce uncertainties in estimating their magnitudes and trends.

1. Introduction

Land Surface Temperature and Emissivity (LST&E) data are increasingly being recognized as important Earth System Data Records (ESDR) by NASA and many other international organizations (CCSP 2006; GCOS 2003; IPCC 2007; King, 1999; NASA 2005), including the recently established EarthTemp network (Merchant, 2012). LST&E data are one of the main indicators of land cover change in the terrestrial biosphere, and as a result are key inputs to hydrological and surface balance models that estimate important climate-related variables such as evapotranspiration, and net longwave radiation.

Establishing consistent long-term data records of land cover change/use is an important objective for many research agencies, for example NASA's Land Cover Land Use Change (LCLUC) Program (http://lcluc.umd.edu/index.php). These types of records include the location, extent, and trends of land cover change/use over time using primarily satellite data sources. The impacts of land cover change can be both biophysical and socioeconomic. For example, agricultural land use changes can have significant effects on human health (Blair & Zahm, 1995), the environment (Lambin et al., 2001), and can affect local and regional climate (Dale, 1997).

The most common approach from the remote sensing perspective for the detection of land cover change is the use of visible to shortwave infrared (VSWIR, 0.4–2.5μm) data, in particular the use of vegetation indices (VIs), such as the Normalized Difference Vegetation Index (NDVI), which rely on red and near infrared reflectance (Hickler et al., 2005; Tucker, Newcomb, Los, & Prince, 1991). However, an often unmentioned shortcoming of VI data is their inability to distinguish between bare soils and dormant vegetation, since the design of VIs is based on the chlorophyll absorption of photosynthetically active vegetation. This can lead to underestimated values of fractional vegetation cover as VI values decrease with plant senescence (French & Inamdar, 2010; French, Schmugge, & Kustas, 2000), leading to surface balance and evapotranspiration modeling errors (Anderson, Kustas, et al., 2011).

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An alternative method for monitoring land cover is to use spectral emissivity information derived from thermal infrared (TIR, 8–12μm) remote sensing data. Silicate minerals such as quartz and feldspars that are ubiquitous in arid landscapes show a minimum emissivity feature at shorter wavelengths (8–9.5μm), while plant canopy spectra are distinct from soils and have a consistently high and spectrally flat emissivity in this region, whether green or dry. These spectral emissivity features allow us to observe changes between proportions of bare and vegetated surfaces regardless of plant greenness with greater sensitivity than what was previously possible with VI data (French et al., 2000; French et al., 2008). Very few studies have used spectral emissivity for monitoring land-cover/land-use changes primarily because emissivity products such as those from ASTER (AST05) are limited by long revisit cycles of at best 16days under clear skies, and the MODIS spectral emissivity product (MOD11B1) is produced at too coarse resolution (~5–6km) with large uncertainties (cloud, misregistration, noise).

The issues with these two emissivity products have been shown to be addressed by applying the ASTER Temperature Emissivity Separation (TES) algorithm (Gillespie et al., 1998) including a Water Vapor Scaling (WVS) method (Tonooka, 2005b) to retrieve LST&E from MODIS thermal data at the native ~1–km resolution at nadir (Hulley & Hook, 2011). A new product, MOD21, will be released with MODIS Collection 6 during the fall 2013 period. The TES algorithm uses an emissivity model based on the variability in the surface radiance data to dynamically retrieve both LST and spectral emissivity (Gillespie et al., 1998). Initial validation and evaluation of the new MOD21 LST product has shown similar accuracy to MOD11 over vegetated and ice/snow surfaces (~1K), while there is significant improvement in accuracy over dryland regions with LST biases reduced from over 3K to less than 1K (Hulley, Hughes, & Hook, 2012). Applying the TES algorithm to MODIS thermal infrared data will for the first time allow the potential for dynamically retrieving multispectral emissivity (bands 29, 31, and 32), twice-daily, and at the MODIS native resolution of 1-km at nadir. This will enable the use of MODIS thermal data to help answer important Earth science questions, for example; soil moisture estimation (Hulley, Hook, & Baldridge, 2010; Mira, Valor, Boluda, Caselles, & Coll, 2007), monitoring and assessing melt zones on glaciers (Tonooka & Kondo, 2007), land cover change and degradation assessment (French et al., 2008), and surface compositional mapping (Hook et al., 2005). Furthermore, an improved LST&E product from MODIS will result in improved surface heat flux estimates over agricultural regions (Anderson, Hain, Wardlow, Mecikalski, & Kustas, 2011; Kustas, Norman, Anderson, & French, 2003), and more accurate water vapor and air temperature retrievals over land (Seemann, Borbas, Knuteson, Stephenson, & Huang, 2008; Yao, Li, Li, & Zhang, 2011).

