Response to review by Reviewer #2

We have listed each review comment, in blue italic font, followed by the response and description of revisions done to address this comment, and in most cases, followed by the revised version of the modified section (sentence to paragraph) from the revised manuscript. Because the revisions we made to the manuscript were extensive, we include the entire revised version of the manuscript at the end of this response letter.

I. General Comments

Parameterization of the momentum exchange between plant canopies and the atmosphere is of great importance in regional and global weather, climate and ecosystem models. The authors used large-eddy simulation (LES) to investigate the effects of four axes of canopy structures on the estimates of roughness parameters. These axes are (1) leaf area index (LAI), (2) vertical profile of leaf area density, (3) canopy height, and (4) canopy gap fraction. Results were compared with existing empirical models and evaluated against observations. These results are interesting and constructive. However, the manuscript needs substantial revision for publication.

Firstly, the authors should be careful about theories and concepts. For example, some statements of MOST were misleading (P16351, L15-16). The canopy roughness sublayer and the layer directly above rough surface are not identical (P16351, L16-17). The use of higher-order closure model is not only caused by the failure of MOST (P16351, L19). The definition of h_a does not agree with what we observe in Figs. 4, 5 and 6.

Secondly, the authors should provide more in-depth discussion for scientific methods, especially those in subsection 2.6. What are the most critical differences among these methods? What are the pros and cons for each method? What do we expect to see for the results? I suggest create a Table to compare these methods. The linear fitting used for Fig. 1 also needs justification. For results shown in Figs. 4, 5 and 6, the reason why Reynolds stress at the canopy top varied by a factor of 2 should be examined and explained.

Thirdly, the manuscript needs to be restructured. For example, section 2 is very long and goes to a lot of directions. It should be divided into at least two sections, one for numerical simulation only and the other for observations and empirical models. Specifically, subsections 2.3 — 2.6 can form a section "Large eddy simulations". The contents for these subsections should be restructured as well. Subsection 2.3 is a mix of model description and model setup. Subsections 2.4 and 2.6 have repetitive contents. I suggest restructure the subsections as "Model description", "Simulation setup" and "Determination of roughness parameters from simulation results". Another important issue is the missing of highlights of important results in the conclusions.

II. Specific Comments and Technical

Corrections Abstract

A. P16350, L1-9: There three sentences give motivation rather than an overview of a paper. They should be shortened to one sentence that occupies two lines at most.

Done as requested. The new section now reads: Surface roughness parameters, namely the roughness length and displacement height, are an integral input used to model surface fluxes. However, most models assume these parameters to be a fixed property of plant functional type and disregard its structural heterogeneity and dynamics.

B. P16350, L20:

a. What does "our model-resolved parameters" mean?

We revised this statement to: "our model-driven 'biometric' parameterization approach".

b. "Frictional velocity" and "friction velocity" were used alternatively throughout the manuscript. Please use the standard term "friction velocity" consistently.

Changed to 'friction velocity' throughout the manuscript.

C. P16350, L21-22:

a. Does "it" mean "friction velocity" or "our model-resolved parameters"?

We revised this sentence to: "We compared the accuracy of these predictions with the friction-velocity predictions" (with the former "it" meaning the accuracy of the predictions of u*)

b. What are the most important differences between "our model-resolved parameters" and "three other semi-empirical models"?

We added "that utilize varying canopy-structure inputs,… from meteorological observations".

D. P16350, L23: Which models used "parameterizations with fixed representations of roughness"?

We revised that to: "We found that the classical representation of constant roughness parameters (in space and time) as a fraction of canopy height performed relatively well. "

E. P16350, L24-25:

a. What are "some empirical approaches"? What models used "some empirical approaches"?

b. In what aspect and to what extent did "some empirical approaches" performed better?

To answer both points above, we clarify this sentence to "Nonetheless, of the approaches we tested, most of the empirical approaches that incorporate seasonal and inter-annual variation of roughness length and displacement height as a function of the dynamics of canopy structure produced more precise and less biased estimates for friction velocity than models with temporally invariable parameters." There is no space in the abstract to list and explain the different methods, we explain them in the results section.

1 Introduction

A. P16351, L15-16:

c. "MOST is expected to be accurate in the inertial sublayer": This statement is wrong, because MOST is an approximation based on certain assumptions.

d. "High above the ground surface in the inertial sublayer": This statement is misleading. ISL does not include all regions "high above the ground surface".

e. "The viscous effects of the rough underlying surface may be neglected" (in the ISL): This statement is wrong, because ISL is defined for wall-boundary-layer flow, where the flow is strongly affected by the wall.

f. "The vertical flux of momentum is constant" (in the ISL): This statement is wrong. The vertical flux of momentum is not constant.

B. P16351, L17-21:

a. "The rough surface" usually indicates a rough wall. Is the layer directly above the rough wall identical to the layer "near forest canopies"?

b. Please clarify the reason why MOST is inapplicable to the canopy roughness sublayer.

c. Please clarify the reason why higher-order closure models were used for the canopy roughness sublayer.

We removed the entire section referred to in comments A.c-f and B.a-c above. These statements relate to the particulars of the formulation used to determine the roughness parameters from observations of wind speed in the forest site and in the model. It is better explained around eq. 5 in the methods section, where the RSL correction term is described.

C. P16354, L4-8:

a. "Unlike most LES": This statement is misleading, as if there were very few existing LES studies resolving the canopy layer.

b. "RAFLES does not use a prescribed 2-D roughness length": This statement is misleading, as if models using roughness-length parameterization and models resolving the canopy layer were designed for the same research objectives.

c. "RAFLES incorporates leaf-level drag heterogeneously in 3-D and dynamically in time": This statement is misleading, as if RAFLES were resolving leaves and having these leaves interact with the flow dynamically.

