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Modeling thermal infrared directional anisotropy over a mature pine forest

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ABSTRACT - *Thermal infrared (TIR) remote sensing measurements are prone to important directional effects that need to be characterized and quantified. Over forest areas, the tree crown architecture plays a significant role, because it influences the distribution of the surface temperatures of the different elements within the tree canopy and the understory that are seen by a sensor. In the present study we model the TIR directional anisotropy over a mature Maritime pine stand, by combining a 3D canopy architecture model with a soil-vegetation-atmosphere transfer (SVAT) model that provides the surface temperature of the different elements. The 3D scene built using the POV-Ray software is validated against ground-based canopy gap fraction measurements. The microstructure effects related to the spatial distribution of needles within the shoots are introduced by adapting the parametric hot spot model of Roujean (2000). The surface temperatures of the different canopy elements and the soil are computed with the multilayer, multileaf SVAT MuSICA model (Ogée, 2000; Ogée et al., 2003). Simulated TIR directional anisotropy is then validated against airborne measurements performed at different times of the day and different dates (i.e., for different sets of solar angles). The results show that the thermal hot spot is satisfactorily reproduced and that the anisotropy is well-captured, although slightly underestimated. The generalization to other pine stands displaying different canopy structures (age, size, density of trees) is now needed before using this TIR directional anisotropy model for practical applications.*

1 INTRODUCTION

Measurements of surface temperature performed in the thermal infrared (TIR) are prone to important directional anisotropy. This first depends on the canopy structure which governs (1) the temperature profiles within the vegetation through the coupled energy and radiative transfers, (2) together with the spatial distribution of the facets seen by the sensor. The directional anisotropy also depends on the solar position. Characterizing directional TIR anisotropy is necessary for different goals: the possibility of retrieving the surface temperature of the different layers within the canopy should allow to improve sensible heat flux etimations, and should facilitate the assimilation of multi-angular remotely sensed TIR data into surface models ; correction and normalization of large swath satellite data are also expected for improving the analysis of temporal series, or of the spatial variability within given thermal images; finally it should help defining the specifications for future spaceborne sensors.

The study of the thermal directional anisotropy originates in the 60's. Experimental measurements of TIR directional anisotropy have been extensively performed in the past over low crops using ground based systems and a number of models have been proposed. Less work has been made over canopies displaying important height such as forest and urban canopies, probably because of experimental difficulties. Lagouarde et al. (2000 and 2004) proposed a method based on the use of an airborne TIR camera equipped with wide-angle lenses. They report important thermal 'hot spots' both over maritime pine stands and urban canopies.

Several modelling approaches have been proposed. The simple geometrical models (Kimes, 1983, and Caselles et al., 1992) or simple multi-layer ones in which the directional temperature is computed from gap frequencies (Prévot et al., 1994) require an *a priori* knowledge of the temperature distribution within the canopy and generally suffer from too poor descriptions of the structure of the vegetation. Recent approaches based on 3D models have been proposed (Guillevic et al., 2003; Luquet et al., 2004). Kurz et al. (2006) and Kurz (2009) have proposed an approach combining a 3D canopy model and a SVAT model in the case of a maritime pine mature stand (*Pinus pinaster Ait.)*. This paper presents the last improvements brought to this method, which mainly concern the 3D tree modelling and the interception simulated processes of the solar radiation within the tree canopy. The long term objective is to build a generic model simulating the TIR anisotropy of maritime pine stands, whatever their age.

The approach is first briefly recalled. The 3D models of a pine tree and of a stand are then described. Each tree crown is modelled as a set of opaque cylinders accounting for the shoot clumps. The first simulations of Kurz et al. (2006) revealed that the initial assumption of opaque crown elements was too high a level of simplification. Kurz (2009) proposed an adaptation to take into account the contribution of of needles within the shoots to the anisotropy. On these bases, we aimed to improve the simulation of directional variations in sunlit and shaded crown fractions seen in the viewing direction and on the parameterization of the size of cylinders and their location on the branches. This is described in section 3, before presenting and discussing the results of directional temperature anisotropy.

2 EXPERIMENTAL BACKGROUND

The experiment was conducted on a mature even-aged maritime pine stand (Le Bray) located in south-western France 20 km west of Bordeaux (44° 42' N, 0° 46' W). The calibration and the validation of TIR anisotropy model were based on the TIR aerial measurements performed in 1996 (Lagouarde et al. 2000) and on the directional gap fraction data of tree canopy measured in situ with DEMON instrument in 1998 (Guyon et al., 2003).

