Remote Sensing of Environment 177 (2016) 248–264

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Driving factors of the directional variability of thermal infrared signal in temperate regions

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ARTICLE INFO

Article history:
Received 29 July 2015
Received in revised form 27 January 2016
Accepted 11 February 2016
Available online 3 March 2016

Keywords:
Thermal infrared remote sensing
Land surface temperature
Directional anisotropy
SCOPE

ABSTRACT

Land surface temperature (LST) is a good indicator of the land surface state. The measurement of LST is however prone to directional anisotropy which may severely affect the interpretation of the measurements if it is not corrected.

This study aims at determining and describing the impact of various factors on anisotropy of continuous crops at mid-latitudes.

The SCOPE (Soil Canopy Observation, Photochemistry and Energy fluxes) model is used as a data generator of directional anisotropy since it enables exploring a very large range of meteorological, biochemical and geometrical conditions. An original indicator, the standard deviation of anisotropy in principal plane, is used in order to investigate the impact of the tested variables and parameters.

We found that anisotropy is, at first order, related to seasonal trends, in relation to the amount of incident radiation and the solar zenith angle. Then the geometrical structure of the canopy modifies the anisotropy (LAI, LADF, hot spot parameter) followed by the coupling between the water status of the soil and the stress of canopy. Wind speed which is known for having a significant impact on temperature level has a very limited influence on anisotropy.

An analysis of the amplitude of anisotropy in the principal and perpendicular planes (from −50° to 50° zenith) showed that anisotropy can reach up to 11 °C and ~3.5 °C respectively.

The impact of satellite orbit on anisotropy is also discussed and it is found that, given the latitudes and the season, the anisotropy can severely affect measurements. This is particularly true when the satellite measurements are acquired in a configuration close to the solar principal plane, which often occur at low latitude.

These results are of great help in the context of developing simple methods which could then be integrated into satellite data processing algorithms.

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1. Introduction

The surface temperature (Ts) measured from space is a key variable to estimate the surface energy fluxes at the landscape scale. The accuracy of the retrieved fluxes is tightly related to the accuracy of Ts measurements. For instance Norman, Divakarla, & Goel, 1995 report that an error of 1 °C in Ts can lead to errors up to ~100 $W \cdot m^{-2}$ in the retrieval of the sensible heat flux. Much work has been done on the correction of satellite Thermal Infrared (TIR) measurements from atmospheric effects and several algorithms have been proposed (single channel - Price, 1983, multi-channel (split window) - Becker & Li, 1990; Prata, 1993; Wan & Dozier, 1996, multi-angle methods - Sobrino, Li, Stoll, & Becker, 1996; Sobrino & Soria, 2004). Attention has also been paid to the 'temperature emissivity separation' problem (Gillespie et al., 1998; Schmugge, French, Ritchie, Rango, & Pelgrum, 2002; Hulley & Hook, 2011; Jiménez-Muñoz, Sobrino, Mattar, Hulley, & Gottsche, 2014). However, a better understanding of directional effects of TIR measurements is still needed. This is obvious for instruments currently operating aboard polar orbiting missions such as MODIS on TERRA and AQUA satellites or VIIRS on SUOMI NPP, for which the across-track scan angle reaches up to ±55°. This also remains true for missions under preparation which target high spatial resolution, with scan angles of about ±35° for THIRSTY (Thermal InfraRed Spatial sYstem, Crebassol, Lagouarde, & Hook, 2014) or ±25.5° for HyspIRI (http://hyspiri.jpl.nasa.gov/) and ECOSTRESS (ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station — http://science.nasa.gov/missions/ecostress/) and for agile off-nadir pointing satellites such as MISTIGRI (Lagouarde et al.,

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http://dx.doi.org/10.1016/j.rse.2016.02.024
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2013). In addition, no simple data processing algorithm to correct measurements for directional effects is available today.

The surface temperature directional anisotropy (simply referred to as DA in what follows), here defined as the difference between off-nadir and nadir surface temperature measurements, can reach several degrees as reported in the literature (Paw U, Ustin, & Zhang, 1989; Lagouarde, Kerr, & Brunet, 1995; Voogt & Oke, 1998), with important hot spot effects.

Many factors have a key impact on the anisotropy. In a first step, it is important to keep in mind that a directional measurement of surface temperature results from the integration of the temperatures of the facets seen by the sensor within the canopy and at the soil surface. As a consequence it highly depends on the temperature profile within the canopies, and on the geometrical structure of canopies which governs both the radiative and energy transfers inside the vegetation and the radiative energy reaching the soil surface. The meteorological forcing and vegetation water status also act together through the energy transfer. Solar radiation being a major determinant of radiative transfer, the directional anisotropy obviously depends on the date and time of the measurements. Through all these processes, the properties of soil and vegetation (i.e. reflectances, resistance to water transfer) also contribute to anisotropy.

A literature survey reveals that either the experimental or the modelling studies performed up to now were generally focusing on the relationship between directional Ts and only a limited number of factors. Despite the study of Huang, Liu, Qin, Du, & Li, 2011, no synthetic results on the combined effects on anisotropy of all other factors abovementioned can be found. Indeed much experimental research has been performed since the 60s (Fuchs, Kanemasu, Kerr, & Tanner, 1967) at the field scale, often motivated by the goal of determining the water stress of crops. For instance Jackson, Reginato, & Idso, 1977 discussed the ability of oblique measurements performed with handheld TIR radiometers to discriminate the contributions of soil and vegetation to evapotranspiration. A particular attention has been paid to the case of row crops which shows very important anisotropy effects, up to 10 K, for instance over cotton (Kimes & Kirchner, 1983) or orange groves (Caselles, Sobrino, & Coll, 1992).

