Studies of BRDF in conifer and deciduous boreal forests using the 4-Scale model and airborne POLDER and ground-based PARABOLA measurements

Jing M. Chen, Sylvain G. Leblanc and Josef Cihlar
Canada Centre for Remote Sensing
588 Booth St., 4th Fl., Ottawa, Ontario, K1A 0Y7 Canada
Tel: (613)947-1266 / Fax: (613)947-1406
email: jing.chen@ccrs.nrcan.gc.ca

Patrice Bicheron and Marc Leroy
CESBIO, 18 avenue Edouard Belin
31055 Toulouse Cedex, France

Donald Deering and Tom Eck
Code 923, Biospheric Sciences
NASA/GSFC, Greenbelt, M. D. 20771, USA

Abstract - An investigation of directional reflectance of boreal forests is conducted using airborne POLDER [1] and ground-based PARABOLA measurements [2] and the 4-Scale model [3]. The model simulates well the pronounced hotspots observed by POLDER and the slight bowl shape in the forward scattering direction observed by PARABOLA. The model is also used to demonstrate the importance of branch architecture in the directionality of NDVI calculated from the red and near infra-red reflectance.

INTRODUCTION

This paper presents an investigation of the angular behaviour of the reflected solar radiation from boreal forest stands using field measurements and a radiative transfer model. The model used is the 4-scale model developed by Chen and Leblanc [3]. The field measurements include airborne POLDER (POLarization and Directional Earth Radiation) and ground-based PARABOLA (Portable Apparatus for Rapid Acquisition of Bidirectional Observations of Land and Atmosphere) data acquired during the Boreal Ecosystem-Atmosphere Study (BOREAS) in summer 1994 in one deciduous and two conifer stands in Saskatchewan, Canada. Because of the difference in the measurement methodology, considerable differences in the bidirectional reflectance distribution function (BRDF) in red and near infrared bands are found between these two sets of measurements. The 4-Scale model is used to investigate the causes of the differences in relation to the effects of various scales of canopy architecture on the BRDF of these forest stands. Ground measurements of leaf area index, leaf optical properties and tree allometry for these sites are used as input parameters of the model.

4-SCALE MODEL

The 4-Scale radiative-transfer model [3-4] was developed with emphasis on the structural composition of forest canopies at different scales (Fig. 1). The 4-Scale is a geometric-optical model employing several new modelling methodologies: (1) The non-random spatial distribution of trees is simulated using the Neyman type A distribution [5] that creates patchiness of a forest stand. The model simulates tree crowns as discrete geometrical objects: cone and cylinder for conifers, and spheroid for deciduous species. The size of the crowns decreases when the trees are found in large clusters and the tree locations are also subject to repulsion effects to better represent the competition for light; (2) Inside the crowns, a branch architecture defined by a single inclination angle is included to improve the calculation of light penetration. A branch is in turn composed of foliage elements (individual leaves in deciduous and shoots in conifer canopies) with a given angle distribution pattern; (3) The hotspot is computed both on the ground and on the foliage based on gap size distributions between and inside the crowns, respectively; (4) The imaginary tree crown surface is treated as a complex medium rather than a smooth surface so that shadowed foliage can be observed on the sunlit side.

For optimum results, the model has multiple parameters that can be separated into three categories; (1) site parameters: domain size (which represents the pixel size), leaf area index (LAI), tree density, tree grouping factor in the sub-domain size, solar zenith angle (SZA), view zenith angle (VZA) and azimuthal angle difference; (2) tree architecture parameters: crown radius and height, apex angle and needle-to-shoot area ratio for conifers, foliage distribution angles (leaves or shoots orientation: α_L, branches inclination α_b, foliage thickness, branch leaf area index and thickness), clumping-index and typical size of the foliage elements; and (3) optical properties (reflectivities) of the foliage and the ground at desired wavelengths. When measurements are not available for some parameters, defaults or best estimates can be used. For canopies with an important understorey such as hazelnut shrubs in the BOREAS Old Aspen site, a double-canopy version of the 4-Scale model is used [4].