Detailed information on the structure and architecture of pine tree (length of branches, insertion angles, number of branches…) comes from destructive measurements performed at INRA in 1995 by Porté et al. (2000, 2002) and Champion et al. (1996, 2001). In 1995 the pine trees were 26 years old. Stand structure data such as tree density (e.g. 518 tree per ha in 1996), height (e.g. mean in 1996 = 17.6m) or DBH were also available in 1995, 1996 and 1998.

The understory vegetation was mainly made up of Molinia (*Molinia coerulea Moech.*) which covered completely the soil. The trees were planted by rows with a direction approximately 35° from North and a 4m spacing.

3 PRINCIPLE OF THE MODELLING APPROACH

The principle followed to simulate the brightness directional temperature $T_b(\theta_v,\varphi_v)$ is based on the aggregation of the surface brightness temperatures of the different sunlit and shaded elements of the canopy seen in the viewing direction defined by the zenith and azimuth viewing angles θ_v and φ_v for a given sun position. The anisotropy is then calculated as the difference with the nadir temperature.

A simplification consists in considering only 6 classes of elements as seen by the TIR sensor: sunlit and shaded crowns, ground and trunks. $T_b(\theta_v,\varphi_v)$ is computed according to Eq. 1:

$$T_b(\theta_v,\varphi_v)=\sqrt[4]{\sum_{i,j}A_{i,j}(\theta_v,\varphi_v)\cdot T_{i,j}^4} \qquad (1)$$

where indices i correspond to sunlit/shaded status and j to the element type respectively.

The A_{ij} fractions are estimated from images of the canopy built using the ray-tracing POV-Ray software (http://www.povray.org/ Persistance Of Vision Ray-tracer) applied on a 3D model of the tree canopy. Images are generated for a large set of viewing directions, for a prescribed solar direction corresponding to the time of airborne acquisitions for comparison purposes. The parameters of the POV-Ray computations are selected to create schematic images of the canopy allowing easy discrimination of the different classes.

The T_{ij} were computed using the Ogée et al. (2003) MuSICA model (Multi-layer simulator of the interactions between a coniferous stand and the atmosphere). This model solves an energy budget equation for each layer of the canopy and computes the temperature of 3 classes (1, 2 and 3 years old) shaded/sunlit needles, and the temperature of the understory. In fact crown temperatures are also estimated by weighing the temperature of needles according to their respective LAI. Moreover the number of classes was reduced to 4, the trunks and the soil displaying similar temperature having finally been merged.

We worked with brightness to avoid facing the difficult problems of directional emissivity and temperature emissivity separation.

4 THE 3D MODEL

4.1 The 3D tree model

We looked for a simplified tree description combining a realistic enough representation of the tree structure and compatible with computer time constraints for POV-Ray simulations.

The trunk was modeled as a cone. The needles, shoots and small branches were concentrated within opaque cylinders placed on the 4th growth unit of main branches (or on the trunk for branches from order 1 to 4). The size of all cylinders remained constant so that two parameters only, their length and radius, suffice to describe the tree (see Figure 1).

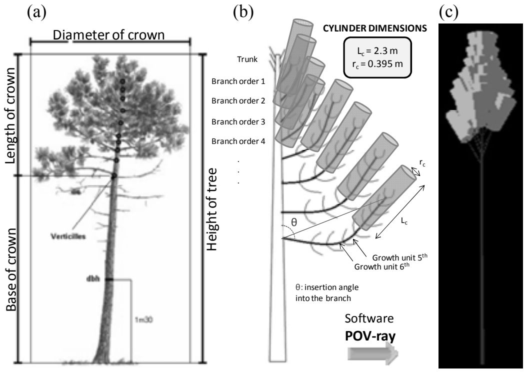

Figure 1. Example of shape of an adult pine tree (a) and principle of the simplified tree description (b) for the 3D model. Example of a POV-ray 3D modelled pine (c).

4.2 The 3D stand model

Tree dimensions were distributed according to the actual Le Bray stand structure. The trees were randomly distributed along the rows taking into account the actual variability of their distance within rows. For realism purpose, a competition effect was simulated by applying to the size of the trees a homothetic coefficient related to their distances within rows. Figure 2 displays an example of 2 simulated images of the stand viewed in 2 different directions.