We could argue that there are only a handful of LES that prescribe 3-D vegetation domains and do not use a vegetation-roughness surface boundary condition. But we would rather not argue about that and have removed that statement. The 'dynamic' part relates to the drag force. With the leaf surface area and stem surface area in each voxel are constant, the drag force is a dynamic function of wind speed and surface area roughness. The new sentence does not state anything about other models, and better explains how vegetation interacts with the flow in RAFLES. It now reads: "RAFLES incorporates a prescribed 3-D domain that includes the vegetation leaf density and stem diameters and dynamically calculates the change to wind velocity as a function of leaf and stem surface drag in each voxel".

2 Materials and methods

2.1 Theory

A. P16355, L1: Why is there a second title "Parameterization of aerodynamic canopy properties" for this subsection? Should it be combines with "Theory"?

Corrected as suggested.

B. P16355, L2-15:

a. “MOST describes the relationships between the mean horizontal wind speed and the friction velocity at all heights within the atmospheric surface layer”: This statement is misleading, because MOST was originally developed for inertial sublayer only.

We revised "all heights" to "the inertial sublayer".

b. “The friction velocity is a property of the turbulence of the flow”: This statement is vague. What specific characteristic of turbulence does friction velocity measure?

We removed this statement. Friction velocity is a basic property and does not need to be explained. In any case, the exact formulation of frictional velocity is listed in equation 3.

c. “MOST relates surface stress to d and z0”: This statement is vague. What does it mean by “relates”?
d. Eq. (1): This is not the original MOST, because MOST was developed for inertial sublayer only. Please clarify that this is a modified version that accounts for the canopy roughness sublayer as well. What are the assumptions associated with modifying MOST to account for the canopy roughness sublayer? How accurate is this equation?

To address comment (c) and to acknowledge that we used a modified version of MOST, we revised this sentence to "MOST describes the functional relationship between surface stress to d and z_0 and wind speed using a logarithmic function. The original MOST formulation was expanded to include the effects of thermal instability and the flow regimen in the roughness sub-layer (RSL). The formulation we used was:"

A reference to each correction term is provided next to the equation that describes it (Eq. 4-5). The evaluation of accuracy of the particular formulation was provided with these original papers that introduced these correction terms. These are, however, standard and very commonly used formulations, and we do not think that it is within the scope of this manuscript to further validate them. In theory, one would need an indented method (that does not rely on relating z_0 or d to wind speed) to measure roughness length and displacement height in order to provide a true validation for any of these formulations. As far as we know, this is not technically feasible in forest environments. But again, this is way beyond the scope of this manuscript.

C. P16356, L8-9:
a. “When conditions are neutrally buoyant”: This statement is potentially confusing, because “neutrally buoyant” is also used to describe materials having the same density as the carrying fluid.
b. “When conditions are neutrally buoyant, $\psi_m(x)$ becomes negligible”: This statement is misleading, because by definition $\psi_m(x)$ is zero for neutral conditions.

In the context of boundary layer meteorology and large eddy simulations, 'neutrally buoyant' is a well-defined and commonly used term. In any case, we changed it to 'boundary layer conditions are near neutral'. Adding 'near neutral' rather than neutral balances the 'approaches 0' which is now a correct statement.

D. P16356, L22: "h_a calculated from the horizontal wind profile": This statement is vague. The determination of h_a was restated on P16360, L18-19. This is difficult for readers to follow. See Comment #13 for additional issues associated with h_a.

This was a typo, and we mixed 'horizontal' with 'vertical'. We fixed that, and further clarified this sentence to read: "In simulation results, where the detailed 3-D wind field is known, we can use Eq. 7 to calculate a simulation-specific λ values using h_a, which can be calculated from the vertical profile of horizontal wind speed and the empirically fitted d and z_0."

E. P16357, L4-6: It sounds like that u_r' is calculated as $u_r' = u_r - \langle u_r \rangle$, where $u_r = (u^2+v^2)^{0.5}$. If this is not the case, please clarify mathematically how u_r' was calculated. If this is the case, please explain the physical meaning of u_r'.

This is not exactly the case. u_r is the downstream velocity on a streamwise-rotated coordinate system such that:

$u_r' = u_r - \langle u_r \rangle$

and $u_r = u\cos(\theta) + v\sin(\theta)$

where $\theta = \mathrm{atan2}(v,u)$; and $\langle u_r \rangle = (u^2+v^2)^{0.5}$

This is a common practice in micrometeorology, but not often done in LES (though it should be done in order to compare LES results to observations if the mean flow is not perfectly towards the same direction at all levels).

We added the following explanation (in section 2.5 of the revised manuscript):

"To calculate flux and wind statistics, we first calculated the mean value of each model variable at each vertical model level over the entire horizontal domain at that height level, and over all 300 time snapshots. We then rotated the horizontal wind coordinates of each vertical level toward the downstream direction, such that the resulting mean rotated downstream velocity is

$$\langle u_r \rangle_{xyt} = \left(\langle u \rangle_{xyt}^2 + \langle v \rangle_{xyt}^2 \right)^{1/2} \quad (8)$$

where $\langle \ \rangle_{xyt}$ marks an average of the simulation results over all voxels in the x (eastward) y (northward) and t (temporal, 300 snapshots) dimensions. Though the wind forcing aloft is eastward a rotation develops, following the Ekman spiral and further amplified by random x-y asymmetries in the simulation domain. The rotation for the horizontal coordinate system of each horizontal layer is necessary to maintain a consistent downstream axis needed for the data analysis. After this rotation, we calculated the instantaneous perturbation of the velocity components from the xyt average for each voxel in space and time along each horizontal layer, such that

$$u_r' = u_r - \langle u_r \rangle_{xyt} \quad (9)$$

where the prime marks an instantaneous perturbation from the mean value, in this example of the u_r (downstream) velocity component. Similar formulation applies to the vertical (w) and cross-stream (v_r) velocity components. Momentum flux at the down-steam direction was calculated as

$$\langle u_r{}'w'\rangle_{xyt} = \left\langle \left(u_r - \langle u_r\rangle_{xyt}\right)\left(w - \langle w\rangle_{xyt}\right)\right\rangle_{xyt} \quad (10)$$

See Bohrer et al. (2009) for more details on the calculation of wind statistics and momentum fluxes from RAFLES output."