Several modeling approaches to simulate the directional Ts have been proposed. For instance, Olioso, 1992 developed a combined radiative transfer–energy balance model that simulates directional temperatures from calculated leaf and soil temperatures. The radiative transfer formulation was adapted from the SAIL radiative transfer model developed by Verhoef, 1984 for the simulation of spectral reflectances (Olioso, 1995; Olioso et al., 1999). Differences in directional temperatures (nadir vs. 45°) up to 3 °C were computed for a grass canopy depending on LAI (Leaf Area Index) and LADF (Leaf Angle Distribution Function). This model was latter used for inverting evapotranspiration from directional TIR signals (Olioso et al., 1999). Francois, Ottle, & Prevot, 1997 tried to retrieve leaf and soil temperatures from two directional measurements, using a parametric model developed from the results of a multilayer canopy radiative transfer model (Prévot, 1985). The parameters and variables tested in this study were the leaf area index (LAI), zenith angle of observation (0° and 55°) and emissivities of soil and vegetation. The latter were found to play a negligible role in resulting directional radiances, contrary to zenith angle observation and LAI. Nevertheless this study did not integrate the impact of other critical parameters and variables such as soil moisture, vegetation water stress, angular inclination and distribution of leaves. Both studies Olioso (1992) and Francois et al. (1997) did not represent the distribution of sunlit and shaded leaf temperatures within the canopy which was a major driver of temperature anisotropy. The hot spot was not simulated either. Improvements were brought using 3D canopy models that were able to represent better the distribution of temperatures inside of the canopy and at the soil surface (Smith, Pedelty, Ballard, & Schmugge, 1997; Guillevic, Gastellu-Etchegorry, Demarty, & Prévot, 2003; Luquet et al., 2004; Lagouarde et al., 2010). Luquet et al., 2003 evaluated the interest of directional surface temperatures to characterize the water status of a cotton crop. Huang, Liu, & Qin, 2010 coupled the 3D Thermal Radiosity Graphics Model (TRGM) and an extended energy balance model CUPID to simulate the seasonal and daily variation of directional brightness temperature of wheat canopies. This study focused on the impact of LAI, row widths and orientation, leaf size, and azimuth viewing angle on the hot spot shape and confirmed previous results (Jackson, Reginato, Pinter, & Idso, 1979; Kimes, 1983; Sobrino & Caselles, 1990; Caselles et al., 1992; Yu et al., 2004). By coupling again TRGM and CUPID, Huang et al., 2011 proposed a fast sensitivity analysis of the factors affecting thermal emission directionality of crop canopies aiming at better understanding the temporal variations of temperature of the heterogeneous crop canopies. The authors found that global radiation, LAI and soil moisture are the main factors affecting the directional effects in the TIR while the impact of the wind speed is less critical. In this same study two indicators adapted to MODIS and ATSR instruments were used: the average and the standard deviation of the anisotropy for a unique zenith viewing angle 55° and merging all azimuth viewing directions.

A correct assessment of TIR DA and of the factors to which it displays more sensitivity is required for several purposes, for instance evaluating the quality of experimental data, or providing guidelines for the design of future spatial missions (such as the trade-offs orbit/coverage/scan angle, etc...). Constructing simplified correction algorithms to be integrated in the ground segment dedicated to the processing of data from space also requires knowledge about the relative weight of the different factors affecting DA. To address this, the goal of our paper is threefold:

1. Evaluate the respective impacts, and interactions, of the ensemble of factors governing the directional anisotropy in the thermal infrared domain over continuous vegetation canopies.
2. Document the orders of magnitude of anisotropy that might occur,
3. Provide an analysis of the influence of anisotropy on satellite measurements (in the specifications of the THIRSTY mission).

We based our analysis on a simulation approach using a deterministic model as a data generator. Such a method allows -provided the model is robust enough- to test a very large range of cases which can practically be met, and to easily discriminate the prevailing key factors which govern DA. An experimental approach obviously cannot be an alternative here because of the number of cases to be investigated and of the cost of measurements possibly requiring airborne campaigns if one wants to describe DA in all zenith and azimuth viewing configurations (Lagouarde, Ballans, Moreau, Guyon, & Coraboeuf, 2000). Moreover literature already provides a number of experimental data, which suffice to check the consistency of the simulation exercises, before generalization by an extensive simulation work.

This was done using the deterministic model SCOPE (Soil Canopy Observation, Photochemistry and Energy fluxes - Van der Tol, Verhoef, Timmermans, Verhoef, & Su, 2009), owing to its ability to simulate TIR anisotropy as demonstrated by Duffour, Olioso, Demarty, Van der Tol, & Lagouarde, 2015. The model was used to generate large data sets from inputs varying in realistic ranges of values. The SCOPE model will be briefly described. Based on a synthetic statistical criterion which will be justified, the sensitivity of each of the input factors will be analyzed and their relative weight on anisotropy discussed.

2. Material & methods

2.1. Approach

We generated TIR anisotropy data by using the SCOPE model, a Soil-Vegetation-Atmosphere Transfer (SVAT) model that solved the energy balance of leaf layers in the vegetation and at the soil surface providing a detailed distribution of leaf surface temperatures as a function of canopy depth, leaf inclination and incident radiation at the leaf surface. The SCOPE model is described in the next section. The range

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