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Modelling directional effects on remotely sensed land surface temperature

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ABSTRACT

Land surface temperature (LST) is a markedly directional variable and its remotely sensed measurement may be strongly affected by viewing and illumination geometries. This study proposes the use of LST products collocated in space and time, but obtained with different viewing angles, to calibrate a simple model capable of characterizing the LST angular variability. The exercise is performed using MODIS (Aqua and Terra) and SEVIRI (Meteosat) LST products, for an area covering Mediterranean Europe and Northern Africa and encompassing the full years of 2011, 2012, 2013 and 2014. The approach relies on a kernel model that is composed by an "emissivity kernel" and a "solar kernel", associated to observation angle anisotropy and to shadowing/sunlit effects on the surface, respectively. The spatial distribution of the kernel coefficients is shown to reflect characteristics of the landscape, both in terms of vegetation cover and topography. Model performance is assessed through several comparison exercises over the 4-year period under analysis. Cross-validation results show that the angular correction by the kernel model leads to a decrease of the root mean square difference between SEVIRI and MODIS daytime (night-time) LST products, from the original uncorrected values of 3.5 K (1.5 K) to 2.3 K (1.3 K). Comparison of both MSG and MODIS LST products against in situ daytime measurements gathered over 2 years at a validation site in Évora (Portugal) reveals that the angular correction leads to a decrease in root mean square error from 4.6 K (2.0 K) to 3.8 K (1.9 K) for MODIS (SEVIRI). The kernel model may be a useful tool to quantify the LST uncertainties associated with viewing and illumination angles.

1. Introduction

Land surface temperature (LST) is defined as the radiometric skin temperature over land that results from the energy balance at the surface (Norman and Becker, 1995). As a component of the surface radiation budget playing a relevant role in the partition between sensible and latent heat fluxes, LST is an important parameter for the diagnosis of surface conditions (e.g. Xu et al., 2011; Wang et al., 2014). Remote sensing observations constitute the most effective means to monitor LST over large areas and on a regular basis. Most satellite LST products rely on measurements in the thermal infrared (IR) atmospheric window, i.e. within the 8–13 μm range (e.g. Li et al., 2013). This band is particularly appropriate as it presents relatively weak atmospheric attenuation under clear sky conditions and includes the peak of the Earth's spectral radiance (considering surface temperature of the order of 290 K that leads to maximum emission at about 10 μm, according to Wien's displacement law).

Since estimates of LST from infrared satellite observations correspond to the radiometric temperature of the surface as seen within the sensor field of view (FOV), remotely sensed LST is a directional variable (Norman and Becker, 1995). Given the high spatial heterogeneity of land surface, such directionality may lead to significant differences among LST products obtained for the same area and observation time, but with different viewing geometries (Lagouarde et al., 2000, 2004; Pinheiro et al., 2004, 2006; Barroso et al., 2005; Trigo et al., 2008; Ermida et al., 2014; Duffour et al., 2015). This effect contributes to enhance the differences among LST satellite products, and therefore increasing the challenge of using multi-sensor and multi-decadal data to provide harmonized LST datasets suitable for long-term climate observations. Accurate estimates of the angular effects on retrieved LST are also crucial when performing in situ and cross-sensor validation exercises (Ermida et al., 2014). Quantification of these effects may also be relevant when using LST for model assessment (e.g. Wang et al., 2014; Trigo et al., 2015) and data assimilation (e.g. English, 2008; Ghent et al., 2010).

The impact of the viewing geometry on LST estimations is related to a large extent with contrasts in the radiometric temperature of the various surface elements. In savannah-like landscapes, the measured

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difference between tree canopy and sunlit background during the dry season may reach over 20 K (Rasmussen et al., 2011; Ermida et al., 2014). Other factors such as orography or emissivity anisotropy may also play an important role (Trigo et al., 2008). The angular dependency of satellite observed LST should therefore be taken into account when combining LST products retrieved by different sensors, e.g., in order to obtain a harmonized variable.

There are several modelling studies of LST angular dependence (Minnis and Khaiyer, 2000; Pinheiro et al., 2006; Rasmussen et al., 2010; Guillevic et al., 2013; Ermida et al., 2014; Duffour et al., 2015). However, the complexity of the processes associated to this dependence leads to physical models with a large number of time and space dependent parameters describing surface and vegetation properties, which makes their application difficult over large areas or long time-periods. Vinnikov et al. (2012) proposed a simple statistical model of angular anisotropy of LST that may be calibrated using collocated multi-sensor observations. The model follows a "kernel" approach commonly used for the description of the Bidirectional Reflectance Distribution function (BRDF) in the visible band (e.g. Jupp, 2000). The adequate characterization of the LST dependence on viewing and illumination angles could be useful to estimate the expected deviations of any given LST retrieval with respect to a reference view angle (e.g. nadir), and ultimately for the derivation of a directionally independent equivalent physical temperature, adequate to climate studies (Vinnikov et al., 2012).