2.2 Site description

2.3 Large eddy simulations

A. P16358, L6-8:

a. "RAFLES resolves the canopy as a 3-D heterogeneous domain where the leaves interact with the flow": Same issue as 1C.

Revised to: "RAFLES (Bohrer et al., 2009) uses a 3-D heterogeneous canopy domain where leaf and stem areas are prescribed within each voxel. The leaf area density and the wind speed within the voxel determine the drag force that is applied to wind flow through that grid cell within each time step. "

b. "The canopy is represented as leaf density and volume restriction terms": Here comes the true description of RAFLES. Please clarify the physical meaning of this type of canopy representation. What specific effects of canopy on the flow were accounted for by RAFLES? What are the other potentially important effects of canopy on the flow that have not been accounted for by RAFLES?

I can spend days and fill volumes providing the most accurate description and justification for the LES model, its numerical approach and all of its parameterizations. I did all of that in my thesis (Bohrer 2007), and in a much more concise way, the model is described in Bohrer et al (2009) and Chatziefstratiou et al (2014), both are referenced in this section. We have to strike a balance between providing enough detail to understand what we did, and not overburdening the readers with too much detail about the inner guts of the model. RAFLES is well established and interested readers can find the details in the listed references that describe the model.

We did add some more details, particularly for items that are related to the effects of the canopy.

"The leaf area density and the instantaneous wind speed within the voxel determine the drag force that is applied to wind flow through that grid cell within each time step. Common to the approach used in most LES, it assumes the leaf area is composed of flat surfaces oriented downstream and neglects higher-order effects of leaf and stem shapes and sub-grid-scale wake generation (shown to be a small effect, Shaw and Patton, 2003). It is combined with radiation attenuation (given the leaf densities in the grid cells above) to determine the sensible and latent heat fluxes emitted in each grid cell. The model uses the finite volume approach for discretization of the simulation domain. It resolves the effects of volume restriction due to the volume of the vegetation (stems, branches) by reducing the aperture areas available for flux exchange between each pair of neighboring grid cells and by reducing the volume that is available for flow within each grid cell according to the volume of the vegetation present within the grid cell (Chatziefstratiou et al., 2014). It resolves sub-grid-scale turbulence using the Deardorff (1978) scheme, and includes a parameterization for sub-grid-scale turbulence dissipation due to leaf drag (Shaw and Patton, 2003)."

B. P16358, L25-27:

a. Were subgrid-scale fluxes and statistics available in the snapshots? If so, were they used in the calculation of fluxes and statistics? At least subgrid-scale fluxes of momentum and scalars should be included in the analysis.

Only sub-grid-scale turbulence (SGS-TKE) is available in the model output, and it is a directionless scalar, and thus, cannot be directly added to the resolved fluxes. The model dynamically calculates the components of the momentum equation that are driven by the sub-grid-scale stresses, as parameterized by SGS-TKE, but this calculation is done at 40 Hz and the statistics of the sub-components of the momentum equation are not recorded as state variables at the 2-second snapshots. In any case, due to the fine resolution of the model, these terms are relatively small in the regions that are used to calculate the roughness length, above 1.5*h* (at that height, SGS-TKE is less than 1% of resolved kinetic energy).

b. The description of how fluxes and statistics were calculated is unclear. Take <u’w’> (Reynolds stress) for example, it sounds like that it was calculated as $\langle u'w' \rangle = \langle (u'w' - \langle u'w' \rangle_{xy}) \rangle_{xyt}$, where subscript xy indicates average over the horizontal plane, and subscript xyt indicates average over the horizontal plane and time. This is not the definition of Reynolds stress. Please clarify the definition of Reynolds stress from Reynolds decomposition. What would be the physical meaning for Reynolds decomposition using mean quantities determined by time, spatial and ensemble averaging, respectively? Which averaging is most appropriate for the analysis performed here?

We added a detailed description and formulation. See the new explanation and formulation in our response to comment E above. We use a consistent Reynolds decomposition, applied in space and in time. We were wrong to relate to $\langle w'u_r' \rangle$ as 'Reynolds Stress', though it is commonly done. There is a factor of air density between the downstream components of Reynolds Stress and $\langle w'u_r' \rangle$. We now use the term streamwise momentum flux instead of Reynolds Stress throughout the manuscript.

C. P16359, L10: What is the mathematical expression for “a reflective top boundary”? Please explain the reason why a reflective boundary condition was chosen.

We replaced the term 'reflective top' with 'no-flux' boundary condition. They are the same thing, but 'no-flux boundary condition' is the proper term to describe it. It is a very standard LES approach and we see no reason to explain it further, especially since the top boundary (at 1 km) has little to no influence on the results at the sub-domain we used for data analysis (at 40-100 m).

D. P16359, L13-14:

a. “Surface boundary layer height”: This is not a defined term. Is it “surface layer height” or “atmospheric boundary layer height”?

b. "Surface boundary layer height was prescribed by the shape of the potential temperature profile": This statement is vague. Please clarify how "surface boundary layer height" was prescribed.
c. The word "prescribed" leads to an impression that the "surface boundary layer height" does not evolve in time. Is it true? If so, please explain why a fix "surface boundary layer height" was used. If not, please replace the word "prescribed" with a more proper word.

For comments D.a-c, we clarify this sentence to: "The prescribed initial vertical profile of the potential temperature described a well-mixed atmospheric boundary layer and was constant from 50 m to the height of the capping inversion, and increased with height above that level. "

2.4 Virtual experiment setup

2.5 Empirical determination of roughness parameters from simulation results

A. P16360, L18-19: Here comes the determination of h_a. What is the corresponding mathematical expression?

We mixed up two different terms in this section. We apologize for that. We cleaned up this section. It now reads: "We determined the effective aerodynamic canopy height, h_a, by identifying the height at which the inflection point in the vertical wind-speed profile. This height marks the transition between the sub-canopy and above-canopy flow regimes (Thomas and Foken, 2007). To find this point we compiled a domain-averaged wind-speed profile using Eq. 8. Then, we determined h_a as the location where the second derivative of the horizontal wind profile crosses zero."

