

Satellite estimation of surface/atmosphere parameters: a sensitivity study

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1. Abstract

The objectives of this study are to characterize the sensitivity of the BIOME-BGC model to errors in satellite derived parameters and to define requirements for future satellite development in terms of spectral and directional sampling as well as radiometric accuracy. The study focuses on key indicators of climate change that can potentially be estimated by passive hyperspectral remote sensing: leaf area index (LAI), fraction of absorbed photosynthetically active radiation (fAPAR), chlorophyll a+b content (C_{ab}), fraction cover and aerosol optical thickness.

The sensitivity analysis of BIOME-BGC, and requirements extracted from the literature are used to design a factorial experiment that allows detection of effects of changes on each parameter on the top of the atmosphere reflectance. The PROSPECT, FLIGHT 5.5 and 6S models are coupled together and used to simulate the top of the atmosphere reflectance at different geometries and spectral bands. The whole spectrum is analyzed and results are shown for those spectral and directional sampling that demonstrated to be of most interest to the retrieval of the parameters at the required accuracy.

Data from three coniferous forest (old black spruce, old and young jack pine) at the BOREAS Southern Study Area (SSA) site were used to drive the models, taking into account the biophysical and structural parameters specific to each canopy type.

Keywords: *Biophysical variables, land surface models, radiometric accuracy, remote sensing, optimal sampling.*

2. Introduction

Understanding the interactions between the biosphere and the atmosphere is critical to address issues such as climate change and the carbon cycle. Studies focused on these types of global processes rely heavily on models to predict and simulate general patterns in vegetation change and atmosphere-biosphere feedbacks (e.g. Kimball *et al.* 1997, Sellers *et al.* 1997b). Global observations of specific parameters are required to initialize and parameterize these models and satellite observations offer a unique means to retrieve data at this global scale.

The new generation of space-borne platforms and sensors, recently launched (VEGETATION, MODIS, MISR, MERIS, POLDER) or scheduled to be launched in the near future, are expected to improve the understanding of climatic and ecological processes. The utility of the technical improvements that have been made on these sensors (including spectral, angular, spatial and temporal resolutions) are presently being explored by the scientific community.

Numerous studies have investigated the potential of specific instruments to extract biophysical variables (Bicheron-Leroy 1999, North *et al.* 1999, Huete *et al.* 2002) from a general perspective but these studies were not linked to real land surface models or to the sensitivity of those models to errors in the retrieved parameters.

Land surface models

Land surface models (LSM) are integrated in global climate models to simulate interactions between the surface and the atmosphere. Therefore LSM are a key component in understanding the carbon cycle and how CO₂ increases in the atmosphere may be moderated by natural terrestrial carbon sinks. The northern latitude boreal forest is a critical component in this cycle because of its potential to sequester or release large volumes of carbon. It has been estimated that boreal forests contain 31% of all forest soil carbon, the second largest percentage of the total world (Schelinger 1991).

BIOME-BGC (BioGeochemical Cycles) model simulates ecosystem development through a life cycle, estimating fluxes of carbon, nitrogen, and water allowing estimation of annual net primary production (NPP). Inputs to the model are daily climate data and key climate, vegetation, and site conditions. Allometric relationships are used to initialize plant and soil carbon and nitrogen pools based on the leaf pools of these elements.

Satellite estimation of parameters

This study focuses on key indicators of climate change that can potentially be estimated by hyperspectral remote sensing. Three key biophysical variables, leaf area index (LAI), the chlorophyll a+b content (Cab) and the fraction cover (fCover) are considered in addition to one atmospheric parameter, aerosol optical thickness (τ).

Remote sensing instruments measure the reflected signal that results from the scattering and the absorption of the electromagnetic radiation by an object. The received signal is a function of the size, shape and biochemical composition of the object. Spectral signature analysis, model inversion and indices are the common methods used to estimate biophysical parameters from high spectral resolution sensors.

Bidirectional reflectance distribution function (BRDF) is strongly anisotropic for both the atmosphere and the vegetation. It is widely accepted that multi-angle measurements would be sensitive to vegetation structure and therefore can provide advanced structural descriptions (Asner *et al.* 1998a, Diner *et al.* 1999, Chen *et al.* 2003). Moreover, multiangular remote sensing has demonstrated to be useful also on the retrieval of atmospheric constituents due to the effect of the different atmospheric pathlengths on the top of the atmosphere (TOA) reflectance (North *et al.* 1999). Different viewing geometries are used in the present study to assess the advantages of multi-view sampling and to define optimal viewing angles to retrieve both atmospheric and land surface parameters.