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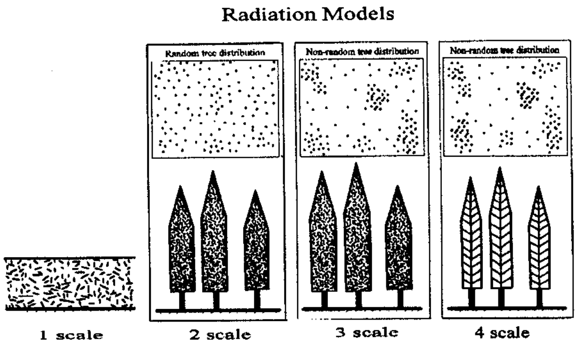

Fig. 1. Concepts of radiation models. The 4-Scale model considers non-random tree distribution and sub-canopy architecture.

RESULTS

The model results are compared with PARABOLA measurements in the BOREAS Old Black Spruce (OBS) site in Fig. 2. The model shows sharp spikes at the hotspot in comparison with the measurements. The gentle variation in the measurements may be a consequence of the low angular resolution (15°) which effectively produced window-averaged results. The effect of the averaging is to dampen and broaden the peak at the hotspot. Figure 2a and 2b shows the simulations and measurements in the red band for SZA of 40° and 55°. Figures 2c and 2d show comparisons between the model and measurements for the reflectance in the near-infrared (NIR) band for SZA of 40° and 60°. The model is able to simulate the measurements closely except for the largest view zenith angles on the backscattering side. The bowl shape of the measurements is simulated by the model in the near infra-red, but is underestimated in Fig. 2d on the forward scattering side, indicating the need to further improve the model.

Figures 3a and 3b show the comparison between the model and POLDER data in the red and NIR band respectively for the OBS site. Only the view zenith angle corresponding to the measurements were simulated. Overall, the model slightly overestimates the measurements, even when using leaf reflectivities in the lower end of measurements. Note that the case presented in Fig. 3a and 3b is about 10° from the principal solar plane, so the hotspot peak was not reached. The NIR modelling shows a very good agreement between the model and the measurements. The only noticeable difference can be seen on the backscattering side for view angles greater than the sun angle where the model shows lower reflectance values than POLDER. For the Old Aspen (OA) site, Fig. 3c and 3d also show good agreements between the model and the measurements. The model can simulate most angles except for large VZA values on the backscattering (Fig. 2d and Fig 3d). The maximum value of the BRDF measured by POLDER is not exactly at the hotspot, but at a larger view zenith angle. This phenomenon can not be simulated by the 4-scale model without accurate consideration of the multiple scattering effect. The small discrepancies between the model and the measurements on the forward scattering side of Fig. 3 may be due to the atmospheric correction algorithm used in the POLDER data processing.

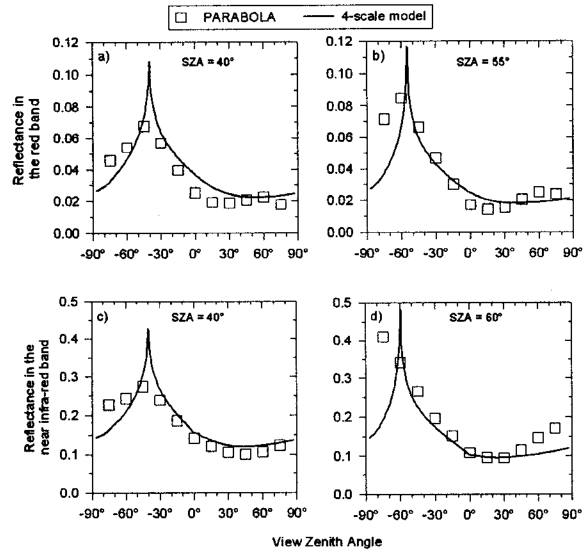

Fig. 2 Comparisons of PARABOLA reflectance measurements in the red and near infra-red bands in the principal plane of the Old Black Spruce BOREAS site.