In this study we demonstrate the capability of using thermal-based approaches with data from a new MODIS LST and spectral emissivity product (MOD21) for the detection of land cover changes over a variety of Earth surface domains over long time periods with better or complementary sensitivity than is currently possible with standard visible-based data techniques. A background on the MOD21 product and retrieval methodology is first described, followed by examples of thermal-based techniques used to detect land cover changes. These include monitoring trends in land degradation over a dryland region of the Jornada Experimental Range, monitoring snow melt dynamics over Greenland, detecting extreme ecosystem disturbances after a wildfire, and discriminating between different land cover conditions due to agricultural practices.

2. The MOD21 land surface temperature and emissivity product

The MODIS instrument acquires data in 36 spectral channels in the visible, near infrared, and infrared wavelengths. Infrared channels 20, 22, 23, 29, 31, and 32 are centered on 3.79, 3.97, 4.06, 8.55, 11.03, and 12.02μm respectively. Channels 29, 31, and 32 are the focus of this study. In this section the TES algorithm and application to MODIS data will be discussed. The TES algorithm is currently used to produce the ASTER standard LST and emissivity products (AST08 and AST05) using ASTER's five thermal bands (10–14). Previous studies have shown that TES can be successfully applied to the three MODIS thermal bands 29, 31, and 32 (Hulley & Hook, 2011; Tonooka, 2005b).

2.1. Theoretical basis for Temperature Emissivity Separation (TES)

The TES algorithm uses surface emitted radiance data as input, which is derived by atmospherically correcting the observed radiance for atmospheric transmission and path radiance. The surface radiance is a combination of two terms; self emission from the Earth's surface, and reflected downward irradiance from the sky and surroundings, and can be written in terms of the observed radiance and atmospheric parameters as follows:

$$L_{s,i} = \epsilon_i B_i(T_s) + (1-\epsilon_i)L_i^{\downarrow} = \frac{L_i(\theta) - L_i^{\uparrow}(\theta)}{\tau_i(\theta)} \quad (1)$$

where: i-Band, θ-viewing angle, $L_{s,i}$-surface radiance, ϵ_i-surface emissivity, $B_i(T_s)$-Planck radiance, $L_i^{\downarrow}$-downward sky irradiance, L_i-observed radiance, $L_i^{\uparrow}$-path radiance, τ_i-transmissivity. The path radiance, transmissivity, and downward sky irradiance are computed with a radiative transfer model (e.g. MODTRAN), using input fields of temperature, relative humidity and geopotential height.

2.2. TES calibration curve

Derivation of ϵ_i and T_s from Eq. (1) is an undetermined problem, and the constraint used for solving the problem is an empirical relationship that predicts the minimum emissivity (ϵ_{min}) from the observed spectral contrast, or minimum–maximum emissivity difference (MMD) for the set of bands being used (Kealy & Hook, 1993; Matsunaga, 1994). This relationship is derived from lab measurements and is called the TES calibration curve shown in Fig. 1. The calibration curve is derived from a subset of spectra of different surface materials (rocks, soils, vegetation, snow, and water) from the ASTER spectral library (Baldridge, Hook, Grove, & Rivera, 2009), and can be adjusted for any sensor's spectral response

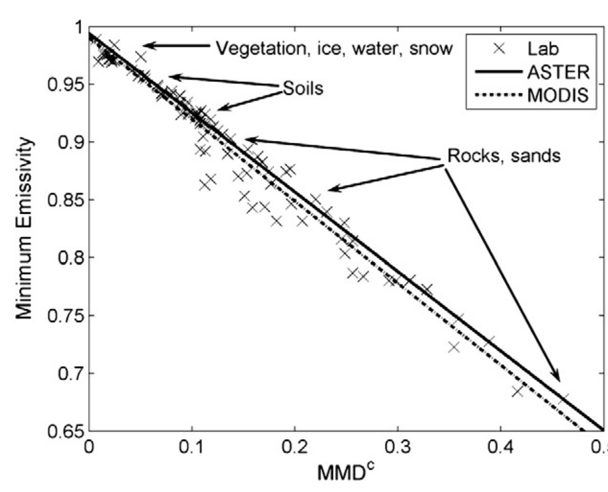

Fig. 1. MODIS and ASTER calibration curves of minimum emissivity (ϵ_{min}) vs. Min–Max emissivity Difference (MMD). The lab data (crosses) are computed from 150 spectra consisting of a broad range of terrestrial materials (rocks, sand, soil, water, vegetation, and ice).