3. Data sets and methods

The first stage of the experiment is to define the ranges of uncertainty for the parameters considered.

Net Primary Production (NPP) requirements can be defined based on the estimate of anthropogenic effect. Global terrestrial NPP has been estimated at about 60 PgC/yr and the average value of global emissions from fossil fuel burning and cement production in the 1990s was 6.3 ± 0.4 PgC/yr (IPPC 2001). Therefore, a useful estimate of NPP must be within an uncertainty of at most 10%. This requirement was used to run BiomeBGC model

and test the LAI uncertainty acceptable to reach this accuracy in NPP estimation.

Other parameter requirements were established based on the literature. One of the systematic observations needed to reduce uncertainty in direct and indirect radiative forcing are satellite measurements of aerosol optical thickness. It has been suggested that a value of 10% for aerosol optical thickness accuracy over the land is needed (Mishchenko *et al.* 2004).

About 10 to 30% of the current total anthropogenic emissions of CO₂ are estimated to be caused by land-use change; fraction of cover measurements provide some information on this change. No requirement was found on the literature and as a change in fraction cover of less than 10% is difficult to verify both by field or remote sensing measurements (Asner G.P. 1998b) this value was used in the study.

No references were found in the literature to optimal values of chlorophyll content estimation. However it has proved to be of great importance in the estimation of NPP (Dawson *et al.* 2003). For a particular LAI, different values of foliar chlorophyll content lead to different remotely-sensed estimates of fPAR, while the actual canopy fPAR value remains relatively constant. In the study by Dawson *et al.* 2003 uncertainties of 47% were obtained in the estimation of fAPAR for Cab values ranging between $\pm 50\%$ of a base value. On the other hand, it has been proposed that NPP can be estimated though modeling using canopy architecture parameters (LAI, clumping index) derived from multi-angle remote sensing (Chen *et al.* 2003) instead of fAPAR. An accuracy value of 10% has been chosen as useful in the estimation of chlorophyll content for the present study.

Sensitivity analysis

Since total leaf area constrains the maximum rate of carbon uptake on woody vegetation, sensitivity of NPP estimated by the model to LAI estimated by satellite was analyzed. fAPAR is linked to LAI in BIOME-BGC so it could not be analyzed independently. LAI was changed in a range between $\pm 50\%$ of the real (field data) value examining the effects on the NPP estimation.

Parameter ranges derived from the BIOME-BGC sensitivity analysis and the literature review were used to design a factorial experiment that allows detection of interaction effects of the parameters on TOA reflectance. To simulate TOA reflectance three models were coupled: a leaf reflectance model (PROSPECT, Jacquemoud-Baret 1990), a land surface radiative transfer model (FLIGHT5.5, North 1996) and finally a radiative transfer model (6S, Vermote *et al.* 1997).

The PROSPECT model was used to compute leaf optical properties for each site. Input parameters were fixed to field data. Meteorological and phenologic data were extracted from the study by Kimbal *et al.* 1999, LAI values used are summarized in Table 1.

FLIGHT (Forest LIGHT) 5.5 was used to simulate the light interaction with the different surface types. This model is based on Monte Carlo simulation of photon transport and allows simulation of 3D inhomogeneous canopy structures calculating the BRDF and absorption. Leaf reflectance results from PROSPECT were used to drive the model together with values of canopy structure and biophysical parameters obtained from the field data (Table 1).

Finally, the surface reflectance from FLIGHT was used as input at the Second Simulation of Satellite Signal in the Solar Spectrum (6S) to simulate the effect of the atmosphere on the radiation. Subarctic summer atmospheric model and biomass aerosol model were considered for the site during the simulation. In a first stage the whole optical spectrum (400nm-2500nm) was analyzed with a bandwidth of 10nm. Then data was used to chose

relevant wavelengths that were analyzed in detail.

Three base-case scenarios were used, one for each site, by driving the models with parameters from the field campaign. For every base-case, each parameter was perturbed by a value equal to the accuracy required on the estimation (e.g. was perturbed by $\pm 10\%$).