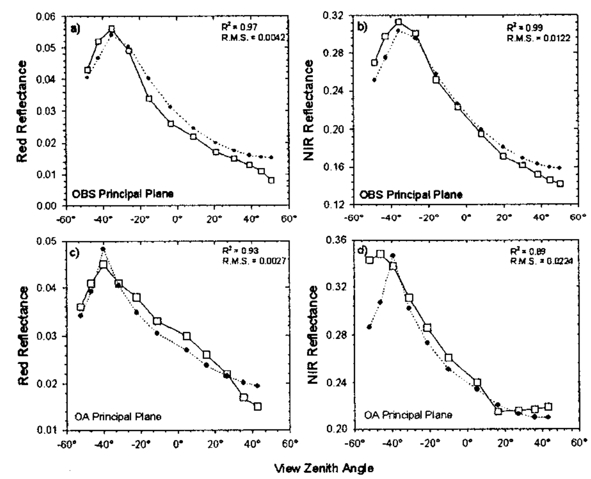

Fig. 3 Comparison between POLDER (□) and the 4-Scale model (•) for the Old Black Spruce BOREAS site (SZA=33.5°) in a) the red band and b) the near infra-red band, and for the Old Aspen site (SZA = 39.3 °) in a) the rd and b) the near infra-red band.

Figures 4a and 4b shows the directionality of NDVI [6] calculated from the red and near infra-red bands reflectance for the cases of near vertical (α_b and α_L at 75°, positive angles representing upward directions) and horizontal branches and shoots (α_b and α_L at 0°) for the OBS and Old Jack Pine (OJP) site, respectively, at SZA=45°. The branch architecture has a pronounced effect on the directional distribution of NDVI in OJP but the effect is much smaller in OBS. The difference in crown foliage density in these two stands is the main cause for the difference in the magnitude of the subcanopy architecture effect.

The foliage density in OJP crowns is low and therefore the change in the foliage organisation and orientation has large effect on the probabilities of light and viewline penetrations through the crowns. In OBS, where tree crowns are dense, the detailed foliage distribution within the crowns only have a secondary effect on NDVI. Near nadir, the NDVI is larger in the case of horizontal shoots and branches because the probability of seeing the background vertically is smaller through the horizontal foliage. At large view zenith angles on the forwardscattering side, the effect of the foliage orientation on NDVI increases. When the branches and shoots are horizontal, the probability of seeing sunlit foliage from the shaded side is larger than when the foliage is almost vertical. The vertical structure can be seen as a "wall" that prevents the viewer to see sunlit foliage through the crown. The NDVI increases because the viewer sees more shaded foliage which has larger NDVI because of the stronger multiple scattering effect on NIR than on red reflectivity. This subcanopy architectural effects should depend on the stand density which modifies the multiple scattering processes.

CONCLUSION

Both PARABOLA and POLDER measurements are of very high quality. These two instruments produced results in reasonable agreement, although considerable differences exist because of the different measurement methodology. The POLDER data have higher angular resolutions and larger spatial coverages than the PARABOLA data but suffer from some uncertainties in the atmospheric correction. The PARABOLA data have the advantage of being able to sample for given angle combinations (such as principle solar plane) and free from atmospheric interference but the measurements were made with a lower angular resolution (15°) and in smaller areas than the POLDER data. With detailed description of the architecture of the deciduous and conifer canopies, the 4-Scale model simulates closely the measurements from both instruments. Compared with PARABOLA, POLDER data generally show smaller reflectance in the red band and similar reflectance in the NIR band. In the 4-Scale simulation of POLDER data, red reflectivities are lowered to 11% and 4% for the foliage and ground, respectively, from 13% and 6% used in the simulation of PARABOLA data. These adjustments are due to the different wavelengths used: 660-680 nm for POLDER, which includes the minimum in the red reflectivity spectrum for conifer needles, and 650-670 nm for PARABOLA, which is located on one side of the minimum. In BRDF, the largest differences of scientific concern between these two types of measurements are found on the forwardscattering side where PARABOLA exhibits bowl shapes while POLDER doesn't. Further investigation is needed to understand the causes of the difference.

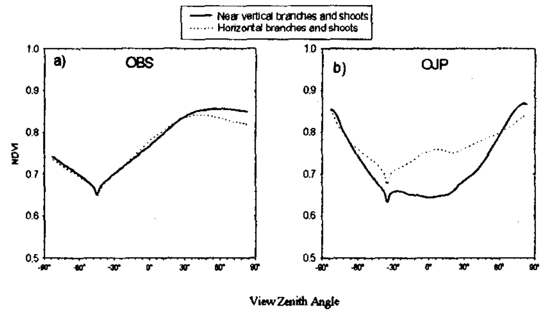

Fig. 4 Simulated principal plane NDVI with horizontal and near vertical shoots and branch structure for a) the Old Black Spruce (OBS) site and b) the Old Jack Pine (OJP) site. SZA = 45°.

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