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A virtual canopy generator (V-CaGe) for modelling complex heterogeneous forest canopies at high resolution

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ABSTRACT

The structure of tree canopies affects turbulence in the atmospheric boundary layer, and light attenuation, reflection and emission from forested areas. Through these effects, canopy structure interacts with fluxes of heat, water, CO_2, and volatile organic compounds, and affects patterns of soil moisture and ecosystem dynamics. The effects of canopy structure on the atmosphere are hard to measure and can be studied efficiently with large-eddy simulations. Remote sensing images that can be interpreted for biophysical properties are prone to errors due to effects of canopy structure, such as shading. However, the detailed 3-D canopy structure throughout a large spatial domain (up to several km^2) is rarely available.

We introduce a new method, namely the virtual canopy generator (V-CaGe), to construct finely detailed, 3-D, virtual forest canopies for use in remote sensing, and atmospheric and other environmental models. These virtual canopies are based on commonly observed mean and variance of biophysical forest properties, and a map (or a remotely-sensed image) of leaf area, or canopy heights, of a canopy subdomain. The canopies are constructed by inverse 2-D Fourier-transform of the observed spatial autocorrelation function and a random phase. The resulting field is expanded to 3-D by using empirical allometric profiles. We demonstrate that the V-CaGe can generate realistic simulation domains.

1. Introduction

The structural variability of canopies is present across many length scales (Wirth et al., 2001). At the smaller scales, differences between trees, and branch structure within trees generate structural variability within the canopy. Canopy structure affects turbulence in and above the canopy (e.g. Finnigan, 2000; Kruijt et al., 2000; Patton et al., 2003; Poggi et al., 2004a,b), and as a result, it affects the rates of heat and vapour fluxes from the surface (e.g. Scanlon & Albertson, 2003; Styles et al., 2002), the release and dispersion of trace gases, such as CO_2 (e.g. Raupach, 1998; Styles et al., 2002; Vesala et al., 2000) and volatile organic compounds (Karl et al., 2004), and biological dispersal of seeds (e.g. Nathan & Katul, 2005; Nathan et al., 2005) and pollen (Katul et al., 2006b). It also affects the chemical dynamics of reacting scalars (Vinuesa & De Arellano, 2003). Canopy-atmosphere exchanges have been studied with eddy-flux covariance measurements, typically from towers in the canopy. Canopy structure and heterogeneity pose a challenge to the interpretation of such measurements (Baldocchi et al., 2000). One reason is that measurements from a single tower do not provide horizontal advection, which could be important in heterogeneous canopies and terrains (Aubinet et al., 2003; Feigenwinter et al., 2004; Staebler & Fitzjarrald, 2005, 2004). Also, determining the origin and source strength of a signal measured by a flux tower is difficult in heterogeneous canopies (Styles et al., 2002). Lagrangian methods are used to calculate a footprint area for the sources of fluxes that are measured at the tower (Rannik et al., 2000; Raupach, 1989a; 1989b). However, to date, these methods of footprint and eddy-covariance data analysis are still limited over heterogeneous canopies and terrains (Finnigan, 2004; Foken & Leclerc, 2004; Kruijt et al., 2004; Sogachev et al., 2005).

Some of the inherent problems of eddy-flux measurements can be elucidated with atmospheric models and, in particular, large-eddy simulations (LES) (Kanda et al., 2004; Katul et al., 2006a; Markkanen et al., 2003; Sogachev et al., 2002). Most atmospheric models solve an energy and mass balance at the lower boundary of the atmosphere. Typically, all sources and sinks of mass and energy exchange are made in the single lowest grid

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layer, which is usually 10-250 m deep. This is labelled the "big leaf" approach to soil-vegetation-atmosphere transfer schemes (SVAT). The "big leaf" is a bulk canopy layer that assumes only vertical exchanges and that the entire canopy behaves as a big leaf covering parts or the entire grid-cell, and which has a single "big stoma" that controls transpiration. LES using the "big leaf" approach are common and were successfully used to determine the effects of land surface heterogeneity on heat, vapour and CO_2 fluxes (e.g. Avissar & Schmidt, 1998; Bou-Zeid et al., 2004; Gopalakrishnan & Avissar, 2000; Markkanen et al., 2003; Scanlon & Albertson, 2003; Vesala et al., 2000), scalar dispersion (Gopalakrishnan et al., 2000; Sogachev et al., 2002), and the dynamics of reacting scalars emitted from the canopy (Vinuesa & De Arellano, 2003). The "big leaf" approach to land surface in LES does not explicitly resolve the effects of the vertical structure of the canopy on airflow. This simplification can lead to errors in calculation of total fluxes (Finnigan, 2004). LES studies using a 3-D horizontally homogeneous canopy with typical horizontally-averaged vertical leaf-density profiles have shown that the presence of the canopy and its vertical structure affect turbulence in and above the canopy layer (Shaw et al., 1988; Shaw & Patton, 2003; Su et al., 1998), modify the effects of flows over topographic features (Katul et al., 2006a; Patton et al., 2006), and the dispersal of volatile organic compound emissions (Patton et al., 2001). LES studies, focusing on the effects of surface heterogeneity on the atmospheric boundary layer (ABL), have determined that the length scale at which the atmosphere is sensitive to surface heterogeneity is between few km (Avissar & Schmidt, 1998; Patton et al., 2005) and few hundreds of metres (Scanlon & Albertson, 2003). However, much higher resolution of surface heterogeneity, and in particular where the "surfaces" are forest canopies, is needed to resolve flow around relevant canopy-scale features, such as windbreaks (Patton et al., 1998; Wang et al., 2001), and forest edges (e.g. Yang et al., 2006), and canopy scale processes such as the release and dispersion of volatile organic compounds (e.g. Patton et al., 2001) and biological dispersal (e.g. Nathan & Katul, 2005). In addition, even in cases where the small-scale features of the canopy do not effect the total mean flux or ABL dynamics, high resolution representation of the canopy is needed in order to compare the model results with point measurements within the canopy (e.g. Kanda et al., 2004; Patton et al., 2005).