The whole simulation process was repeated for a range of geometries. The sun position was allowed to vary in the range 30-70 degrees corresponding to the possible values at the considered site. Both principal and perpendicular plane were analyzed and direct and diffuse radiation were considered.

The difference between the base-case TOA reflectance value at each wavelength and the value simulated for each perturbation was used as merit-of-change value. This value corresponds to the radiometric accuracy that the instrument should have to be able to detect changes on the parameters greater or equal to the perturbation value used.

Sites description

Models were driven by field data collected between 1994 and 1998 during the Boreal Ecosystem-Atmosphere Study (BOREAS) project (Sellers *et al.* 97a), conducted in Canada. Three coniferous forests at the BOREAS Southern Study Area (SSA) site were investigated, old black spruce (OBS), old and young jack pine (OJP and YJP respectively), taking into account the biophysical and structural parameters specific to each canopy type. Meteorological data, soil and bark reflectances as well as aerosol optical thickness values were extracted from BOREAS data sets (http://www-eosdis.ornl.gov/BOREAS/boreas_home_page.html). Values for May-June 1994 were chosen.

4. Results

BIOME-BGC Sensitivity analysis

The estimation of NPP showed similar results for the three cases (*Fig. 1*). It is clear that the larger the LAI the less sensitive the results are to errors in LAI estimation. At larger LAI the amount of sunlit leaves decreases and that of shaded leaves increases, reducing the sensitivity of canopy photosynthesis. This effect was particularly clear in the case of the OBS (LAI = 5.6) where an error of 50% on the estimation of LAI corresponds to an error of 20% in the NPP predicted by the model. To achieve the 10% accuracy proposed for the NPP, a mean value of LAI error of 10% was estimated.

Optimal spectral sampling

As was expected, water absorption bands (around 940nm, 1100nm, 1450nm, 1950nm and 2500nm) and carbon dioxide absorption bands (1400nm, 1600nm and 2000nm) strongly affected the top of the atmosphere reflectance reducing the variability of the signal at the point of making the reflectances of the different cases indistinct (*Fig. 2*).

Excluding those absorption bands, can be noted from Figure 2 that the smaller spectral variability occurs both at the lowest and at the highest wavelengths of the spectrum. At low wavelengths the signal is highly affected by Rayleigh scattering (caused by molecules much smaller in diameter than the wavelength of the light). In fact, TOA reflectance registered at 440nm was almost completely due to the atmosphere effect (top of the canopy values around 0.8% produced a TOA reflectance around 15%). The shortwave infrared (SWIR) bands are sensitive to leaf water content, but this parameter was constant during the simulation which could explain the low variations obtained.

The reflectance variability was higher in the near infrared (NIR, 700-1300nm) due to the leaf effects as have been reported in previous studies (e.g. Asner 1998b). To distinguish the simulated reflectances in this region of the spectrum minimum absolute radiometric accuracy requirement ranges between 0.001 for the OJP site and 0.004 for the OBS site.

The aerosol effect was very small as the aerosol optical thickness value used corresponds to very clear sky (0.05). Comparison of TOA reflectance at different viewing angles did not show clear differences that could be related to the aerosol content as would be expected because of the different atmospheric path lengths.

Mean merit-of-change values for each of the forests studied are shown in Figure 3. The graph shape is similar for the three cases and resembles slightly the spectral reflectance curve of the TOA reflectance. OJP (Fig. 3b) presents the lower value which implies that a higher accuracy will be required on the measurements in order to distinguish between cases. This is due to the sparse distribution of the trees in this site and the lower LAI of the sites studied. As result, understory, composed of mixtures of lichens, mosses and short herbs, has a strong effect on the signal smoothening TOA reflectance effects due to the analyzed parameters.

In general the NIR region and the green peak (560 nm) presented the highest values which means that less radiometric accuracy is required to detect changes at those wavelengths. OJP site requires mean absolute radiometric accuracy of approximately 0.0045 ± 0.002 at 870 nm while values of 0.0069 ± 0.002 and 0.0095 ± 0.0025 were obtained for the YJP and OBS sites respectively. The green peak requires radiometric accuracies of 0.0038 ± 0.0013 for YJP and OBS. The spectral difference is smaller at the OJP site with a mean value of 0.0025 ± 0.0012 .