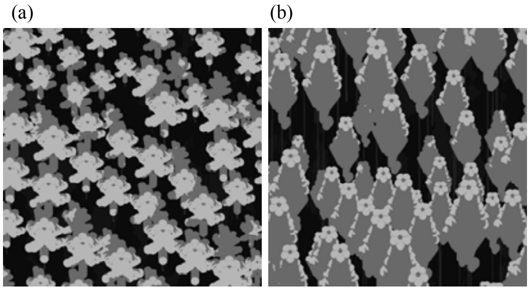

Figure 2. POV-ray simulations of the stand for a solar fixed position (θ_s=38.5º, φ_s=164.3º) and two viewing configurations: (a) θ_v=10º, φ_v=340º; (b) θ_v=40º, φ_v=340º. The four grey tones correspond to the Ai,j fractions oft sunlit and shaded elements (only crown and ground elements are simulated).

4.3. Parameterization of the tree model

The calibration of the tree model consists of determining the cylinder dimensions by minimizing errors between DEMON measurements of directional gap fraction under the tree canopy and their simulation by POV-Ray. The directional gap fraction is equal to the fraction of ground seen on the simulated image in hot spot viewing configuration, i.e. $A_{sunlit,,ground}$ (with $A_{shaded,,ground}$ =0). The results of the calibration step were L_c=2.3 m and r_c=0.395 m (Fig. 3).The maximum observed in figure 3 corresponds to DEMON measurement performed in the directions of rows (the sun azimuth angle of 204° indicated in fig. 3 corresponding to the 35° row direction).

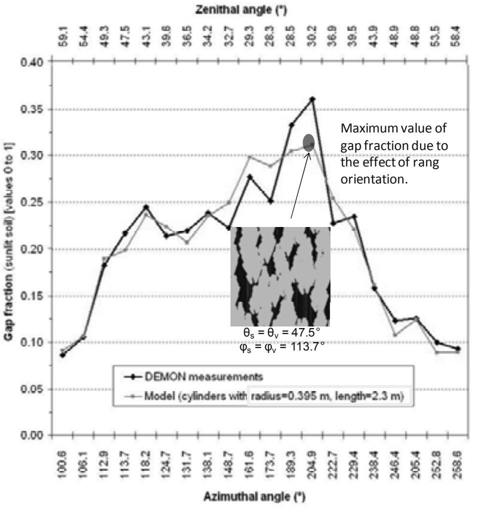

Figure 3. Modeled directional gap fraction against in situ measurements from DEMON in various zenith and azimuth angles.

The comparison between simulated and actual diameters of crowns (Fig. 4) provides additional elements of validation of the tree-stand model.

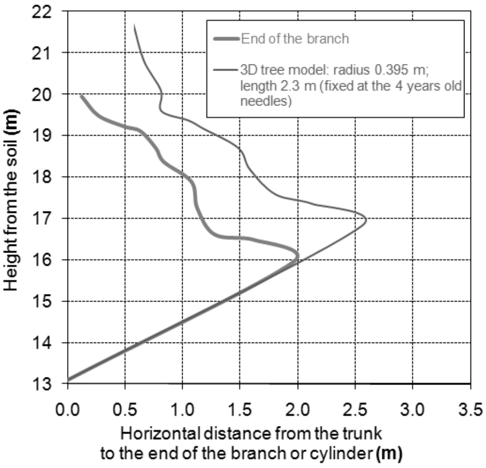

Figure 4. Shape of the crown as defined by the 3D tree model described in this work, compared with the shape of the ends of the tree branches (results for the mean 29 years-old tree in 1998).

We also tried to check if the model was able to reproduce the actual vertical LAI profile. In fact our approach does not allow one to simulate a LAI, but we considered the vertical profile of frontal area averaged in all azimuthal viewing horizontal directions of the tree. This was normalized by its maximum value and compared against the expected vertical LAI profile (obtained from Porté et al., 2000) and similarly normalized. As shown in Figure 5, there is a relatively good agreement between these profiles despite unavoidable discrepancies due to the simplicity of our cylinder approach. Nevertheless we considered these tests were confirming the consistency of our 3D stand model.