With the constant improvements in parallel computing it is now technically feasible to simulate small domains (several km^2) at a grid spacing as high as 1 m^3 within a reasonable time (few CPU days for few real-time hours), and this will improve with future faster and larger computers. These simulations are essential to generate hypotheses and promote the general understanding of the interaction between canopy heterogeneity and atmospheric turbulence, and in the cases described above in particular. High-resolution canopy LES are also needed to help plan unbiased observation frameworks and to improve the interpretation of observations from eddy-flux measurements. But to date, LES of realistic, spatially heterogeneous (3-D) canopies is currently held back by the lack of high-resolution, explicit canopy information needed in the simulation domain. Therefore, even though some models are technically capable of using fully heterogeneous 3-D canopy domains, current LES studies are conducted using synthetic, over simplified, and horizontally homogeneous canopies. Another motivation for the over-simplification of canopy representation in environmental models is the desire to have only a few controllable variables that describe the canopy so that the models results are easier to interpret.

Remote sensing studies of forests over large spatial domains have largely ignored the higher resolution, 3-D structure of the canopy. Understanding the statistical properties of shadowing is a step forward in developing better ways to interpret carbon cycle, hydrology, and land cover from satellite imagery (Asner et al., 1998; Asner & Warner, 2003). Shadows present a challenge to remote sensing because they represent a lack of signal. Inverse radiative models are used to infer biophysical properties from the remotely sensed signal. These methods are using light attenuation models to make a "best guess" about what type of canopy led to the observed signal after it was reflected and scattered from the canopy. Another way to obtain biophysical information from multi-spectral images is the spectral-mixing method (Asner et al., 2005; Fitzgerald et al., 2005). This method assumes that different canopy elements have different spectral absorption profiles, and use statistical methods to approximate the composition of these elements in the canopy, which led to the observed mixed signal. Correcting for shadows have been shown to improve the signals correlations to biophysical variables (Toivonen et al., 2006) but typically these methods treat shadows as uniformly dark (Fitzgerald et al., 2005) and cannot account for subpixel shadow patterns. The lower-resolution satellite images, such as Landsat and AVHRR are likely to be affected by inter- and intra-canopy shadowing that cannot be easily quantified. Higher resolution images, such as IKONOS, can be used to study shadows but at any given location these images are not available at all times of the day (revisit time of the satellite is around 3 days) and may be obstructed by clouds. Although it is possible to use the mean-shade statistics from high-resolution images to improve the information obtained from the lower-resolution products (Asner & Warner, 2003), the non-linear effects of canopy structure on absorption, reflection and shading at different wavelengths makes the general application of these shadow-correction methods difficult. By using a detailed 3-D high-resolution model canopy, with some assumptions about leaf clumping and leaf angle distribution, the details of light reflection and shading at different wavelengths, for different days of the year and times of the day could be readily calculated using radiative transfer models.

In order to model the effects of structural variability of the canopy on the environment, or on remotely sensed image, it is necessary to replicate the canopy at the scale that is relevant to the processes that facilitate these effects (e.g. turbulence and

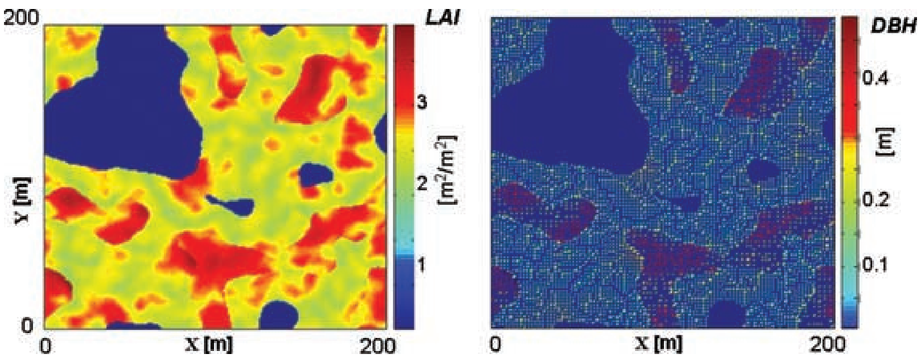

Fig. 1. Canopy properties of a virtual canopy with 3 patch types: hardwood, pine and grass. This virtual canopy was generated randomly, based on properties of the vegetation in the Duke Forest in April. Left panel – *LAI* based on mean observed LAI [m^2/m^2] per patch type. Right panel – *DBH* [m] of stem in the same virtual canopy. Note, grassy patches do not have stems.

dispersal, shading and reflection patterns of sunlight). In forest canopies, this scale is rather small (less than a few metres). At the same time, it is necessary to describe the canopy structure using a small number of variables. Although relevant information is known for a few well-studied canopies, e.g. the Duke Forest Free Air Carbon Enrichment (FACE) site, explicit 3-D mapping of leaf density and stem volume throughout the canopy domain is rarely available (for a rare example see Wirth et al., 2001). Advances in LiDAR technology (Lefsky et al., 2002; Weishampel et al., 2000) may be used in the future to map canopies in 3-D but are currently not widely applicable, and are still subject to trade-offs between large- and small-footprint technologies that either limit the horizontal spatial resolution or the ability to sample very large spatial domains and, therefore, are only applied in short field campaigns over limited areas. In addition, for experimental purposes, it is not realistic to manipulate study sites to obtain different structural configurations over large domains (e.g. create gaps, change canopy top variability). Thus, having realistic simulation capabilities over large domains of 3-D forest canopies is essential.