Optimal directional sampling

When comparing merit-of-change values for each view zenith angle, (Fig. 4) nadir view and near the hot-spot (sun behind the sensor) directions present the highest sensitivities.

In the visible wavelengths the nadir view attained improved estimates with requirements of 0.0011 ± 0.001 at 550nm while other viewing angles sensitivity was ten times lower.

The best retrieval was obtained at viewing angles around the hot-spot in the near infrared with values up to 0.0116 ± 0.002 at 870nm for the OBS compared to values of 0.0052 ± 0.002 at nadir for the same wavelength. These figures correspond to variations of the parameters in the ranges analyzed while Figure 4 shows the specific case of LAI error between 0% and 50%.

Thus, directional sampling in the principal plane and near the hot spot and at nadir directions appeared to be optimal for biophysical variable estimation.

5. Conclusion

We have shown that some view angles (nadir view and near the hot-spot direction) are more sensitive to changes in biophysical parameters. The radiometric accuracy can be reduced by an order of magnitude compared with other sun-sensor geometries.

As was expected NIR showed higher spectral variability in vegetated areas. NIR showed the lowest requirements in terms of radiometric accuracy with values ranging between 0.0045 ± 0.002 and 0.0095 ± 0.0025 at 870nm. These wavelengths are optimal for the retrieval of biophysical parameters according to the result obtained.

Clear sky conditions were used and as a consequence the effects of atmospheric scattering by aerosols was not significant at the different sun-sensor geometries.

6. References

- Asner, G.P., Braswell, B.H., Schimel, D.S and Wessman, C.A., 1998a. Ecological Research Needs from Multiangle Remote Sensing Data, *Remote Sensing of Environment* 63, 2, Pages 85-193
- Asner, G.P., 1998b, Biophysical and biochemical sources of variability in canopy reflectance, *Remote Sensing of Environment* 64, Pages 234-253
- Bicheron P, Leroy M, 1999, A method of biophysical parameter retrieval at global scale by inversion of a vegetation reflectance model, *Remote Sensing of Environment* Volume 67, 3, Pages 251-266
- Chen J.M., Liu J., Leblanc S.G., Lacaze R, Roujean JL, 2003, Multi-angular optical remote sensing for assessing vegetation structure and carbon absorption, *Remote Sensing of Environment*, 84 (4): 516-525
- Dawson T.P., North P.R.J., Plummer S.E., Curran P.J., 2003, Forest ecosystem chlorophyll content: implications for remotely sensed estimates of net primary productivity, *International Journal of Remote Sensing*, 24 (3): 611-617
- Diner D.J., Asner G.P., Davies R., Knyazikhin Y., Muller J.P., Nolin A.W., Pinty B., Schaaf C.B., Stroeve J., 1999, New directions in earth observing: Scientific applications of multiangle remote sensing *Bulletin of the American Meteorological Society* 80 (11): 2209-2228
- Gower S.T., Vogel J.G., Norman J.M., Kucharik C.J., Steele S.J., Stow T.K., 1997 Carbon distribution and aboveground net primary production in aspen, jack pine, and black spruce stands in Saskatchewan and Manitoba, Canada. *Journal of Geophysical Research-Atmospheres*, 102, 29029-29041.
- Huete A, Didan K, Miura T, Rodriguez EP, Gao X, Ferreira LG, 2002, Overview of the radiometric and biophysical performance of the MODIS vegetation indices, *Remote Sensing of Environment*, 83 (1-2): 195-213.
- IPCC, Climate Change 2001: The Scientific Basis: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, [Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johoson (eds)], Cambridge University Press, United Kingdom and New York, NY, USA, 881pp., 2001.
- Jacquemoud S, Baret F (1990), "PROSPECT: A model of leaf optical properties spectra," *Remote Sensing of Environment*, vol. 44, pp. 281-292
- Kimball, J.S., Thornton, P.E., White, M.A and Running, S.W, 1997. Simulating forest productivity and surface-atmosphere carbon exchange in the BOREAS study region, *Tree Physiology* 17, 589-599.
- Leblanc SG, Bicheron P, Chen JM, Leroy M, Cihlar J, 1999, Investigation of directional reflectance in boreal forests with an improved four-scale model and airborne POLDER data, *IEEE Transactions on Geoscience and Remote Sensing*, 37 (3): 1396-1414 Part 1
- Mishchenko, M.I., Cairns, B., Hansen, J.E., Travis, L.D., Burg, R., Kaufman, Y.J., Martins, J.V., Shettle, E.P., 2004, Monitoring of aerosol forcing of climate from space: analysis of measurement requirements, *Journal of Quantitative Spectroscopy & Radiative Transfer* 88 -149161
- North, P.R.J., 1996, Three-dimensional forest light interaction model using a Monte Carlo method, *IEEE Transactions on Geoscience and Remote Sensing*, 34(5), 946-956.
- North P.R.J, Briggs S.A., Plummer S.E., Settle J.J., 1999, Retrieval of land surface