B. P16361, L2: What does "the lateral forcing of wind speed was effective" mean?

We removed that statement.

C. P16361, L6-8: The mean u_* and Obukhov length were used, implying u_* and Obukhov length varied with height. What are the degree of variations? What caused the variation? What averaging method was used to obtain the mean? Please also justify the physical meaning of the averaging method.

Obukhov length is a direct function of elevation as it is dependent on the virtual temperature, which varies with height. In the MOST formulation it is used as a ratio z/L and at each z there is a corresponding L. $u*$ is invariable over a range far from the ground. In the model there are very small (<0.1%) variations in $u*$ within the range 3.5-4.5h, and we used the average value of $u*$ from this range.
When interpreting tower observations, z is used as the tower height and both L and u* are calculated at the tower height.
"We calculated the characteristic domain-averaged u_* for each simulation case by calculating the horizontal-temporal average u_* for each for each horizontal plane of grid cells within the 3-D virtual

domain and further averaging these vertically over the range from 3.5-4.5*h* (u_* values are nearly invariable with height in that range). Obukhov length was calculated for each horizontal plane of grid cells within the 3-D virtual domain as a function of the characteristic u_*, surface heat flux (which was prescribed) and the mean potential virtual temperature at each horizontal plane of grid cells. Next, the vertical profile of horizontal mean wind speed from vertical layers above 1.5h_a and below 4.5*h* (95 m) above ground was fitted to Eq. 1 to determine *d* and z_0 using the characteristic friction velocity and the Obukhov length. "

2.6 Surface roughness parameters:forest structure effects

A. P16361, L14-17: This sentence provides the same information as P16360, L3-6.

We removed the entire 2.6 section.

2.7 Testing empirical models linking roughness parameters to biometric measurements

A. P16361-16362: Please clarify the difference among the three methods: (a) "Biometric", (b) "Raupach (1994)" and (c) Nakai et al. (2008a). Why are they chosen as representatives for the determination of roughness parameters? What performance do we expect from a theoretical perspective?

B. P16363, L7-8: Please clarify the approach of "Yearly Observed".

A-B: We rewrote this section and moved it to the 'Results' (following a request by Reviewer #1). The methods are now explained in a clearer way. The difference between the approaches are clearly provided by the detailed descriptions of the methods. We added a discussion of the differences in the type of input needed for each method and the significance of that for potential application of each model in the discussion section. Please see revised sections 3.1 and 3.2 for explanation of the different approaches, and revised section 4.2 for discussion of differences between them.

3 Results

3.1 Virtual experiment to explore canopy-roughness relationships

3.2 Canopy-roughness improvements to surface flux models 4 Discussion

4.1 Response of roughness parameters to canopy structure change

A. P16367, L2-3: What does "the ability for eddies to transport momentum" mean? Does it precisely describe the physical meaning of the eddy penetration depth shown in Fig. 3a? What does the comparison "weakened" point to? Is it a comparison within a specific type of eddies or for the distribution of eddies on some characteristics scales?

We completely rewrote this section and this sentence is no longer included in the revised version.

B. P16367, L4: What does "sub-canopy turbulence" mean? Is it well characterized by vertical momentum flux only?

We meant "turbulence kinetic energy inside the canopy domain." We revised it accordingly.

C. P16367, L16-17: Please specify "environmental forcing". Through what mechanism does "environment forcing" affect the values of roughness parameters?

This statement is no longer included in the revised section.

4.2 Integrating canopy-structure characteristics into flux models

5 Conclusions

A. P16371, L4-22: I do not see highlights of the most important results from this paper.

We added them. We prefer to limit the conclusions section to concluding remarks that integrate what we have found in the study and put it in a broader context, and not to act as a second abstract. We did however revise the conclusions section, and we hope that you find the revised version improved relative to the previous one. The revised conclusions section:

"In this study we used an LES, long-term meteorological observations, and remote sensing of the canopy to explore the effects of canopy structure on surface roughness parameters in a forest site. We performed a virtual experiment to test the sensitivity of roughness parameters with respect to four axes of variation in canopy structure: (1) leaf area index, (2) the mode of the vertical profile of LAD, (3) canopy height, and (4) gap fraction. We found consistent relationships between the aerodynamic canopy height and *LAI*, maximum height, and gap fraction and between d and maximal canopy height. We found that the predicted values of friction velocity are not sensitive to roughness length. As a result, most of the roughness-based approaches we tested for simulating friction velocity performed similarly well. This is despite having very different approaches for determining the values of z_0 and d, and having large differences in the range of z_0 and d values. This is good news for modelers, because it limits the error from using the current approaches that do not vary in time and do not incorporate canopy structure.

Nonetheless, most of the approaches we tested which used annually variable z_0 and d and that incorporated canopy structure provided better approximation for friction velocity than the 'Classical', time-invariable method. Many easily obtainable metrics of canopy-structure characteristics are available through a suite of measurements, such as on-site meteorological and biometric observations or satellite-derived site characteristics. Additionally, many ecosystem models and ecosystem modules within earth system models resolve the growth of the forest and accurately predict canopy height and *LAI*. Some models, such as the Ecosystem Demography model (Medvigy et al., 2009) even resolve the distribution of stem sizes. Such demographic models could readily incorporate the approach by Raupach (1994) for a significant improvement in surface roughness parameterization. For other models that resolve, or are forced by observed leaf area and vegetation height, our LES-derived 'Biometric' approach could offer an easy way to dynamically affect the roughness-length parameterization. This could provide an improvement of surface flux modeling, especially when canopy structure variations are large. Due to limited spatial coverage by direct meteorological measurements, remote sensed structure statistics, and stand inventories, we suggest utilizing site- and time-specific biometric measurements of canopy structure to estimate site-level *d* and z_0. The effectivity of these model improvements will, of course, be dependent upon the quality, quantity, and resolution of the datasets available at the forest of interest."