Given the chaotic nature of turbulence, it is customary to describe it in atmospheric studies by its statistical properties (i.e. mean, and higher order statistical moments) and not by explicit, instantaneous structures. This implies that it is not possible to simulate any specific observed eddy or the precise actual dispersal path of a single particle. One could argue that only the statistical properties of the canopy are likely to influence the statistics of turbulence and, therefore, only these properties need to be represented properly in LES domains and the explicit, fine details of the simulated vegetation canopy are not needed. The inverse modelling of remote sensing data described above is also a case in which the precise details of the small-scale structure should not be necessary and the statistical description of the fine structure is sufficient to understand the spectral components of large imagery pixels.

Here, we propose a method to generate a "virtual forest" that describes the 3-D statistical properties of the canopy structure at high resolution, hereafter referred to as the "Virtual Canopy Generator" – V-CaGe. A common Fourier transform method is used to generate a surrogate 2-D field that represents the canopy and preserves the observed spatial features of the canopy. This field is used as a platform and expanded to form the virtual canopy in 3-D. The structural characteristics of the resulting 3-D fields (i.e. height, leaf area and density, stem diameter) are consistent with the canopy structure, but unlike for explicit canopies, the information needed to generate the virtual canopies is readily available or could be obtained using remote sensing images at many forest sites.

2. Canopy construction

The Virtual-Canopy model generates a random canopy field, λ (Fig. 1) using a 2-D Fourier transform (FFT) with a specified correlation function and a random phase:

$$\lambda = \left|\mathrm{FFT}^{-1}\left(\left|\mathrm{FFT}\left(\mathbf{F_{ac}}\right)\right| \times e^{2\pi i\,\mathrm{rnd}(\mathbf{F})}\right)\right|, \quad (1)$$

where rnd(**F**) is the phase matrix containing uniform-random values with the same dimensions as the autocorrelation matrix $\mathbf{F_{ac}}$. Similar methods of surrogate data generation using random-phase FFT algorithms were previously used, for example, to generate fields of vegetation-cover surface-parameters (Albertson et al., 1998; Gilbert et al., 1990), precipitation (Ferraris et al., 2003; Venugopal et al., 2005), 2-D and 3-D clouds (Venema et al., 2006), and 3-D turbulence (Rogallo, 1981).

The autocorrelation matrix can be obtained by Fourier decomposition of any horizontal field that describes the canopy, such as a map of accumulated leaf area index (LAI), or the height of the canopy top. These maps can be obtained by ground observations, or derived from LiDAR measurements (e.g. Lefsky et al., 2002; Weishampel et al., 2000), or stereoscopic imaging (Gong et al., 2000). Abstract autocorrelation functions that do not translate directly into canopy properties, but were shown to be correlated, with other biological features of the forest, can be obtained from high-resolution aerial images (Couteron et al., 2005) or high-resolution satellite imagery such as IKONOS (Asner & Warner, 2003). These can also be used to generate the virtual canopies, if some observed information (obtained either by LiDAR of from the ground) about the mean and variance of canopy height and LAI exists, at least at some small subdomain of the area in the satellite images or in another biologically comparable area.

As a synthetic alternative to using an observed autocorrelation function, a theoretical canopy can also be generated by using a fitted, smoothed, exponential autocorrelation function, controlled by a prescribed parameter for the length-scale of heterogeneity, L, which is defined such that:

$$\mathbf{F}_{\mathbf{ac}}^{(xy)} = \exp\left(\frac{\sqrt{\left(\mathbf{X}^{(xy)}\right)^2 + \left(\mathbf{Y}^{(xy)}\right)^2}}{-L}\right), \tag{2}$$

where **X** and **Y** are coordinate matrices on shifted scale:

$$(\mathbf{X})^{(xy)} = -\Delta x\left(\frac{(Nx-1)}{2} - (x-1)\right); \quad (\mathbf{Y})^{(xy)} = -\Delta y\left(\frac{(Ny-1)}{2} - (y-1)\right), \tag{3}$$

and Δx and Δy are the grid spaces, and Nx and Ny are the number of grid points in the x and y directions, respectively. This simplified autocorrelation function is useful in studies of the effects of surface discontinuities at different scales because it is driven by a single controllable parameter, L.