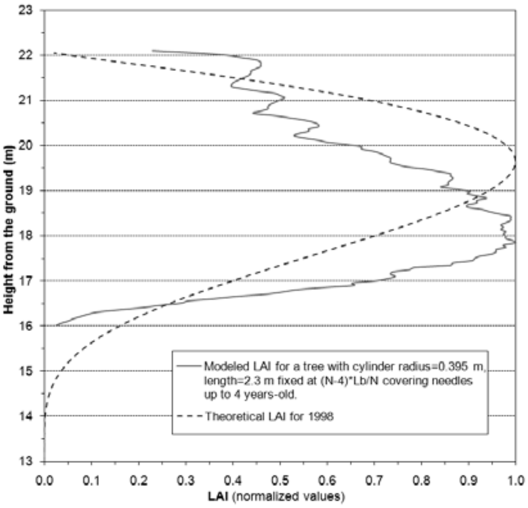

Figure 5. Comparison of LAI profiles of the modeled tree and the theoretical values obtained from horizontal area profiles (results for the mean tree in 1998, 29 years-old).

5 INTRODUCING THE IMPACT OF THE DISCRETE STRUCTURE OF CROWNS

The opaque cylinders of the 3D model only allow one to take into account the contribution of the 'macrostructure' (i.e. crowns and rows) of the stand to the TIR directional anisotropy. In fact, crowns have a discrete structure, and small size elements (referred to as 'micro structures') as needles largely contribute to the anisotropy. As a matter of fact, assuming that the surfaces of sunlit and shaded needles within crowns which effectively govern the anisotropy can be simply estimated as the sunlit and shaded surface of the envelope of crowns is too crude an approximation, and comes to ignore the diffuse nature of the media within crowns. The coefficients $A_{i,j}$ estimated at the stand scale (from images such as those presented in fig. 2) and used in the computation of the brightness temperature according to equation (1) are therefore not directly suited to compute the directional brightness temperature. They have been corrected by adapting a hot spot parameterization proposed by Roujean (2000) introducing a function F_{HS} which depends only on Sun and viewing directions:

$$F_{HS} = \sqrt{\tan\theta_s^2 + \tan\theta_v^2 - 2\tan\theta_s \tan\theta_v \cos\varphi} \qquad (2)$$

φ is the relative azimuth between Sun and viewing directions. $A_{1,1}$ and $A_{2,1}$ are replaced by $A_{1,1CORR}$ and $A_{2,1CORR}$, respectively, following:

$$A_{1,1CORR} = A_{1,1} \cdot e^{-k \cdot F_{HS}} \qquad (3)$$

$$A_{2,1CORR} = A_{2,1} + A_{1,1} - A_{1,1CORR} \qquad (4)$$

with $k = LAI_c/4$ (5)

The correction concerning the radiative transfers within crowns, LAI_c refers to their leaf area projected at ground. We therefore have $LAI_c = LAI / F_c$, F_c being the fraction cover of crowns and LAI the leaf area of the stand. As LAI ~ 2.2 and F_c ~ 0.7, we have finally k ~ 0.8.

6 RESULTS

TIR anisotropy airborne measurements were performed at different dates in 1995 and 1996 and different times of day to explore the impact of solar position.. The experimental results revealed important hot spot effects and differences of brightness temperatures reaching 4 K between vertical and oblique measurements (up to 60°). All details can be found in Lagouarde et al. (2000). In this paper we only focused on acquisitions performed on September 9th, 1996, over the stand of Le Bray.

Figure 6 displays the comparison between airborne measured and simulated TIR directional anisotropy around 13:20, 15:00 and 17:40 local time (wich corresponds to 11:20, 13:00 and 15:40 UT). In all cases, the results show that the hot spot is well-positioned (opposed to the sun position) and that the angular variations are satisfactorily simulated. The comparisons performed in the solar principal plane reveal a general agreement with measurements around the hot spot. Some discrepancies are observed for the first 2 flights for zenithal angles lower than -20°. These have been examined in details and are easily explained by experimental artefacts; as a matter of fact investigating all azimutal directions requires flying several lines in different directions. As a consequence, time fluctuations in micrometeorological conditions (windspeed particularly) may possibly induce systematic variations in surface temperatures for some of the lines flown which in turn affect the anisotropy polar plots as those presented in fig. 6.

7 CONCLUSIONS

The TIR directional anisotropy was satisfactorily simulated over a mature pine stand at different times of a given day using a simple approach combining a

3D model of the tree and of the stand with the SVAT MuSICA model.

Regarding the macrostructure of the pine tree, a simple 3D tree model made of (1) a trunk, (2) first order branches and (3) cylinders set on them and concentrating all the crown vegetation (rest of branches from order 2 and needles) was calibrated against *gap fraction* measurements. We considered in a first step that this model was offering a good compromise between realism and simplicity. The consistency of crown diameter and of an indicator of the vertical LAI profile against actual characteristics of the studied stand was checked. Moreover on a practical point of view, the calibration of the model was made easy by the reduced number of parameters (a unique set 2 parameters only, radius and length of cylinders).

