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Validation of remotely sensed surface temperature over an oak woodland landscape — The problem of viewing and illumination geometries

Sofia L. Ermida [a,*], Isabel F. Trigo [b], Carlos C. DaCamara [a], Frank M. Göttsche [c], Folke S. Olesen [c], Glynn Hulley [d]

[a] Instituto Dom Luiz (IDL), University of Lisbon, Lisbon, Portugal
[b] Instituto Português do Mar e da Atmosfera (IPMA), Lisbon, Portugal
[c] Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
[d] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, USA

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ABSTRACT

Satellite retrieved values of Land Surface Temperature (LST) over structured heterogeneous pixels generally depend on viewing and illumination angles as well as on the characteristics of the land cover. Here we present a method to quantify such dependencies on land surface characteristics, sun illumination and satellite position. The method uses a geometric model to describe the surface elements viewed by an air-borne sensor and relies on parallel-ray geometry to calculate the projections of tree canopies and sunlit and shaded ground: these are considered as basic surface elements responsible for most of the spatial variability of LST. For a woodland landscape we demonstrate that modeling the fractions of these basic surface elements within the sensor field-of-view allows us to quantify the directional effects observed on satellite LST with sufficient accuracy.

Geometric models are an effective tool to upscale in situ measurements for the validation of LST over discontinuous canopies (e.g. forests). Here we present the application of a model to observations of brightness temperature from the LSA-SAF validation site in Évora (Portugal), an area of oak woodland, over the one-year period from October 2011 to September 2012. The resulting composite temperature is compared against LSA SAF LST products from the Spinning Enhanced Visible and InfraRed Imager (SEVIRI) onboard Meteosat as well as against MYD11A1/MOD11A1 (collection 5) products from the MODerate resolution Imaging Spectroradiometer (MODIS) onboard AQUA and TERRA. Comparisons with modeled ground LST show that SEVIRI LST has a bias of 0.26 °C and a RMSE of 1.34 °C, whereas MODIS LST (MYD11A1 and MOD11A1, collection 5) has a bias of −1.54 °C and a RMSE of 2.37 °C. Both MODIS and SEVIRI LST are closer to in situ values obtained with the geometric model than to those obtained when disregarding the effects of viewing and illumination geometry. These results demonstrate the need to consider the directional character of LST products, especially for validation purposes over heterogeneous land covers. For the new MODIS LST product (MOD21), which is based on the Temperature-Emissivity Separation (TES) algorithm, comparisons with in-situ LST show an improved bias of −0.81 °C and a RMSE of 1.48 °C (daytime values only). The TES based product presents lower emissivity values than those used for retrieving MYD11A1/MOD11A1 LST, which may partially explain the improved match with in-situ LST.

Discrepancies between LST retrievals obtained from different sensors, especially those on different orbits can also be partly explained by their viewing/illumination geometries. In this study the geometric model is used to correct LST deviations between simultaneous MODIS and SEVIRI LST estimations related to those effects. When the model is used to correct the variable MODIS viewing geometry there is a reduction in standard deviation of about 0.5 °C.

1. Introduction

Land Surface Temperature (LST) is an important climatological variable (Sellers, Hall, Asrar, Strebel, & Murphy, 1992) as well as a diagnostic parameter of land surface conditions. It plays an important role in the surface energy balance, and as such it has long been used to infer surface heat fluxes (Caparrini, Castelli, & Entekhabi, 2004; Mannstein, 1987), soil moisture (Carlson, 1986; Nemani, Pierce, & Running, 1993), evapotranspiration (Kustas & Norman, 1996) and vegetation properties (Lambin & Ehrlich, 1997), including vegetation hydric stress (Jackson, Idso, Reginato, & Pinter, 1981).

Remote sensing constitutes the most effective method to observe LST over large areas and on a regular basis. Satellite LST products generally rely on measurements within the atmospheric window in the

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[*] Corresponding author at: Faculdade de Ciências da Universidade de Lisboa, Campo Grande, Ed. C8, sala 8.3.15, 1749-016 Lisboa, Portugal. Tel.: +351 217 500 868.
E-mail address: snermida@fc.ul.pt (S.L. Ermida).

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thermal infrared (e.g., Li et al., 2013). As such, remote sensing retrievals of LST correspond to the directional radiometric temperature of the surface within the field of view of the sensor (e.g., Norman & Becker, 1995). The validation of LST retrievals is however not trivial, given its high variability in space and time, along with the anisotropic effects. Validation exercises are commonly performed through comparisons of LST against ground-based measurements or through a radiance-based method (e.g., Wan & Li, 2008). The latter involves using radiative transfer calculations to reconstruct top-of-atmosphere observations from the LST retrievals and assuming surface emissivity and atmospheric profiles are known. The former is usually performed over homogeneous areas such as lakes, deserts and dense or very homogeneous vegetation covers, where station measurements are representative of pixel scale values (Göttsche, Olesen, & Bork-Unkelbach, 2013; Wan, Zhang, Zhang, & Li, 2002, 2004). For heterogeneous surfaces, however, validation can be much more complex as an effective upscaling of the ground measurements is needed (Guillevic et al., 2012).