Regardless of the data source for the autocorrelation function, the resulting field represents the relative size (on an arbitrary scale) of the canopy feature, whose spatial structure fits the autocorrelation function. This field represents a canopy of a particular patch-type. A patch-type defines a set of observed canopy properties. Patch types differ in their intra-patch autocorrelation function. They also differ in stand density, in the mean and standard deviation of canopy top height, LAI, and stem diameter at breast height (*DBH*), and in the vertical profile of leaf area density and stem radius. Values for these patch properties are obtained from observations or calculated from other correlated values using empirical allometric functions. A correlated set of biophysical properties per patch type, $\mathbf{CH}^{(PT)}$, (e.g. canopy top height, LAI, *etc*.) can be determined by transforming $\lambda^{(PT)}$ based on the observed means and standard deviations of the properties per patch type:

$$\mathbf{CH}^{(PT)} = \max\left(0, \left(\lambda^{(PT)} - \bar{\lambda}^{(PT)}\right) \times \frac{\sigma_{CH_{obs}}^{(PT)}}{\sigma_{\lambda}^{(PT)}} + \overline{CH}_{obs}^{(PT)}\right), \tag{4}$$

Where a superscript $^{(PT)}$ represents a patch-type specific value, $\overline{CH}_{obs}^{(PT)}$ is the observed mean field value for that property in that patch type, and $\sigma_{CH_{obs}}^{(PT)}$ is its standard deviation (Fig. 1).

With this representation, *DBH*, is calculated from the canopy height based on empirical allometric functions (e.g. Naidu et al., 1998). To account for the observed stand density, a coarser grid mesh is calculated for each patch so that the density (i.e. grid cells per unit area) of the coarse-grid cells is equal to the stand density of that patch type. The coarse mesh size is rounded so that each of the coarse-grid cells includes an integer number of the original fine-grid cells. One virtual stem is assigned to each coarse-grid cell. The location of this stem is determined by the location of the fine-grid cell with the tallest canopy (among all fine-grid cells) within the considered coarse-grid cell. *DBH* for that stem is calculated based on LAI and canopy top height at the fine-grid cell that is colocated with the stem. The remaining fine-grid cells within the coarse cell are assigned a $DBH = 0$ (i.e. they do not include a stem) (Fig. 1). The result is three correlated, 2-D arrays of canopy properties (canopy top height; *LAI*; and *DBH*). Other correlated canopy properties, such as canopy-top albedo, can be calculated in the same way, based on observations-derived mean and variability, or as functions of the above-mentioned canopy properties.

The 3-D canopy volume is filled by applying an observed, normalized, per-patch, mean vertical profile of leaf area density (*LAD*, m^2_{leaf}/m^3), and an empirically fitted stem-radius taper function. These profile functions have normalized vertical spacing of Δz_{norm} and a maximal height of 1 metre. At each horizontal location, the profile functions are de-normalized vertically by linearly stretching the normalized height scale, z_{norm}, to the actual height, z (from ground to canopy top), using the horizontal field of canopy top height. In each grid element (at the 3-D volume), the vertical distribution of stem radius, r_z, is multiplied by the value of the horizontal field *DBH* at that location. *LAD* is multiplied by LAI/Δz_{norm} in each grid element, so that it will sum to *LAI* when integrated vertically (Fig. 2).

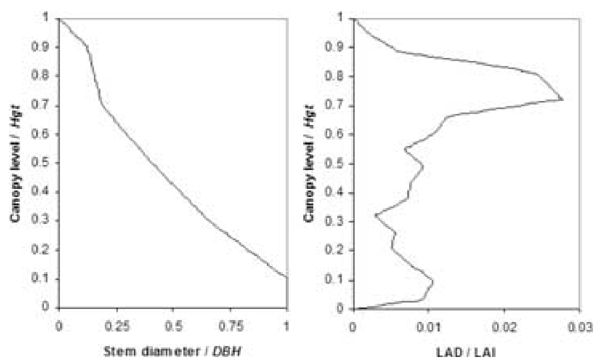

Fig. 2. Profile functions used to interpolate the values of stem radius, r_z (left) and *LAD* (right) in space. These normalized profiles are constant for each patch type. This example shows the profiles used for hardwood canopy at the Duke Forest, in December. The vertical axis represents a normalized height (z_{norm} = Canopy level/*Hgt*), where *Hgt* is the canopy top height at that point in the domain. The horizontal axis represents a normalized profile of canopy property ($2r_z/DBH$, left; *LAD/LAI*, right). To obtain the value of r_z and *LAD* at each grid-point in the canopy volume, the vertical axis is de-normalized to the canopy height at that point ($z = z_{norm} \times Hgt$), and the profile values are multiplied by *DBH* for r_z, and by $LAI/\Delta z_{norm}$ for *LAD*. Data for this example was obtained from the Duke Forest FACE site (McCarthy et al. 2007; Schäfer 2002).

V-CaGe can be used to generate domains with more than a single patch type. First, eq. (1) is used repeatedly to generate independent, equally dimensioned domains with a different autocorrelation function for each patch-type. Each of these $\lambda^{(PT)}$ fields is expanded to a full, single-patch, virtual canopy using eq. (4) and the process described above. An additional, independent field, $\lambda_{\mathbf{r}}$ is generated, this time with a regional inter-patch autocorrelation function. The typical length scale of the regional-field autocorrelation function describes the mean size of a patch and is therefore larger than the length-scale of the intra-patch autocorrelation functions (these describe the size of individual trees or tree clusters). A filter function is applied to the regional field, $\lambda_{\mathbf{r}}$, in order to divide it into patch types, PT, which occupy prescribed portions,%p, of the total area. A cut off filter value is calculated from the histogram of $\lambda_{\mathbf{r}}$, so that the area of the $\lambda_{\mathbf{r}}$–field, in which values are below that of the cut off, occupies%p of the total domain (Fig. 3). A specified patch type is assigned to this subdomain. This method can be used to specify any number of patch types. In this way, the resulting patch-type distribution map corresponds to the observed regional-scale spatial structure of the landscape. This patch-type map is used as a mask to compile a multi-patch canopy. Each single-patch canopy field, $\mathbf{CH}^{(PT)}$, is multiplied by an index function, I, which equals one in the locations (on the patch-type map) that belong to PT, and zero everywhere else. The full canopy is obtained by adding up the fields of the different patch types,

$$\mathbf{CH} = \sum_{PT=1}^{\#\text{patch types}} \mathbf{CH}^{(PT)} \times I_{\{\lambda_{\mathbf{r}} \in PT\}} \quad (5)$$

Alternatively, when the observed patches are artificial or are distributed according to other, non-biological features of the landscape (e.g. topography, geology, human disturbance) the area and positions of the different patches can be prescribed explicitly.

