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An evaluation of SCOPE: A tool to simulate the directional anisotropy of satellite-measured surface temperatures

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ABSTRACT

This study assesses the performance of the SCOPE model (Van der Tol et al., 2009) to reproduce directional anisotropy of remote sensing thermal infrared measurements. A calibration/validation exercise over two datasets (winter wheat and young pine stand) on energy balance fluxes is presented. Surface sensible and latent heat fluxes are correctly simulated (with RMSE in the range of 30–50 $W \cdot m^{-2}$) together with directional temperatures in 4 different viewing geometries (RMSE < 1.4 K) for both canopies. The sensitivity of the model to two critical but uncertain parameters, the maximum carboxylation capacity V_{cmo}, and a stomatal parameter λ (the marginal water cost of carbon assimilation) is discussed; it is shown that anisotropy displays limited sensitivity to both parameters for the experimental conditions met over a well-watered wheat field. The ability of SCOPE to simulate anisotropy is finally illustrated by a qualitative comparison against experimental measurements obtained over a mature pine stand using an airborne TIR camera. SCOPE-simulated TIR directional anisotropy appears to be consistent with the experimental data.

1. Introduction

Thermal infrared (TIR) satellite data represent an essential source of information to estimate surface fluxes with the scope of monitoring agro-ecosystems and assessing their water status, a large range of applications being found in the fields of agriculture, hydrology and meteorology particularly. However TIR measurements are prone to strong directional anisotropy (we define it as the difference between off-nadir and nadir temperature measurements) and 'hot spot' effects possibly reaching up to 10 °C and even more in the case of row crops such as vineyards (Lagouarde, Dayau, Moreau, & Guyon, 2014). The experimental evidence of TIR directional anisotropy has widely been reported on various surface types, vegetation (Balick & Hutchinson, 1986; Fuchs & Kanemasu, 1967; Kimes & Kirchner, 1983; Lagouarde, Ballans, Moreau, Guyon, & Coraboeuf, 1995, 2000; Lagouarde, Kerr, & Brunet, 1995; Luquet, Bégué, Vidal, Clouvel, et al., 2003; Nielsen, Clawson, & Blad, 1984; Paw, Ustin, & Zhang, 1989) or urban areas for instance (Lagouarde et al., 2012; Voogt & Oke, 1998). Modeling efforts briefly discussed below have been developed in parallel. Practical applications based on TIR remotely sensed data obviously require the anisotropy to be assessed and corrected.

Efforts are currently being made to propose new missions combining high spatial resolution (<100 m) and high revisit capacities (a few days) such as MISTIGRI (Lagouarde et al., 2013a), HyspIRI (Abrams & Hook, 2013) or the forthcoming THIRSTY project developed in cooperation between NASA in the USA and the France space agency CNES (Crebassol et al., 2014). In this context the data processing algorithms adapted to these missions must be prepared from now on. The Sun-synchronous orbits of MISTIGRI and THIRSTY have been conceived to allow observing the same site at ground with the same viewing geometry. This minimizes the impacts of directional anisotropy, at least for temporal analysis purposes at a given location, although it cannot eliminate the contribution related to the variations of solar position throughout the year. An accurate assessment of the anisotropy nevertheless remains mandatory as soon as one wants to analyze energy balance or map evapotranspiration across the swath of the image or to compare different fields at regional, because of differences in viewing geometry depending on their location, to which differences in time, i.e. sun position, may add as a result of a swath width reaching about 900 km with THIRSTY.

Another motivation lies in activities of calibration/validation of satellite data and products. Indeed in-situ measurements are often performed using infrared radiometers aiming at a surface sample which size — generally a few meters — is chosen to take into account the small scale spatial variability of the sample, and to retrieve a temperature measurement considered to be 'representative' of the studied

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surface. Nevertheless anisotropy complicates direct comparison of in-situ measurements to satellite data because (i) experimental setups are generally not designed to perform measurements in the same viewing direction as the satellite, and because (ii) the radiometer operates an integration of several directional temperatures within its FOV (field of view) whereas the space sensor 'sees' the surface in a unique direction. Cal/val exercises should therefore rely on accurate models of TIR directional anisotropy.

Today no operational method is available to correct for directional anisotropy in the processing of surface temperature products (level 2 or more). A number of approaches have nevertheless been proposed to simulate directional temperatures over different surface types. They require as input data too many pieces of information not easily accessible by remote sensing and/or parameters requiring specific calibration. Indeed, similarly to the surface temperature, the directional anisotropy results from the coupled energy and radiative transfers within the canopies and depends on a lot of factors: the canopy structure governs the distribution of sunlit (i.e. warmer) and shaded (i.e. colder) elements seen by the sensor in a given direction, but it also governs through energy transfers the temperature profiles within the vegetation or on the facets of discontinuous or row crops; the water status and some physiological parameters are also a critical factor (Fuchs & Tanner, 1966), and meteorological conditions, wind speed in particular, play a significant role not yet enough documented to our knowledge. Some models have been developed with the objectives of retrieving the component temperatures of the canopies from directional measurements either using simple geometrical descriptions of the canopies, for instance for row crops (Caselles & Sobrino, 1989; Kimes, 1983) or homogeneous canopies (Olioso, 1992; Timmermans, Verhoef, van der Tol, & Su, 2009). More sophisticated approaches based either on multilayer models or 3D-models were developed to better describe the processes governing directional temperatures and emissivity and to perform sensitivity studies (Guillevic, 2003; Luquet et al., 2004; Norman, 1979; Van der Tol et al., 2009).