bidirectional reflectance and aerosol opacity from ATSR-2 multiangle imagery, IEEE Transactions on Geoscience and Remote Sensing, 37 (1): 526-537 Part 2

Schlesinger, W.H., Biogeochemistry: An analysis of global change, Academic Press, 1991.

Sellers, P.J., F.G. Hall, R.D. Kelly, A. Black, D. Baldocchi, J. Berry, M. Ryan, K.J. Ranson, P.M. Crill, D.P. Lettenmaier, H. Margolis, J. Cihlar, J. Newcomer, D. Fitzjarrald, P.G. Jarvis, S.T. Gower, D. Halliwell, D. Williams, B. Goodison, D.E. Wickland, and F.E. Guertin. 1997a. BOREAS in 1997: Experiment Overview, Scientific Results and Future Directions. Journal of Geophysical Research 102(D24): 28,731-28,770.

Sellers PJ, Dickinson RE, Randall DA, Betts AK, Hall FG, Berry JA, Collatz GJ, Denning AS, Mooney HA, Nobre CA, Sato N, Field CB, Henderson-Sellers A., 1997b, Modeling the Exchanges of Energy, Water, and Carbon Between Continents and the Atmosphere, Science. 275(5299):502-9.

Vermote, E., Tanre, D., Deuze, J.L., Herman, M. and Morcrette, J.J., 1997, Second simulation of the satellite signal in the solar spectrum: An overview, IEEE Trans. Geosci. Remote Sensing, 35, 675-686.

7. Acknowledgments

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FIGURES

Figure 1

Sensitivity of NPP estimation to error in LAI for three forest sites (NPP is presented in absolute value)

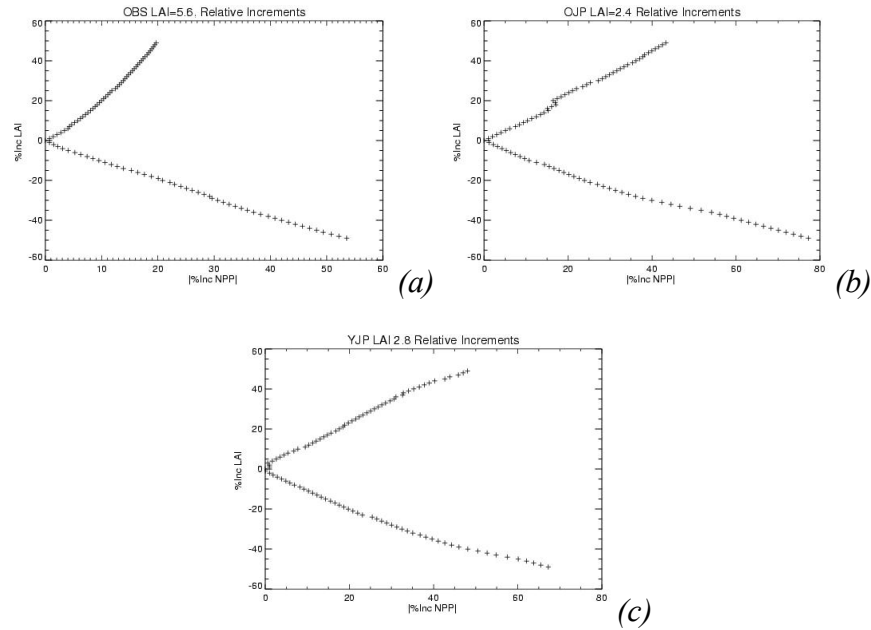


Figure 2

Mean merit-of-change values at each site in the full spectrum (400nm-2500nm). The merit function gives the sensitivity range required for instrumentation to detect biophysical parameter changes at a level useful for land surface modeling.