The resulting virtual canopy gives a detailed 3-D description of leaf densities, stem volumes, canopy top heights and locations of trees in each patch type in a virtual domain that represents the structural statistics of an observed forest at any specified high resolution. For example a virtual representation of a loblolly pine canopy at the Duke Forest, at a resolution of $2 \times 2 \times 2$ m^3 is illustrated in Fig. 4. An advantage of this method is that the resulting canopy-property arrays have cyclic boundaries (because FFT assumes infinitely repetitive waves), which correspond to the typical cyclic-boundary conditions of LES models. Furthermore, an unlimited number of virtual canopies with identical properties can be produced to represent different spatial realizations of the same canopy (Fig. 5). Such realizations are particularly useful to generate ensembles of simulations of the same forest. A realistic canopy ensemble can be used for validation purposes. But in addition, the virtual canopy can be readily manipulated to generate various hypothetical canopies for studying the effects of the canopy properties on turbulence, the atmospheric boundary layer, light attenuation and dispersal, among many others. For example, canopies with similar properties but different length scale of discontinuity (Fig. 5), or canopies with different distributions of patches (e.g. larger proportions of grassy patches), can be generated to study the possible effects of forest discontinuity, such as selective logging and invasion by exotic species.

3. V-CaGe application

The Duke Forest-Atmosphere Carbon Transfer and Storage (FACTS-I) facility is used for studies of carbon balance and ecosystem dynamics in ambient and elevated CO_2 conditions. This forest consists of mixed hardwood patches, several patches of allepo pine trees (the FACE experiment is located in one of them), and a large deforested grass patch. A remote

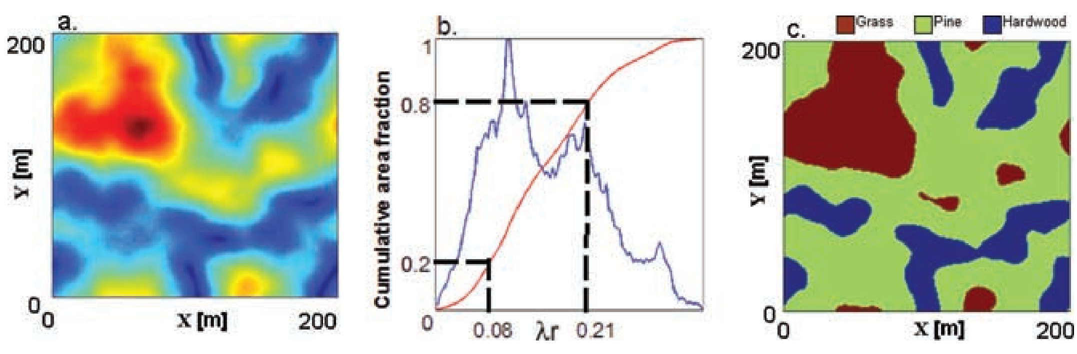

Fig. 3. Random regional-level field, λ_r (a) with arbitrary values between 0 and 0.33 is generated in this example with an autocorrelation length of 25 metres. λ_r is split into patch types using a histogram filter (b) to generate a patch-type map (c). This patch-type map was used in Fig. 1. The accumulated fraction of the total domain area that each patch type occupies is specified (b. horizontal dashed lines). The accumulated distribution function of λ_r values (b. red line), calculated from the histogram of λ_r (b. blue line), is used to calculate cut off values of λ_r that separate patch types (b. vertical dashed lines). In this example the area is split to 3 patch types that represent hardwood, pine, and grass patches (c. red; green; and blue areas, respectively), which are assigned 20%, 60%, and 20% (20%, 80%, 100% accumulated) of the area (respectively). The corresponding cut off values that separate hardwood from pine and pine from grass are 0.08 and 0.21 (respectively).