The comparison of LST estimations obtained from sensors on-board different platforms provides useful insight on product consistency (e.g., Jiménez et al., 2012; Trigo, Monteiro, Olesen, & Kabsch, 2008). There are, however, many possible sources of LST differences, and it is difficult to ascertain the actual accuracy of each retrieval. Discrepancies between LST products may be associated to differences (i) in the top-of-atmosphere measurements (sensor calibration, spatial resolutions), (ii) in the algorithm and auxiliary data used for atmospheric and surface emissivity correction, (iii) in cloud mask, and (iv) in angular anisotropy (e.g., Barroso, Trigo, Olesen, DaCamara, & Queluz, 2005; Pinheiro, Privette, & Guillevic, 2006; Rasmussen, Pinheiro, Proud, & Sandholt, 2010). Furthermore, remotely sensed LST is a directional variable, unless some sort of compositing of observations from different viewing angles is performed. As such, hypothetical LST retrievals obtained for the same scene, using the same sensor, but at different viewing angles would likely produce different temperature values, depending on factors like surface type, soil characteristics and slope orientation relative to sun. Although surface structure exerts an important role on the temperature, due in particular to shadowing effects that result in a dependence of LST on the zenith and azimuth view angles, these effects are often disregarded. In validation exercises involving comparisons of LST estimations with in situ observations, or inter-comparisons of LST products, the viewing and illumination geometries should be taken into account.

The effects of viewing and illumination geometries are usually considered by means of geometrical–optical models that have been developed mainly to describe forests and other discontinuous canopies. They operate by assuming that the canopy may be described by an array of geometrical objects arranged in space according to some statistical distribution. The interception and reflection of radiation are computed analytically from geometrical considerations. For these models, the overall radiance at any angle is calculated as a weighted average of the radiances from each component (usually, sunlit and shaded background and sunlit and shaded canopy).

This study presents a geometrical model that allows estimating the projected areas of the different components using parallel-ray geometry to describe the illumination of a three-dimensional vegetation element and the shadow it casts. The proposed model not only allows the correction of LST differences between sensors associated with their viewing geometries, but it is also an effective means for the validation of satellite-derived LST with ground-based measurements.

This type of geometric-optical model has been used by several authors to solve radiative transfer problems associated with surface heterogeneities related to vegetation (Franklin & Strahler, 1988; Lagouarde, Kerr, & Brunet, 1995; Li & Strahler, 1986, 1992; Ni, Li, Woodcock, Caetano, & Strahler, 1999; Strahler & Jupp, 1990), as well as in studies of surface temperature anisotropy (Minnis & Khaiyer, 2000; Pinheiro et al., 2006; Rasmussen et al., 2010; Guillevic et al., 2013). Instead of relying on a rigid analytical approach, the procedure developed here has the advantage of using a simple computational method to calculate the geometrical projections, while making very few a priori assumptions. The method consists of projecting a three-dimensional vegetation object onto a fine grid, which allows the use of any vegetation shape and size or the combination of different shapes and sizes.

The model is applied to in situ measurements of brightness temperature gathered at Évora validation site to obtain the ground temperature corresponding to any observation and illumination angles. The site is located in a region dominated by sparse canopies of evergreen oak trees (Southern Portugal; Kabsch, Olesen, & Prata, 2008). The resulting temperature is compared against LST data as obtained from the Spinning Enhanced Visible and Infrared Imager (SEVIRI) onboard Meteosat Second Generation (MSG) satellites (Trigo et al., 2011) and from the MODerate resolution Imaging Spectroradiometer (MODIS) onboard AQUA and TERRA (Salomonson, Barnes, & Masuoka, 2006). Finally, the geometric model is used together with in situ measurements to estimate and remove the LST differences between MSG and MODIS associated with the different viewing geometries.

2. Data and methods

This study concerns the validation of satellite LST products with in situ measurements collected at Évora validation site in Southern Portugal. The period under analysis spans from October 2011 to September 2012, although the data are limited to clear sky observations. All comparisons with ground data from Évora are for the LST estimations for the satellite pixel nearest to the station.

2.1. Satellite LST products

2.1.1. MSG/SEVIRI

The Satellite Application Facility for Land Surface Analysis (LSA-SAF) provides an LST product (Trigo et al., 2011) obtained with a generalized split-window algorithm (Freitas, Trigo, Bioucas-Dias, & Göttsche, 2010) from top-of-atmosphere brightness temperatures measured by MSG/SEVIRI in the thermal infrared, namely in SEVIRI channels IR10.8 and IR12.0. The LSA-SAF LST is produced at full SEVIRI spatial and temporal resolutions, with a 15 minute sampling interval and a spatial resolution of 3 km at the sub-satellite point, which degrades with increasing distance from nadir, reaching a size of about 16 km^2 over Portugal. The product is available for all land pixels within the Meteosat disk under clear sky conditions; the actual area coverage depends on product uncertainty (LST retrievals with error estimates above 4 °C are masked out) and can reach view zenith angles up to 70° (Freitas et al., 2010).

As described in Section 2.2, in situ measurements are available every minute and the temporal matching with SEVIRI observations accounts for the SEVIRI scanning delay, which for Évora corresponds to adding 10 min to the nominal image acquisition time (value taken from SEVIRI level 1.5 segments overlapping the site). Since SEVIRI is on a geostationary platform, its viewing geometry is fixed; over Évora, this corresponds to zenith and azimuth viewing angles of 45° and 166°, respectively.

2.1.2. MODIS

This study considers two LST products derived from MODIS: (i) level 3 daily LST obtained from AQUA (product MYD11A1, collection 5) and from TERRA platforms (product MOD11A1, collection 5), yielding a maximum of four clear sky observations per day (Wan, 2008) and referred to hereafter as MODSW LST; and (ii) a daytime LST and emissivity obtained through the application of the ASTER Temperature Emissivity Separation (TES) algorithm (Gillespie et al., 1998) recently adapted by Hulley, Hook, and Baldridge (2011) to MODIS bands 29, 31 and 32, referred to hereafter as MODTES LST. This product, slated for the MOD21 product slot, is expected to be released with MODIS Collection 6. The