References

A. *P16377, L4: "Reynolds" should be capitalized.*

Corrected.

Tables

Table 3

A. The value of r^2 is 0.80 for all cases. If it was calculated, please explain the reason why the same value was found for all cases. If it was prescribed, please clarify and explain why it was not calculated.

We redid this analysis and expanded the period over which we model u* values. We provide the r^2 values of the revised analysis to the 3rd significant figure, and they are not all identical.

B. How do Biometric estimates of d and z_0 compare with observations and other models? Please discuss the discrepancies among d and z_0 and the effects of these discrepancies on the estimates of u_*.

d estimates from the 'Biometric' approach are within the range of the inter-annual variation of the observed values. z_0 values are about twice as high, and at the highest range among all approaches. However there is very little agreement between any of the methods about the values of z_0. We added the following section to the end of section 3.2 (results):
"The values of d and z_0 as determined by each of the parameterization approaches are listed in Table 3. The range for yearly observed mean *d* values was 18.3-26.0 m and for z_0 0.99-1.99 m. The 'Classical' approximation based on *h* resulted in a significantly lower *d* = 14.0 m (outside the range of the inter-annual variability over 12 years), and a slightly above-range z_0 = 2.10 m. The 'Explicit-LES' resulted in a very similar *d* to the 'Classical' approach. The 'Biometric' approach predicted high but within-range *d* values (24.0-25.0 m) but extreme z_0 values (3.64-3.82 m). There was nearly no overlap between the values of z_0 prom each of the approaches, indicating poor agreement between approaches for this parameter."

Fig. 1

A. How do LES results of d and z_0 compare with other models? Please discuss the discrepancies.

We added this discussion to the results. See response above.

B. The definition of "leaf-off" and "leaf-on" were given in the figure caption. They should also be stated in the text where these terms were first mentioned.

We added this at section 2.4 of the methods.

Fig. 2

A. Figs. 2a and 2c: The variation of h_a is within 0.3 m for the range of LAI (2a) and within 0.2 m for the range of gap fraction (for a fixed value of LAI in 2c). The dependence of h_a on LAI and gap fraction would only be convincing if the variation of ha is much larger than the uncertainty associated with the determination of h_a. What are the uncertainties associated with the estimates of h_a?

The statistics of these relationships are provided in Table 2. The relationship between h_a and gap fraction, and *LAI* are strongly significant.

Fig. 4 — 6

1. Figs. 4a, 5a and 6a: It was stated on P16360, L18-19 that h_a was determined as the height of inflection point. However, in the figures the inflection points were visually below the corresponding values of h_a provided in Table A1. Please explain.

We made a half-pixel shift of the y-axis labels used in the figure. We thank the reviewer for catching this error and we fixed the figures to list the correct heights.

2. Fig. 4b, 5b and 6b: What caused Reynolds stress at the canopy top vary by a factor of two? Were all these simulations forced by the same geostrophic wind? To what degree did the atmospheric boundary height vary from one simulation to another?

All simulations are forced by the same wind speed aloft, initialized by the same vertical profile of potential temperature (which determines the atmospheric boundary layer height) and have the same surface heat flux, so the growth rate of the ABL should be similar in all simulations, and the wind profiles directly comparable. Reynolds stress has a sharp gradient and therefore, when showing it up to an arbitrary height near the canopy top, differences in *d* lead to differences in the value at that particular arbitrary height. We revised the figure to extend to a higher elevations (3*h*), and further normalize the momentum flux by u_*^2 and the results align across all simulations.

3. "Reynold's stress" used in the figure captions is incorrect. See P16377, L4, "Reynolds stress" is the correct term.

This was a typo, but we changed the term to Momentum flux, following other comments.

Large eddy simulations of surface roughness parameter sensitivity to canopy-structure characteristics

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Abstract

Surface roughness parameters, namely the roughness length and displacement height, are an integral input used to model surface fluxes. However, most models assume these parameters to be a fixed property of plant functional type and disregard the governing structural heterogeneity and dynamics. In this study, we use large-eddy simulations to explore, *in silico*, the effects of canopy structure characteristics on surface roughness parameters. We performed a virtual experiment to test the sensitivity of resolved surface roughness to four axes of canopy structure: (1) leaf area index, (2) the vertical profile of leaf density, (3) canopy height, and (4) canopy gap fraction. We found roughness parameters to be highly variable, but uncovered positive relationships between displacement height and maximum canopy height, aerodynamic canopy height and maximum canopy height and leaf area index, and eddy-penetration depth and gap fraction. We also found negative relationships between aerodynamic canopy height and gap fraction, and between eddy-penetration depth and maximum canopy height and leaf area index. We generalized our model results into a virtual 'Biometric' parameterization that relates roughness length and displacement height to canopy height, leaf area index and gap fraction. Using a decade of wind and canopy structure observations in a site in Michigan, we tested the effectiveness of our model-driven 'Biometric' parameterization approach in predicting the friction velocity over heterogeneous and disturbed canopies. We compared the accuracy of these predictions with the friction-velocity predictions obtained from the common simple approximation related to canopy height, the values calculated with large eddy simulations of the explicit canopy structure as measured by airborne and ground-based lidar, two other parameterization approaches that utilize varying canopy-structure inputs, and the annual and decadal means of the surface roughness parameters at the site from meteorological observations. We found that the classical representation of constant roughness parameters (in space and time) as a fraction of canopy height performed relatively well. Nonetheless, of the approaches we tested, most of the empirical approaches that incorporate seasonal and inter-annual variation of roughness length and displacement height as a function of the dynamics of canopy structure produced more precise and less biased estimates for friction velocity than models with temporally invariable parameters.