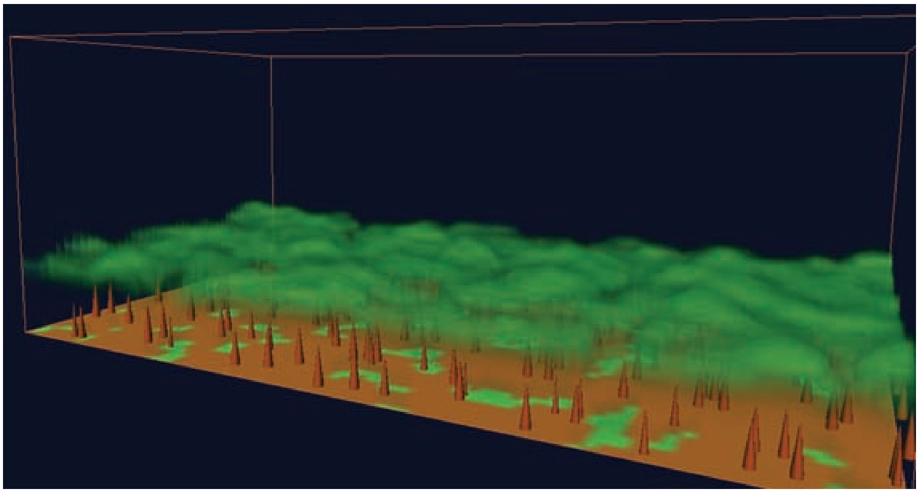

Fig. 4. Visualization of a virtual loblolly-pine canopy based on a stand at the Duke Forest FACE site (McCarthy et al. 2007; Schäfer 2002) with 15% prescribed grassy patches. This canopy was constructed at a resolution of $2 \times 2 \times 2$ m^3. Maximal canopy height is 20 metres and the visualization domain size is 80×60 metres. Patch type is projected on the forest "floor", brown marks pine and green marks grassy patches. Leaf density is presented as green "clouds". Brown cones represent stems. Stand density controls the number of stems in the domain, and stem diameter is proportional to the diameter of the brown cones and scaled by a factor of 10. This visualization was produced with AMIRA 3.1.1 (Mercury Computer Systems, Inc.).

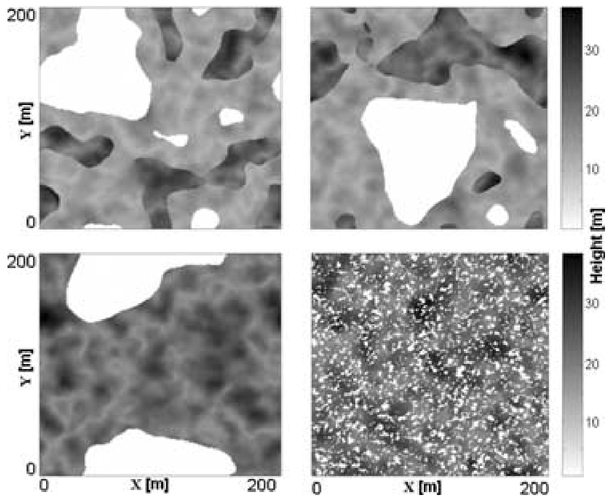

Fig. 5. Virtual canopy-top heights realizations. Top panels show two different random realizations of the same canopy properties (top left panel is the same realization shown in Figures 1, 3). Bottom panels show two realizations of a canopy with different regional length scales of discontinuity (left, 50 metres; right, 1 metre) that may represent different deforestation patterns such as farming and selective logging (respectively). In both bottom panels the canopy has two patch types, 80% hardwood and 20% grass. The vegetation properties per patch type in these to panels are identical.

sensing mission to measure the topography and canopy structure of a section of this forest, including the FACE site and its adjacent hardwood and mixed pine-hardwood stands, was flown on Oct 23, 2002. The equipment module and method for this mission was designed by Slaymaker et al. (1999) and consisted of an airborne digital video camera, a laser altimeter, a differential GPS system, a 3-axis solid state inertial reference system, and a PC-based recording system. A series of overlapping stereoscopic 4-band color-IR aerial images with a single-line LiDAR scan for height verification were produced. These images were interpreted and processed into a map of canopy top heights. In the interpretation process, standard aerial triangulation was performed using Erdas Imagine's Photogrammetry Suite (Erdas Imagine 8.7, Leica Geosystems) and sample points in the canopy were generated from the most nadir views using OrthoBase Pro's automated DTM extraction techniques (OrthoBase Pro 8.7, Leica Geosystems). Ground observations together with a data set collected by LiDAR at several points were used to validate the processed maps. After filtering obvious outliers, a raster canopy elevation model was interpolated at 1-metre resolution, averaging 3.5 control points per 2 metres of the final raster. Finally, a map of canopy-top heights was generated by subtracting an independently generated LiDAR-based ground elevation model (North Carolina Floodplain Mapping Program, http://www.ncfloodmaps.com/default_swf.asp) from the canopy elevations.

The resulting map of canopy top heights covers a limited and irregularly shaped area (Fig. 7). There are few reasons that led to those missing data points. Stereoscopic data was not available for an area at the end of the flight line that does not appear in two overlapping images. A particularly strong distortion at the extreme edges of the images reduces the overlapping area between images. In addition, in some areas the lack of independent control points prevented confident validation of the imagery-derived canopy elevation data.

