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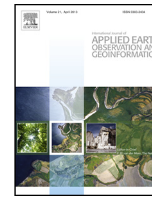

Short communication

Inter- and intra-annual variations of clumping index derived from the MODIS BRDF product

Liming He[a,*], Jane Liu[a,b], Jing M. Chen[a], Holly Croft[a], Rong Wang[a], Michael Sprintsin[c], Ting Zheng[a], Youngryel Ryu[d], Jan Pisek[e], Alemu Gonsamo[a], Feng Deng[f], Yongqin Zhang[g]

[a] *Department of Geography and Program in Planning, University of Toronto, Toronto, ON M5S 3G3, Canada*
[b] *School of Atmospheric Sciences, Nanjing University, Nanjing 210093, China*
[c] *Forest Management and GIS Department, Jewish National Fund-Keren Kayemet LeIsrael, Eshtaol, M.P. Shimshon, 99775, Israel*
[d] *Department of Landscape Architecture and Rural Systems Engineering, Seoul National University, Seoul, Republic of Korea*
[e] *Tartu Observatory, Tõravere, 61602 Estonia*
[f] *Department of Physics, University of Toronto, Ontario, M5S 1A7, Canada*
[g] *Department of Biological Sciences, Delta State University, Cleveland, MS 38733 USA*

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ABSTRACT

Clumping index quantifies the level of foliage aggregation, relative to a random distribution, and is a key structural parameter of plant canopies and is widely used in ecological and meteorological models. In this study, the inter- and intra-annual variations in clumping index values, derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) BRDF product, are investigated at six forest sites, including conifer forests, a mixed deciduous forest and an oak-savanna system. We find that the clumping index displays large seasonal variation, particularly for the deciduous sites, with the magnitude in clumping index values at each site comparable on an intra-annual basis, and the seasonality of clumping index well captured after noise removal. For broadleaved and mixed forest sites, minimum clumping index values are usually found during the season when leaf area index is at its maximum. The magnitude of MODIS clumping index is validated by ground data collected from 17 sites. Validation shows that the MODIS clumping index can explain 75% of variance in measured values (bias = 0.03 and rmse = 0.08), although with a narrower amplitude in variation. This study suggests that the MODIS BRDF product has the potential to produce good seasonal trajectories of clumping index values, but with an improved estimation of background reflectance.

1. Introduction

The spatial distributions of leaves in a canopy are often non-random because they are organized in various structures (Chen and Black, 1992). The non-randomness of leaf distribution can be quantified by a vegetation dispersion parameter called the clumping index (Ω) in a simple canopy radiation transfer model at a given zenith angle θ (Nilson, 1971):

$$P\left(\theta\right) = e^{-G(\theta)L\Omega(\theta)/\cos\theta} \quad (1)$$

where P is the gap fraction; G is a parameter describing leaf angular distribution and L is the leaf area index (LAI). If leaves of a canopy are randomly distributed, Ω is equal to 1. The Ω value can be larger than one when the foliage is regularly distributed. As leaves in a canopy become more clumped, Ω decreases, and its value is generally less than one. As optical vegetation indices are sensitive to effective LAI, Ω is used to convert the effective LAI to true LAI (Chen and Black, 1992). Leaf clumping affects radiation interception and distribution within canopies, consequently modulating evapotranspiration, energy partitioning and carbon uptake (Baldocchi and Harley, 1995; Chen et al., 2012). Consequently, Ω is identified as a key variable for describing canopy architecture within ecosystem models (Duthoit et al., 2008; Fang et al., 2013; Govind et al., 2013; Hill et al., 2011; Ryu et al., 2011; Sprintsin et al., 2011). In the two-leaf ecosystem models, Ω is used to accurately separate sunlit leaves from shaded leaves, and without considering foliage clumping, both the gross primary production and evapotranspiration estimates can be biased (Chen et al., in revision; Chen et al., 2012). Spatially-distributed information on the variability in Ω across different temporal scales, and for a range of ecosys-

* Corresponding author.
E-mail address: liming.he@gmail.com (L. He).