Introduction

Our ability to accurately predict mass and energy fluxes from the land surface to the atmosphere at any time scale depends on the accuracy of the surface drag parameterization (Finnigan, 2000;Mahrt, 2010). Over forested environments, vertical mixing of canopy air with the free atmosphere above, which is the process responsible for the exchange of energy, water vapor, and CO_2 between the land surface and the atmosphere, is a function of the turbulent eddies created through interactions between vegetative structure (e.g., trees, tree-stems, leaves) and the wind (Thomas and Foken, 2007a). In many regional models, estimation of surface drag, and thus surface fluxes, is typically dependent upon parameterization of the friction velocity, u_*, based on Monin-Obukhov similarity theory (MOST) (Monin and Obukhov, 1954) using parameters that describe the effects of drag generated by the surface on the shape of the curve describing the vertical distribution of wind speed. These parameters are displacement height, d, and roughness length, z_0. Though they represent different physical properties of the surface effects on the velocity profile, we will refer to them throughout the manuscript using the combined term 'roughness parameters'. In many land surface, vegetation, ecosystem, and hydrology models, such as the Community Earth System Model (CESM) (Gent et al., 2011), Mapping Evapotranspiration with Internalized Calibration (METRIC) (Allen et al., 2007), and Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen et al., 1998), the surface sensible and latent heat fluxes are functions of the aerodynamic resistance for heat transfer, r_{ah}. r_{ah} is a function of the turbulence at the surface layer, defined through the friction velocity, u_*. In models which cannot directly resolve u_*, r_{ah} is parameterized as a function of d and z_0. In these models d and z_0 may be derived from different canopy structure characteristics. By the simplest approach, d and z_0 are linear functions of site-level canopy height (h) – typically: $d \approx 0.66h$ (Cowan, 1968) and $z_0 \approx 0.10h$ (Tanner and Pelton, 1960). The accuracy of these estimates may be limited, however, by the dynamic nature (space and time) of canopy structural characteristics. First, the canopy is a complex structure that is hard to describe using simple low-variable-number formulations. Second, estimates of the canopy structural characteristics are limited by the typical absence of data about the vertical distribution of leaf area (Massman and Weil, 1999;Shaw and Pereira, 1982) and tree-top heights, and the difference between coarse model grid-cell resolution and the finer scale at which canopy structure characteristics vary and affect roughness and momentum and flux transfer.

One common approach to incorporate canopy structure in the parameterization of roughness length into models in a more realistic way utilizes satellite imagery products to estimate vegetation structure and relate it to canopy-roughness relationships. For example, the SEBAL model (Moran, 1990) utilizes a function based on the Normalized Difference Vegetation Index (NDVI) while the METRIC model employs Perrier Function (Perrier, 1982). These canopy-roughness relationships have been shown to improve evapotranspiration estimates (Santos et al., 2012), but are specific to sparse or short vegetative environments, such as agricultural systems, and are not typically recommended for forest environments (Bastiaanssen et al., 1998).

To incorporate the effects of canopy structure in denser and taller vegetative environments such as forests, empirical functions have been proposed using coarse canopy metrics such as canopy area index (the total, single-sided area of all canopy elements within a 1 x 1 m^2 ground area) (Raupach, 1994), stand density (stems per area), or leaf area index (*LAI*, the total surface area of leaves found within a 1 x 1 m^2 vertical column of vegetation) (Nakai et al., 2008a). However, the data required to use these functions are typically not available at most sites and, with the exception of *LAI*, are not yet obtainable through large-scale satellite remote sensing. In many climate models, surface-layer grid cells are prescribed with biome-specific qualities, i.e., sets of parameters describing constant vegetation structure and flux-driving characteristics for all model cells containing a specific biome or plant functional type (PFT). For example, the Ecosystem Demography model version 2 (ED2, Medvigy et al., 2009) provides twenty different vegetation functional types, seven of which are representative of forested environments, to describe all land surfaces across the globe. Each such vegetation functional type is characterized by fixed, canopy-height driven roughness parameters. Similarly, aerodynamic resistance to surface flux in the advanced hydrological model tRIBS+VEGGIE (Ivanov et al., 2008) is only driven by vegetation height, with is either prescribed, or set as a default per PFT.

Roughness parameters have been shown to scale with structural characteristics, such as the influence of area-index (vegetation area per ground area) terms on d and z_0, through numerical studies (Shaw and Pereira, 1982;Choudhury and Monteith, 1988) and wind-tunnel experiments (Raupach, 1994). Above-canopy meteorology data has shown estimates of roughness parameters to be highly variable both spatially and temporally (Maurer et al., 2013;Harman, 2012;Zhou et al., 2012). As evidence for canopy-roughness relationships has risen, various studies have attempted to generalize small-scale interactions between roughness parameters and canopy structure by deriving d and z_0 from above-canopy meteorological measurements (Braam et al., 2012;Maurer et al., 2013;Raupach et al., 1996;Nakai et al., 2008a), remote-sensing (Schaudt and Dickinson, 2000;Weligepolage et al., 2012), numerical experiments (Grimmond and Oke, 1999;Wouters et al., 2012), and large-eddy simulations (LES) (Aumond et al., 2013;Bohrer et al., 2009;Bou-Zeid et al., 2007;Bou-Zeid et al., 2009). Although the understanding of these small-scale canopy-roughness interactions has grown, accounting for fine-scale canopy structure effects on roughness parameters in larger-scale climate models requires further development.

In this study, we use the Regional Atmospheric Modeling System (RAMS)-based Forest Large-Eddy Simulation (RAFLES) (Bohrer et al., 2008;Bohrer et al., 2009) to conduct a virtual experiment to estimate the sensitivity of surface roughness parameters to specific characteristics of fine-scale canopy structure. RAFLES incorporates a prescribed 3-D domain that includes the vegetation leaf density and stem diameters, and dynamically calculates the change to wind velocity as a function of leaf and stem surface drag in each voxel (Chatziefstratiou et al., 2014). The level of detail at which vegetation is represented in RAFLES makes it particularly suitable for conducting this series of virtual experiments that simulate the drag parameters over a simplistic set of virtual canopy structures that vary by structural component, including stand density and patch fraction, canopy height, leaf area index and vertical profile of leaf density. The approach of prescribing drag in LES to resolve site-level roughness was previously tested and shown to provide higher accuracy than the traditional roughness parameterization (Aumond et al., 2013). Finally, we use 10 years of direct observations of canopy structure and roughness parameters (Maurer et al., 2013) to estimate the sensitivity of modelled friction velocity to temporal variation in canopy structure and its effects on roughness length. We compare these results with other approaches that may be used to represent canopy structure when modelling roughness parameters.