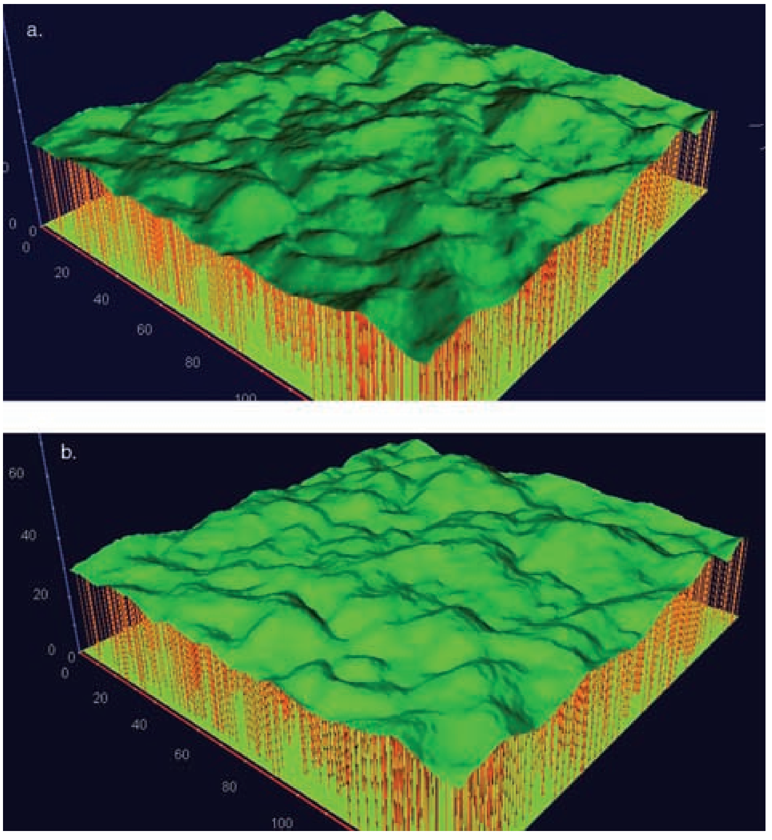

Fig. 6. Use of the V-CaGe to predict canopy shading. The image illustrates two different shading patterns of the same V-CaGe generated canopy from the same point of view but with two different light source locations. Both images show a 125 × 125 m^2 patch of virtual canopy based on the Duke Forest hardwood stand. Observed mean canopy height is 23 metres and the standard deviation of canopy top height is 3.8 metres. (a.) light source is positioned at the low east of the horizon. (b.) the light source is positioned above and slightly south of the image. In this simple illustration, light projection calculation and visualization was done using AMIRA 3.1.1 (Mercury Computer Systems, Inc.) assuming the canopy top is a continuous, uniformly green surface and, thus, accounts only for the effects of the canopy top shape. More sophisticated light attenuation models can also include the affects of *LAD* in the canopy volume.

These images and ground-based observations are the basis for several simulation studies of light attenuation, forest growth and regeneration, turbulence in and above the canopy and seed dispersal by wind. All of these studies require a continuous simulation domain. Thus, to overcome the gaps in observations, we used V-CaGe to produce a "Duke Forest virtual canopy" over a continuous and square domain. For this purpose, we processed the map of canopy top heights (described above) and calculated the mean and variance of canopy top heights, and the autocorrelation function. We used ground-based observations of mean vertical profile of *LAD*, stand density and the mean and variance of *LAI* (McCarthy et al., 2007; Schäfer, 2002), and empirically fitted stem taper functions for oak from Naidu et al. (1998). As illustrated in Fig. 7, the resulting virtual canopy has the same characteristics as the observed one, but individual features such as the locations of trees and gaps are randomly positioned within the domain.

4. Potential applications

While this section does not intend to provide an exhaustive list of all potential applications of V-CaGe, a few obvious ones (relevant to this special issue for the Integrated Land Ecosystem – Atmosphere Processes Study, iLEAPS) are summarized here. Virtual canopies can be used as high-resolution forest platforms that represent real forest canopies by a wide range of atmospheric and other environmental models. Leaf density can be used to calculate the drag force that canopy elements will exert on airflow in LES (for example of drag formulation as a function of leaf area see Shaw & Patton, 2003). LES that use the shaved grid-cell method (Adcroft et al., 1997) can account for the effects of stem and leaf volume that restrict the open space and aperture areas available for airflow.

The detailed description of leaf density (i.e., leaf area or volume per volume of air) can also be used by light attenuation schemes to calculate the amount of light that penetrates the forest floor, or the fraction of light that is reflected to the atmosphere. The structural heterogeneity of the canopy that is statistically captured by V-CaGe generates spatial heterogeneity of light attenuation and reflection that is typically neglected when homogeneous canopies are assumed. Furthermore, as illustrated in Fig. 6, with V-CaGe it is possible to use simple light attenuation models, or more complicated ones that include the penumbral effects as well as the effects of leaf-clumping (e.g. Stenberg, 1995), or even consider the full geometry of the canopy along the path of the light given the location of the sun and the observer, to predict the amount of reflected light and the distribution of shade at different wavelengths. These calculated radiation fields can also be used as a "null hypothesis" to reduce variables and improve the estimates of inverse radiative transfer models and spectral-mixing methods in remote sensing interpretation. They can also be used to improve the subpixel parameterization in