Here we describe a feasibility study with the objective of assessing whether the kernel model proposed by Vinnikov et al. (2012) may be used to model the angular dependency of LST products using multi-sensor observations. For this purpose, the kernel model is applied to LST from sensors on board geostationary and polar-orbit platforms obtained over a large area covering Mediterranean Europe and over a multi-year time period. The model is evaluated for landscape-level thermal LST directionality, including vegetation and land cover-induced impacts as well as topographic effects. A description of the model is given in Section 3, which also includes information on the LST products considered and the description of the model calibration/verification strategy. The model is then calibrated, verified and validated using LST data as obtained from the Spinning Enhanced Visible and Infrared Imager (SEVIRI) on-board Meteosat Second Generation (MSG) satellites (Trigo et al., 2011) and from the MODerate resolution Imaging Spectroradiometer (MODIS) on-board Aqua and Terra (Salomonson et al., 2006). The model performance is also assessed by comparing both SEVIRI and MODIS LST products against in situ measurements of LST obtained at a validation site in Évora, Portugal. Results are discussed in Section 4 and the main findings are summarized in Section 5.

2. Data

Encompassing Mediterranean Europe, the study area is defined as the region between the latitude circles of 34.5° and 45.8°N and between the meridians of 12.4°W and 30°E (Fig. 1). The region is covered by very heterogeneous vegetation, ranging from dense to sparse forest, cultivated areas and shrubland (Fig. 1).

2.1. Satellite LST data

The kernel model was applied to satellite-observed LST obtained from two sensors: 1) the LST product retrieved from SEVIRI on-board MSG satellites provided by the EUMETSAT Satellite Application Facility on Land Surface Analysis (LSA-SAF) (Trigo et al., 2011); and 2) level 2 daily LST obtained from MODIS on-board Aqua (product MYD11, collection 5) and Terra (product MOD11, collection 5) (Wan and Li, 2008). SEVIRI and MODIS LST for the whole area of study were obtained from the GlobTemperature portal (http://data.globtemperature.info/), which provides LST data in a standardized format, facilitating collocation in space and time and organization of needed auxiliary variables (including viewing geometry and sun angles).

The LSA-SAF LST is estimated with a generalized split-window algorithm (Freitas et al., 2010) from top-of-atmosphere brightness temperatures measured by MSG/SEVIRI in the thermal infrared, namely in SEVIRI channels IR10.8 and IR12.0. It 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 4 km over Southern Europe. 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 uncertainty estimates above 4 K are masked out) and can reach view zenith angles up to 70° (Freitas et al., 2010). According to Göttsche et al. (2016), comparisons with four LSA SAF dedicated stations resulted in a mean absolute bias of SEVIRI LST of 0.1 K, with daytime and night-time biases up to 0.7 K (but with opposite signs). Land Surface Emissivity (LSE) used by the LSA SAF in the derivation of LST is estimated with the Vegetation Cover Method (Caselles and Sobrino, 1989; Peres and DaCamara, 2005; Trigo et al., 2008). The method allows the determination of effective LSE as the weighted average of the emissivities of the dominant bare ground and vegetation type within a scene, using daily values of Fraction of Vegetation Cover (FVC) to obtain the respective weights. Emissivity values for vegetation and soil types were obtained from the

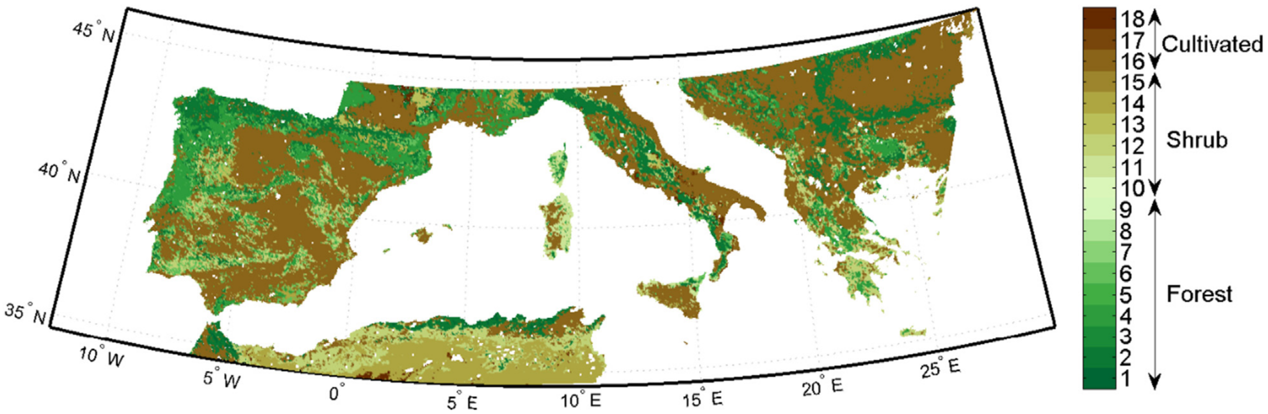

Fig. 1. Land cover classification according to GLC2000. Values of the colorbar correspond to GLC2000 labels. A detailed description may be found in http://bioval.jrc.ec.europa.eu/products/glc2000/legend.php. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)