Materials and methods

Theory

Monin-Obukhov similarity theory (MOST) describes the relationships between the mean horizontal wind speed and the friction velocity in the inertial sublayer (Monin and Obukhov, 1954). Further details on the formulation of MOST used in this work are described in Maurer et al., (2013). In brief, MOST describes the functional relationship between surface stress and the parameters d and z_0 and wind speed using a logarithmic function. The original MOST formulation was expanded to include the effects of thermal instability and the flow regime in the roughness sub-layer (RSL), as follows:

$$\frac{\kappa \bar{u}_z}{u_*} = \ln\left(\frac{z-d}{z_0}\right) - \psi_m\left(\frac{z-d}{L}\right) + \psi_m\left(\frac{z_0}{L}\right) + I\psi_u\left(\frac{z-d}{L}, \frac{z-d}{z_* - d}\right) \quad (1)$$

where $\bar{u}_z$ is the mean horizontal wind speed at height z, above the ground. When the data is derived from meteorological observations, an over-bar over a variable represents the 30-minute mean of the 10 Hz time series of that variable. Given the mean eastward and northward wind velocities, $\bar{u}$ and $\bar{v}$, $\bar{u}_z$ is rotated toward the wind direction such that:

$$\bar{u}_z = \left(\bar{u}^2 + \bar{v}^2\right)^{1/2} \quad (2)$$

where κ is the von Kármán constant, ~0.4, z_* is the upper limit of the RSL estimated as $2h$ (Mölder et al., 1999;Raupach et al., 1996), h is the canopy height. I is an indicator function defined as (I = 1 for $z \leq z_*$; or I = 0 for $z > z_*$). u_* is the friction velocity defined as:

$$u_* = \left(\overline{u'w'}^2 + \overline{v'w'}^2\right)^{1/4} \quad (3)$$

where each prime term (e.g., w') is the perturbation of the specific variable from its mean (e.g., $w-\overline{w}$). The atmospheric-stability correction function, $\psi_m(x)$, was described by Paulson (1970) for unstable atmospheric conditions ($z/L < 0$) as:

$$\psi_m(x) = 2\ln\left[\frac{1+(1-16x)^{1/4}}{2}\right] + \ln\left[\frac{1+(1-16x)^{1/2}}{2}\right] - 2\tan^{-1}\left[(1-16x)^{1/4}\right] + \frac{\pi}{2} \qquad (4)$$

where x is either $(z-d)/L$ or z_0/L.

Current understanding of aerodynamic properties near forest canopies within the roughness sub-layer (RSL) has led to empirical corrections to the MOST model (Harman and Finnigan, 2007;De Ridder, 2010;Cellier and Brunet, 1992;Garratt, 1980;Mölder et al., 1999;Physick and Garratt, 1995;Raupach, 1992). These corrections allow us to utilize MOST with meteorological observation within the RSL, which typically includes the height range where eddy-covariance measurements of forest flux dynamics are conducted across the globe. The RSL correction we used, $\psi_u(x_1,x_2)$, was described by De Ridder (2010) as:

$$\psi_u(x_1,x_2) = (1-16x_1)^{-1/4}\left[\left(1+\frac{\upsilon}{\mu\cdot x_2}\right)x_1\right]\frac{1}{\gamma}\ln\left(1+\frac{\gamma}{\mu x_2}\right)\exp(-\mu x_2) \qquad (5)$$

where $x_1 = (z-d)/L$, $x_2 = (z-d)/(z_*-d)$, and υ, μ, and γ are empirical constants provided by De Ridder (2010) as 0.5, 2.59, and 1.5, respectively. The inclusion of the RSL correction ($\psi_u \neq 0$) occurs when the calculation is performed within the RSL ($z \leq z_*$, $I = 1$). Flux data is typically observed within the RSL at one point in space, requiring the implementation of the RSL correction. When boundary layer conditions are near neutral, $(z-d)/L$ and z_0/L approach zero, and thus, $\psi_m(x)$ becomes negligible (Eq. 4).

Contrary to the classic estimate of z_0 (function of h), Thom (1971) suggested a relationship between z_0 and (h - d), as opposed to a relationship between z_0 and h alone, where the ratio of $z_0/(h-d)$ was defined as λ, a dimensionless, stand-specific parameter. This allows z_0 to be dependent on the spacing of the surface roughness elements and not only their height. For example, (h - d) will theoretically be smaller for more densely packed surfaces, providing a smoother surface and smaller roughness length. This relationship can be written as:

$$z_0 = \lambda(h - d) \tag{6}$$

Nakai et al. (2008b) substituted the aerodynamic height, h_a, for the canopy height, h, into this relationship and rearranged the equation to read:

$$h_a = d + \frac{z_0}{\lambda} \tag{7}$$

In simulation results, where the detailed 3-D wind field is known, we use Eq. 7 to calculate λ for each simulation using h_a, which can be calculated from the vertical profile of horizontal wind speed and the empirically fitted d and z_0.

We investigated the eddy penetration depth (δ_e), which is the length scale describing the vertical distance from the top of the canopy that is influenced by turbulent mixing from above. It is defined as the distance between h_a and the height where the momentum flux value is 10% of its value at h_a (Nepf et al., 2007).