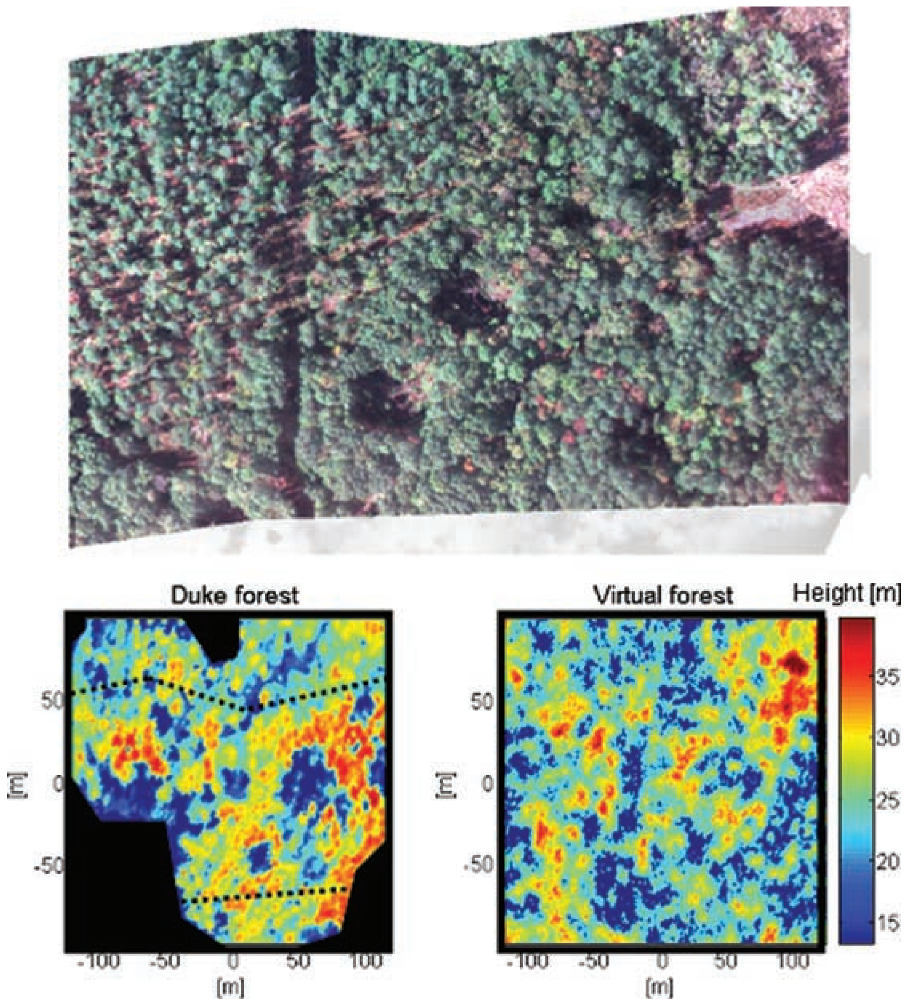

Fig. 7. Stereoscopic aerial photography of the Duke Forest (top panel, true colors) overlaid on a LiDAR-based topographic map (top panel, semi-transparent gray scale) was used to study the canopy top heights at a section of this forest. Bottom left panel shows the resulting map of canopy top heights, dashed lines mark the area presented in the aerial image in the top panel, several partially overlapping strips were used to generate this map. The black mask areas in the map are areas where canopy top information could not be obtained from the aerial images due to shading or distorting artefacts at the edge of at least one of the stereoscopic images. The mean, variance and autocorrelation function of this map were used to generate a V-CaGe realization of the Duke Forest (bottom right). Colours represent canopy top height [m]. The size of both domains is 250 × 200 metres, at a resolution of 1 × 1 m^2. The virtual canopy can be extended (assuming the same canopy statistics) to fill any specified area, and make up for missing gaps in the observations.

many remote sensing interpretation schemes (e.g. Asner et al., 1998; Asner & Warner, 2003; Fitzgerald et al., 2005; Houser et al., 1998; Toivonen et al., 2006).

Stem dimensions and locations can be used for explicit, tree-level, hydrological calculation of sap flow (Bohrer et al., 2005; Chuang et al., 2006). Leaf-density and canopy-structure driven light attenuation, tree hydrology, and airflow can be combined in a multi-layered energy balance approach to calculate the pseudo 3-D distribution of leaf temperature, and the latent and sensible heat fluxes exchanged between the lower atmosphere, the vegetation and ground surface. This calculation can be calibrated to be biologically consistent with simulated species and can be linked to carbon uptake by using a transpiration parameterization (e.g. Farquhar et al., 1980; Leuning et al., 1995), or a volatile organic compound release-functions, which typically needs the detailed canopy structure as an input.

5. Conclusions

Non-linear interactions between subgrid-scale canopy structure, energy redistribution, and soil moisture can significantly affect grid-averaged fluxes and soil moisture in environmental models (Burke et al., 2004; Li & Avissar, 1994; Peters-Lidard et al., 2001). Therefore, an explicit, high-resolution representation of the canopy can improve the simulation of turbulence and turbulent dispersal with LES (e.g. Bohrer et al. in preparation; Patton et al. 2001; Patton et al. 2003), subgrid-scale parameterization in, and initialization of ecological dynamic models (e.g. Hurtt et al., 2004; Jackson et al., 2005; Moorcroft et al., 2001; Walko et al., 2000), fire prevention (Falkowski et al., 2005), watershed hydrology and soil moisture models (Houser et al., 1998; Peters-Lidard et al., 2001). The Virtual Canopy Generator (V-CaGe) is a new and effective way of generating such high-resolution, 3-D, heterogeneous canopy domains.

V-CaGe-produced canopies are statistically similar to real ones. They are based on the observed means and standard deviations of leaf area and canopy top heights, the observed mean vertical profiles of leaf density and stem radius (or a stem taper function), and a high-resolution map or image of some biophysical property of the canopy. These variables are commonly observed at forest research sites and can be interpreted from remotely-sensed images. The resulting virtual canopy maintains the same spatial structure as the observed canopy and represents the allometric relationships between canopy properties (such as the positive correlation between leaf density and tree height) in a biologically consistent way. It also defines the structure of the canopy in terms of these few controlled variables and allows meaningful manipulation of canopy structure in virtual experiments.

Different virtual canopies representing different ecological and biological conditions can be easily generated and used in LES and other environmental models to study the effects of heterogeneous canopy properties on various processes such as turbulence, fluxes, dispersal and light attenuation. We are using it in an LES coupled to a Eulerian-Lagrangian particle dispersal model to study the long distance dispersal of seeds and pollen at the Duke Forest and in Barro Colorado Island (Panama). These applications are beyond the scope of this paper and will be presented in future publications.

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