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tems, is therefore essential. However, retrieving the intra-annual variations of Ω from remotely sensed data, e. g. the Bidirectional Reflectance Distribution Function (BRDF) product of the Moderate Resolution Imaging Spectroradiometer (MODIS), is difficult because short-term fluctuations have been found in the derived Ω time series, implying that the Ω seasonality might be contaminated (He et al., 2012b).

The difficultly in modeling Ω from remotely-sensed data has led to relatively little research into retrieving spatially-continuous Ω values over large spatial extents. He et al. (2012b) produced a global Ω map at 500 m spatial resolution for one year (2006). However, they used a single annual-median value, therefore neglecting any potential seasonal variations in Ω. This study therefore focuses on investigating the magnitude and temporal trends of the seasonal variability of Ω for different vegetation types. Specifically, the objectives of this work are (1) to examine if the observed abrupt seasonal Ω fluctuations in the satellite data are caused by background changes due to rain events, (2) to examine the inter- and intra-annual variations of Ω for forested ecosystems, and (3) to quantify the magnitude of MODIS Ω (Ω_{MODIS}) values in mid-summer. For these purposes, we collect seasonal trajectories of Ω from ground measurements with several vegetation types and soil moisture data to identify noise in the Ω_{MODIS} time series; then we reconstruct the seasonality of clumping index using a smoothing algorithm; we analyze the reconstructed Ω_{MODIS} trajectories for multiple years and validate the magnitude of Ω_{MODIS} by ground data collected from 17 sites.

2. Methodology and data collection

2.1. Ground measurements of clumping index

For conifers, the Ω can be separated into two components (or scales), as either larger or smaller than the conifer shoot, which are measured in the field and in the laboratory, respectively (Chen, 1996):

$$\Omega\left(\theta_s\right) = \frac{\Omega_e\left(\theta_s\right)}{\gamma_e} \tag{2}$$

where θ_s is the solar zenith angle; Ω_e is the clumping of basic foliage elements larger than conifer shoots that can be indirectly measured by a field-based instrument; γ_e, the needle-to-shoot area ratio, accounts for clumping of needles within a shoot (Chen and Leblanc, 1997). For broadleaves, γ_e is assumed to be one if the foliage element is a single leaf. If the individual leaves are arranged in whorls or their petioles are very short, the identifiable foliage element might be larger than single leaf, and then the γ_e can be larger than one, as shown in the discussion section. When effective plant area index (PAI_e) (defined as one-half the total surface area of leaves and supporting woody materials per unit ground surface area) by LAI-2000 (LI-Cor Co.) in the middle of growing season, and L obtained from litter-fall data or allometry are available, Ω can also be estimated by solving the following equation (Chen, 1996):

$$L = (1-\alpha) \times PAI_e/\Omega \tag{3}$$

where α is the woody-to-total area ratio. Assuming that the measurements of PAI_e, L, and α are independent, the absolute error of Ω (σ_Ω, given as a standard deviation) is calculated as (Bevington and Robinson, 2003):

$$\left(\frac{\sigma_\Omega}{\Omega}\right)^2 \approx \left(\frac{\sigma PAI_e}{PAI_e}\right)^2 + \left(\frac{\sigma_L}{L}\right)^2 + \left(\frac{\sigma_\alpha}{1-\alpha}\right)^2 \tag{4}$$

We refer the derivation of Eq. (4) from https://en.wikipedia.org/wiki/Propagation_of_uncertainty