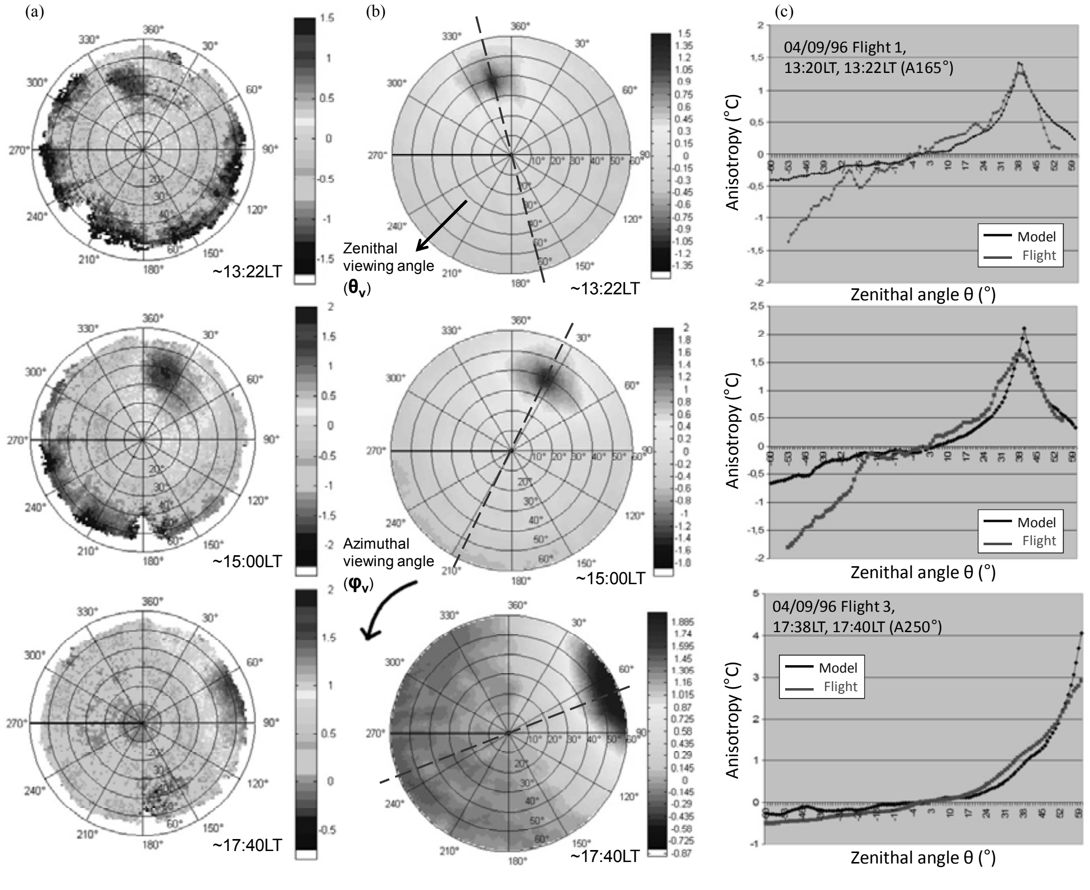

Figure 6. Comparison between (a) the anisotropy measured by airborne measurements on September 9th, 1996 over the experimental maritime pine stand of Le Bray in south-western France, and (b) the anisotropy simulated with the combined MuSICA and hot spot parameterization approach, in all azimuthal angles, and (c) in the principal solar plane.

Regarding the microstructure (needles, shoots and small branches) of the pine, the hypothesis of considering opaque cylinders was too restrictive, and a correction adapted from the parametric approach of Roujean (2000), allowed one to simulate the directional variations around the hot spot satisfactorily.

The forthcoming steps of this work consists in testing the generalization of the model to other pine stands displaying different canopy structures (age, size, density of trees). Nevertheless the geometrical description of the tree/stand model we proposed here remains very crude, and one may think it will be difficult to find simple and unique parameterizations of the dimensions of the cylinders to prescribe them *a priori* for other stands. We could therefore suggest in a further step to test an improved and more detailed 3D model of the pine tree by using smaller cylinders (aggregating vegetation from second order branches instead of main branches) with the hope of approaching a unique elementary cylinder size more adapted to any class of stand age and structure.

8 ACKNOWLEDGMENT

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