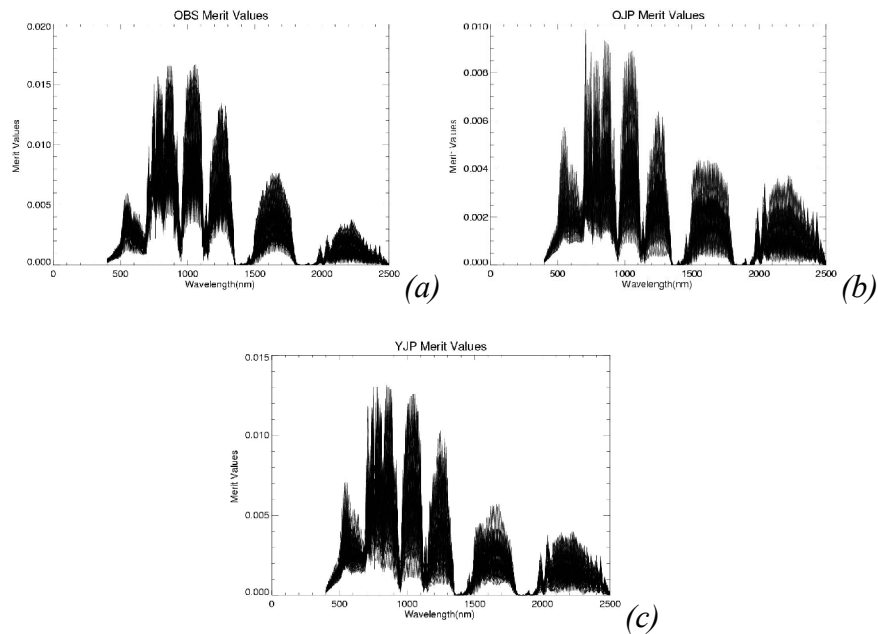


Figure 3

Mean merit-of-change values at each site at 16 wave bands corresponding to existing or recommended spectral sampling for satellite instruments. Error bars show $\pm\sigma$.

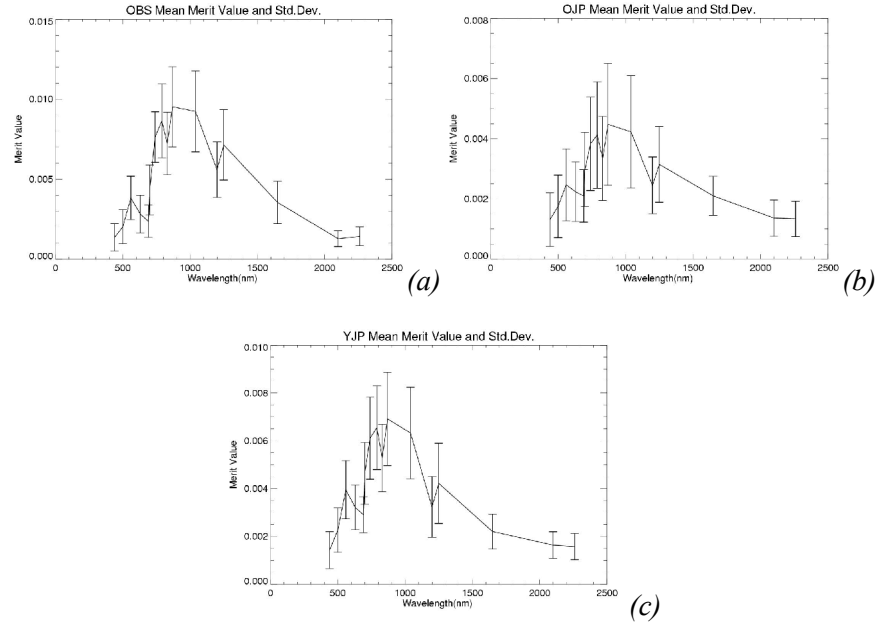


Figure 4

Merit-of-change values for the OBS site at 630nm (a) and 870 nm (b) for solar zenith of 30° , variation in visual zenith angle 0° - 80° in the backscattering direction (x axis) and LAI error between 0 and 50% (y axis).

