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A two parameter model to simulate thermal infrared directional effects for remote sensing applications

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ABSTRACT

Measurements of land surface temperature (LST) performed in the thermal infrared (TIR) domain are prone to strong directional anisotropy. Instead of detailed analytical physical TIR models requiring too much input information and computational capacities, simplified parametric approaches capable to mimic and correct with precision the angular effects on LST will be deemed suitable for practical satellite applications. In this study, we present a simple two parameters model, so-called RL (Roujean-Lagouarde), which shows capabilities to properly depict the directional signatures of both urban and vegetation targets within an accuracy better than 1 °C. This latter value is the RMSE (root mean square error) obtained as the best adjustment of the RL model against in situ datasets. Then the RL approach was compared to a synthetic dataset generated by the model Soil Canopy Observation, Photochemistry and Energy fluxes (SCOPE) in which large variability in meteorological scenarios, canopy structure and water status conditions was accounted for. Results indicate RMSE ≤0.6 °C which is a very hopeful result. Besides, the RL model performs even better than the popular parametric model of Vinnikov that encompasses two unknowns. The ability of RL model to better reproduce the hotspot phenomenon explains this feature.

The RL model appears as a potential candidate for future operational processing chains of TIR satellite data because it fulfills the requirements of both simple analytical formulation and limited number of input parameters. Efforts nevertheless remain to be done on inversion methodologies.

1. Introduction

Thermal infrared (TIR) measurements are widely used to retrieve land surface temperature (LST) which is a useful proxy to derive surface fluxes, especially evapotranspiration. However these measurements are prone to strong directional anisotropic effects. Those can be defined as the difference between off-nadir and nadir temperatures. Such difference can reach up to 15 °C according to various authors (Kimes and Kirchner, 1983; Lagouarde et al., 2014).

Efforts have been made in the past to model the TIR radiation anisotropy in following geometric, radiative transfer, 3-dimensional and parametric approaches. A review can be found in Verhoef et al. (2007). Duffour et al. (2015b) recently demonstrated the ability of the Soil-Vegetation-Atmosphere Transfer (SVAT) model SCOPE (Van der Tol et al., 2009) which combines a detailed description of both physical and physiological processes to simulate TIR directional anisotropy. Actually, TIR data processing is in need of simple models for several purposes. First reason is to be able to correct TIR remote sensing data from directional effects using a fast and computationally efficient method. For such, one must only consider algorithms (i) requiring a few input data and (ii) being analytically interpretable for ease of implementation into operational satellite data processing chains. Secondly, simple models are very helpful for a rapid assessment of the impact of the angular sampling, which is particularly relevant for the design of experimental campaigns with the concern of optimizing the instrumental protocol.

Simple parametric models are attractive in many ways. Because of their limited number of input parameters, the inversion procedure is more certain. Another asset is that they can be relevant at any spatial scale, in particular when linearity of the model is possible. Moreover, parametric models may be more robust to measurement noise compared to deterministic models which are affected by the cumulative uncertainties of the large input datasets they require. Parametric models can be totally empirical or based on physical assumptions. Although parametric models are widely used to correct optical BRDF (Bi-directional Reflectance Distribution Function), such an approach has not yet been developed so far to process and analyze TIR data. One limitation however would be the prescription of a priori values for the input parameters, unless their physical meaning may be well determined through field experiments for instance.

When approaching TIR satellite measurements through modeling, a primary assumption is that any sensor pixel is the sum of dissociated elementary photometric quantities. These latter can be further modeled

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as a linear combination of mathematical functions sketched by kernels being trigonometric functions of the geometry of observation. In the optical domain, the kernel approach has been successful to mimic the BRDF (Wanner et al., 1995; Jupp, 2000; Bréon et al., 2002; Vermote et al., 2009). In the TIR domain, it has been applied to simulate the directional anisotropy of surface emissivity (Snyder and Wan, 1998; Su et al., 2002). In order to model the radiation anisotropy on TIR signal and further on temperature from geostationary satellites observations, Vinnikov et al. (2012) developed a parametric model of TIR anisotropy based on only two kernels.

Generally speaking, the solution to the inverse problem may be obtained by generating first Look Up Tables (LUTs) issued from simulations of a sophisticated TIR model, at the cost of some training for initiate some machine learning. Even so, and to our knowledge, this possibility has not been evaluated yet in the TIR domain. However, in the context of remote sensing applications, the robustness of the solution is indeed a real concern in order to comply with possibly noisy and sparse observations.

This justifies for another approach here consisting in the derivation of analytical expressions departing from simplified assumptions on the physics. For instance Roujean (2000) and Bréon et al. (2002) have proposed two models of hot spot simplifying the radiative transfer processes inside canopies for optical remote sensing applications. In the TIR, Lagouarde and Irvine (2008) adapted the Roujean (2000) model to derive a parametric expression of directional anisotropy requiring two parameters only to be known or adjusted. A first favorable test was obtained against experimental measurements acquired over an urban canopy. The simplicity of the model makes it very attractive to characterize the directional anisotropy.

Nevertheless it still requires to be extensively evaluated. Such is the goal of this paper. In a first section, the model will be described and its ability to simulate DA over vegetation demonstrated. The scarcity of available experimental DA datasets providing both azimuth and zenith angular information led us to assess the reliability of the model in a second step by testing it against a synthetic dataset generated by a deterministic model, SCOPE. Here, SCOPE is used as a data generator, for a large range of realistic conditions that can be met: structure of the canopy, water status, meteorological forcing. A third section finally proposes a comparison with the Vinnikov's approach which was considered to correct satellite data for DA effects. Since to our knowledge, Vinnikov's model has no equivalent so far, the mutual assets of both approaches for remote sensing applications are further discussed.