2.2. Clumping index from MODIS (Ω_{MODIS})

The individual Ω_{MODIS} for a specific time is retrieved from MODIS BRDF product (Schaaf et al., 2002) using the same method described in He et al. (2012b). A brief explanation is provided in the supplementary material. We combine the individual Ω_{MODIS}, corresponding hotspot, dark spot reflectance, and NDHD (Normalized Difference between Hotspot and Dark spot) into a time series and compare them with a soil moisture time series at the same locations, in order to identify Ω_{MODIS} noise possibly caused by rain events and changes in background. Here we choose soil moisture rather than precipitation and background reflectance because soil moisture data are available from flux tower sites; and for future application they are available from remote sensing (e. g. the Soil Moisture and Ocean Salinity (SMOS) mission and Soil Moisture Active-Passive (SMAP) mission). The noisy Ω_{MODIS} time series is then smoothed and reconstructed by a method named locally adjusted cubic-spline capping (LACC) (Chen et al., 2006).

2.3. Data collection

Ground measurements of Ω_e time series for 6 sites (4 conifer forest, 1 mixed forest, 1 oak-savanna) were collected from previous studies (Table 1) and used to calculate Ω (Eq. (2)) to compare to the seasonal Ω_{MODIS}.

The TP39 (42.71° N, 80.36° W), and TP74 (42.707° N, 80.348° W) sites in Ontario, Canada, are both needleleaf evergreen forests dominated by Mature White Pine (*P. strobus*) (Peichl et al., 2010). The RAdiation transfer Model Intercomparison (RAMI) pine site is dominated by Scots pine (*P. sylvestris* L.) stand in Järvselja, Estonia (58.31° N 27.30° E) (Kuusk et al., 2013). The Yatir site in Israel (31.35° N, 35.03° E), is a monocultured plantation which is dominated by Aleppo pine (*Pinus halepensis Mill.*) (Sprintsin et al., 2011). The Borden Forest site in Ontario, Canada (44.32° N, 79.93° W), a mixed deciduous forest from natural regrowth, is dominated by Red maple (*Acer rubrum* L.), Eastern white pine (*Pinus strobes* L.), Large-tooth aspen (*Populus grandidentata Michx.*), and White ash (*Fraxinus Americana* L.) et al. (Froelich et al., 2015). The Tonzi ranch site, an oak-savanna ecosystem in California, USA (38.43° N; 120.96° W), is dominated by blue oak trees (*Quercus douglasii*) with occasional gray pines (*Pinus sabiniana*) (Baldocchi et al., 2004). (1) Tracing Radiation and Architecture of Canopies (TRAC) was used to measure Ω_e for a whole canopy at a given solar zenith angle (θ_s) along transects at TP39, TP74, Yatir, and Borden Forest sites (Chen and Cihlar, 1995); (2) Digital Hemispheric Photographs (DHPs) taken by fisheye lens under diffuse illumination conditions were used to retrieve Ω_e for the RAMI (Radiation transfer Model Intercomparison) pine site. Pisek et al. (2013) and Leblanc et al. (2005) provided detailed descriptions of the measurements and method used at this site, respectively; (3) At Tonzi Ranch site, the Ω_e was estimated from the upward-pointing digital images (Ryu et al., 2012) using the method of Macfarlane et al. (2007). The γ_e values for conifer species were collected from laboratory measurements (Chen et al., 1997) in this study or from literature.

To test if the median magnitude of Ω_{MODIS} over a whole season (He et al., 2012b) is in the reasonable range, we collected values of PAI_e, L and α from literature for 17 sites and used eq. (3) to calculate independent values of Ω as listed in Table 2.

Values for α were obtained from published data \(Supplemental material, Table 1) and a mean of 0.2 was used in the calculation of Ω. The MODIS BRDF product (MCD43A1) and corresponding data quality product (MCD43A2) from 2000 to 2013 were downloaded from Land Processes Distributed Active Archive Center (https://lpdaac.usgs.gov). We extracted the snow-free and high quality MODIS BRDF model parameters and derived Ω_{MODIS} for sites mentioned in Table 1 and Table 2. The soil moisture data (volumetric soil water