Only few authors focused on the correction of satellite data. Pinheiro, Privette, Mahoney, and Tucker (2004) showed that the observation geometry of the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) implies directional effects which can be related to fraction cover of shaded and sunlit elements of the scene. Rasmussen, Gottsche, Olesen, and Sandholt (2011) compared the Meteosat Second Generation observation geometry to nadir view over savannas and they found differences larger than 1 °C during the day, which cannot be neglected. Guillevic et al. (2013) put into evidence the difficulty of the comparison of different satellite LST products because of the effects of anisotropy.

In this framework it appears necessary to develop simple methods adapted to the routine processing of data from space. These could be statistical approaches such as kernel models (Snyder and Wan, 1998). All of them require important volumes of reliable anisotropy data to be available to be built and calibrated. Experimental data are too scarce and limited to only a few surfaces and conditions to be used for this purpose. An alternative approach can be based on a robust deterministic model helping in a first step to identify the variables and surface parameters to which the directional anisotropy displays the highest sensitivity, and in a second step used as a data generator to derive and calibrate simpler methods. The paper focuses on the first step and is based on the SCOPE (Soil Canopy Observation, Photochemistry and Energy fluxes) model (Van der Tol et al., 2009) developed for continuous vegetation. This was selected both for its realism confirmed in several previous studies where it was used for its ability to simulate energy fluxes (Denis, 2013; Timmermans et al., 2011) or chlorophyll fluorescence (Lee et al., 2013) and for its interest for remote sensing applications as it includes a detailed modeling of the coupled energy and radiative transfer within the vegetation, and derives up to the outgoing radiances in a large range of wavelengths. After a brief description of the model, an evaluation of the model against field data will be presented. Its potential for simulating the directional anisotropy in a wide range of viewing geometries will finally be illustrated, and the perspectives opened to develop operational methods of directional effects correction will be discussed.

2. SCOPE (soil canopy observation of photochemistry and energy fluxes)

The SCOPE model (Van der Tol et al., 2009) was developed for the combined simulation of directional TOC (Top Of Canopy) reflected solar radiation, emitted thermal radiation and sun-induced fluorescence signals together with energy, water and CO_2 fluxes. It is based on a combination of several models describing radiative, turbulent and mass transfers inside the canopy, taking into account leaf biochemistry processes. The main features of the model are briefly recalled here, and for more details, the reader is referred to the original paper.

Considering radiative transfer calculations, the scene is described with 60 canopy layers of equal leaf area, and one soil layer. In each of them, discrimination is made between shaded and sunlit parts (leaves or soil). The orientations of leaves are characterized with 13 zenithal (θ_l) and 36 azimuthal angles (φ_l). The leaf angle distribution function of θ_l depends on the vegetation type. The unified 4SAIL model (Verhoef, Jia, Xiao, & Su, 2007) allows to compute extinction coefficients and to derive gap fractions. The radiative transfer is computed on the 0.4–50 μm range of wavelengths.

An energy budget is solved separately for sunlit and shaded parts of each layer; an iterative process with a convergence criterion on the residual of the energy budget allows computing the corresponding surface temperatures. The net radiation R_n is computed by combining the components of incident radiation (shortwave and longwave) together with the 4SAIL derived optical and thermal contributions with the Stefan–Boltzmann emittance within the layer. In the thermal infrared domain, uniform emissivity values are prescribed for the vegetation and the soil. The PROSPECT model (Jacquemoud & Baret, 1990) allows computing the optical properties of vegetation (transmittance and reflectance spectra), which require several characteristics of leaves to be known, such as their chlorophyll (C_{ab}), dry material (C_{dm}), water (C_w) and senescent material concentrations and thickness parameter (N). Directly measured spectra can also be used as an alternative. The same spectrum is used for all leaves, independently of their position in the canopy. A soil reflectance spectrum must also be prescribed.

The sensible (H) and latent (LE) heat fluxes are classically calculated for each layer, and for shaded and sunlit leaves (resp. soil), from the vertical gradients of temperature and humidity between the considered layer and the reference level of meteorological measurements above the canopy. The net leaf CO_2 assimilation rate A is computed simultaneously from Farquhar, von Caemmerer, and Berry (1980). The aerodynamic resistance is taken from Wallace and Verhoef (2000). An aerodynamic resistance is calculated for the soil and for the canopy each time step as a function of LAI, canopy height, wind speed and atmospheric stability. This resistance holds for all leaves (no differentiation is made according to position of a leaf in the canopy). The stomatal resistance (r_s) is calculated after Cowan (1977) and requires some biochemical parameters to be known (the stomatal resistance formulation has been modified in a later version of SCOPE, but we use the original published model, see Van der Tol's paper for details).

In what follows (Section 4), a particular attention will be paid to two of these, the maximum of carboxylation (V_{cmo}) and marginal cost of assimilation (λ), which control the photosynthetic capacity and describe the compromise between the loss of water by transpiration and uptake of CO_2 through stomatal cavities respectively. At the ground level, a storage heat flux G is estimated as the residual of the energy budget equations for shaded and sunlit soil, and the corresponding surface temperatures are computed using a classic force-restore approach (Bhumralkar, 1975), with soil surface resistance and thermal inertia either computed from water content or prescribed.