2. The parametric RL model

2.1. Analytical formulation

The RL model has been adapted from the reflectance model proposed by Roujean (2000) by replacing the reflectance (see expression 25 in Roujean's paper) by the surface temperature. To obey the definition of anisotropy we have adopted (i.e. difference between off-nadir and nadir temperatures), the nadir temperature (T_N) is introduced which leads to the following expression (see Eq. 1 in Lagouarde and Irvine, 2008):

$$T(\theta_s,\theta_v,\varphi)-T_N=(T_{HS}-T_N)\frac{[exp(-kf)-exp(-kf_N)]}{[exp(-kf_{HS})-exp(-kf_N)]} \tag{1}$$

The difference $T(\theta_s,\theta_v,\varphi)-T_N$ (called ΔT) sizes the anisotropy for given zenith viewing angle (θ_v) and viewing azimuth (φ_v). The difference ($T_{HS}-T_N$) (called ΔT_{HS}) is the anisotropy in the hot spot geometry (the subscript HS stands for Hot Spot). θ_s is the solar zenith angle, and φ the relative azimuth between Sun (φ_s) and observer (φ_v). It is worth reminding that what is referred to as ‘hot spot’ here corresponds to the highest values of brightness temperature obtained when the viewing direction coincides with the Sun direction (Sun being backward): this is related to the fact that in the exact Sun direction, the target displays only sunlit elements which are also the warmest ones. When the viewing direction departs from the Sun one, more and more shaded elements can be seen by the sensor and contribute to decrease the measured directional temperature. Therefore both hot spot in the thermal and in the visible/near (VNIR) infrared spectral ranges are associated to the same geometric configuration though somewhat different physical meanings may arise. In the VNIR the directional anisotropy is governed mainly by the radiative transfer processes within the canopy. In the TIR domain the coupled energy transfers are further added to the physics of DA. Indeed, these latter govern the vertical profile of the surface temperature within the canopy according to its attributes (leaf elements, stems, whorls, etc.) seen by the sensor, possibly down to the soil. This explains the dependence of TIR DA with all factors governing the energy exchanges: canopy structure (for radiation, but also wind penetration), meteorological forcing, water availability for soil evaporation and plant transpiration. In addition, thermal inertia effects could also affect the TIR directional anisotropy. At the opposite to urban canopies where a small bias of hotspot position *versus* Sun angles is observed (e.g., Lagouarde et al., 2010), there is no significant impact for vegetation canopies. Worth mentioning that we only treat herein the case of reference of a turbid vegetation canopy. In fact, it was already the case of the urban canopy for which Eq. (1) was originally derived. Besides, we shall examine its applicability for vegetation in what follows. The case of discrete incomplete canopies such as savannahs for instance (Pinheiro et al., 2006), sparse vegetation (Kabsch et al., 2008; Guillevic et al., 2013) or even row crops (such as vineyards, see Lagouarde et al., 2014) for which TIR directional anisotropy displays different patterns will not be investigated here.

The function *f* measures the angular distance between the directions of the sun beam and the observer. It is defined as:

$$f=\sqrt{tan^2\theta_s+tan^2\theta_v-2\,tan\theta_s\,tan\theta_v cos\varphi} \tag{2}$$

At nadir ($\theta_v=0$) *f* takes the value $f_N=\tan\theta_s$ while in hotspot geometry ($\theta_v=\theta_s$ and $\varphi=0$) $f_{HS}=0$. Thus Eq. 1 can be rewritten as:

$$\Delta T(\theta_s,\theta_v,\varphi)=\Delta T_{HS}\frac{[exp(-kf)-exp(-ktan\theta_s)]}{[1-exp(-ktan\theta_s)]} \tag{3}$$

In what follows ΔT_{HS} and k are considered to be the two parameters of the model.

Fig. 1 is provided to illustrate the potential of analytical expression (3) to describe the anisotropy, with arbitrary prescribed values $k=0.1$ and 2 and $\Delta T_{HS}=1$ °C and 3 °C, and with a Sun position ($\varphi_s=210°$, $\theta_s=25°$) corresponding to an acquisition time in early afternoon. The parameters k and ΔT_{HS} have here been chosen only to provide a realistic range of anisotropy values. Fig. 1a first shows the directional anisotropy (grey-color coded) simulated by RL (with $k=2$ and $\Delta T_{HS}=3$ °C). A polar plot representation is adopted here (see Lagouarde et al., 2010). It indicates the viewing direction (relative to the observer position): the radii are oriented according to the azimuth view angle φ_v, and concentric circles correspond to zenith view angles θ_v. A way of easily figuring this representation is to imagine a hypothetic observer placed on the vertical axis passing through the centre of the polar plot and looking at the surface in the directions corresponding to those of the polar plot. For instance, if this observer looks towards N-NE ($\varphi_v=30°$, with a zenith view angle $\theta_v=25°$, a maximum of anisotropy will be catched. This is explained by the fact the canopy elements therefore seen are those directly facing the Sun. They form the warmest elements because they only concentrate the contribution of the direct radiation beam impinging the surface. The maximum anisotropy effect obtained when viewing the surface in the exact Sun direction, with the Sun in the back, is referred to as ‘hot spot’. The Sun position is also indicated in Fig. 1a by a white cross occupying a position opposite to the hot