Site description

The data used to test the effectivity of our LES-driven, and other modeling approaches originates from a mixed, deciduous forest site at the University of Michigan Biological Station (UMBS) in northern, lower Michigan, USA (45° 33' 35" N, 84° 42' 48" W, elev. 236 m above sea level). The forest is dominated (~30% of leaf area index) by early-successional bigtooth aspen (*Populus grandidentata*) and paper birch (*Betula papyrifera*), with a mean age of 85-90 years (Gough et al., 2013). The remaining leaf area is mostly represented by red oak (*Quercus rubra*), red maple (*Acer rubrum*) and white pine (*Pinus strobus*). Mean canopy height is roughly 20-25 m with an average stem density of ≈ 750 stems ha^{-1} (including only trees with DBH > 8 cm). Eddy covariance flux measurements have been ongoing at the site since 1999 and data is available through AmeriFlux (http://ameriflux.lbl.gov/), site code: US-UMB. Empirical allometric equations, fitted to measurements in this site (Garrity et al., 2012) are used to determine canopy height from a tree census and measurements of diameter at breast height (DBH). Full censuses were conducted in 2001 and 2010, and partial censuses of DBH for 993 are measured annually. Leaf area index is measured weekly using an optical sensor (LAI2000, Licor Biosciences, Lincoln, NE, USA). Additional details on the calculation of roughness length parameter from wind observations in the site and the determination of canopy structure are described in Maurer et al., (2013). Portable canopy lidar measurements (Hardiman et al., 2013) were used to determine the mean leaf area density profile that was used as the 'natural' leaf area density case. Airborne lidar measurements were conducted by the National Center for Airborne Lidar Mapping (NCALM) in summer 2009. The lidar data and processing for our site are described in Garrity et al., (2012). This dataset was used to determine the mean and variation of canopy top height and gap fraction, and to prescribe the explicit canopy structure in the 'Realistic' LES test case (see section 2.4).

Large eddy simulations

We used wind fields and heat fluxes from RAFLES simulations results to calculate surface roughness parameters of simplified virtual forests. RAFLES (Bohrer et al., 2009) uses a 3-D heterogeneous canopy domain where leaf and stem areas are prescribed within each voxel. The leaf area density and the instantaneous wind speed within the voxel determine the drag force that is applied to wind flow through that grid cell within each time step. Common to the approach used in most LES, it assumes the leaf area is composed of flat surfaces oriented downstream and neglects higher-order effects of leaf and stem shapes and sub-grid-scale wake generation (shown to be a small effect, Shaw and Patton, 2003). It is combined with radiation attenuation (given the leaf densities in the grid cells above) to determine the sensible and latent heat fluxes emitted from each grid cell. The model uses the finite volume approach for discretization of the simulation domain. It resolves the effects of volume restriction due to the volume of the vegetation (stems, branches) by reducing the aperture areas available for flux exchange between each pair of neighboring grid cells and by reducing the volume that is available for flow within each grid cell according to the volume of the vegetation present (Chatziefstratiou et al., 2014). It resolves sub-grid-scale turbulence using the Deardorff (1978) scheme, and includes a parameterization for sub-grid-scale turbulence dissipation due to leaf drag (Shaw and Patton, 2003).

Simulations consisted of three hours of simulation time at a time step of 0.02 s. RAFLES uses a nested time stepping scheme with higher frequency calculations for turbulence and still higher frequency calculations for pressure perturbations. Eight pressure and four turbulence time steps were nested in one model time step. Output data snapshots of all grid cells in the simulation domain were recorded every 2 seconds. The initial 2.5 hours of simulation time were used as a ‘spin-up’ period to ensure satisfactory turbulent mixing and semi-stability of the vertical profiles of turbulence and potential temperature. The latter half hour of simulation time was used for analysis, consisting of 300 2-sec snapshots.

Synthetic virtual domains covered 1.25 x 1.25 x 1.4 km^3 (length x width x height) at a horizontal grid spacing of 5 x 5 m^2, which approximately corresponds to the mean size of individual tree-crowns. Vertical grid spacing was 3 m in the lower sub-domain, from the ground to 100 m above ground level. Above that region, vertical grid spacing was gradually increased by 12% per each subsequent horizontal layer up to a maximal grid spacing of 30 m. The vertical grid spacing then remained constant above that height up to the model top at 1.4 km. The model has periodic boundary conditions at the lateral boundaries, no-slip boundary conditions at the bottom boundary and a no-flux top boundary with Rayleigh friction to dampen vertical perturbations at the top 6 model layers (180 m). Initial conditions were horizontally homogeneous and followed a prescribed vertical profile for potential temperature, humidity, and wind speed. The prescribed initial vertical profile of the potential temperature described a well-mixed atmospheric boundary layer and was constant from 50 m to the height of the capping inversion, and increased with height above that level. Latent and sensible heat fluxes were prescribed based on observed mean noontime observations for August 2011 above the canopy at US-UMB. For each column of the horizontal simulation domain, the sum of the fluxes and Bowen ratio were distributed around the prescribed mean as an empirical function of *LAI*. Fluxes were further distributed vertically following a leaf-area dependent empirical exponential profile. More details on the numerical setup of the model and the approach for flux forcing are provided in Bohrer et al. (2009).

Virtual experiment setup: Sensitivity analysis to quantify the effects of specific canopy-structure characteristics on roughness parameters

Forest canopies are a complex array of 3-D structures. Many structural characteristics, such as tree height, LAI, vertical leaf area density (LAD) profile, and gap fraction, among others, affect the airflow inside and above the canopy and, consequently, affect the resulting roughness parameters and aerodynamic properties of the surface that describe such canopy structure. Using synthetic cases representing different aspects of canopy structure, we conducted a virtual experiment to test the sensitivity of roughness parameters to four axes of canopy structure: (1) mean site-level *LAI*, ranging from observed leaf-off conditions ($LAI = 1.0$ m^2 m^{-2}) to typical, mid-growing season leaf-on conditions ($LAI > 1.0$ m^2 m^{-2}); (2) LAD ($m^2 m^{-3}$) profile, defined through the vertical bias of the vertical leaf density distribution (See *Appendix Figure 1*); (3) canopy height ranging from 9 to 27 m; and (4) canopy patch-level continuity (gap fraction) ranging from 0 to 50% (see *Appendix Figure 2*). Based on the available computing resources, we selected twenty combinations of the structural characteristics listed above. A list of all simulation cases and the canopy-structure characteristics is presented in Table 1.

In the gap fraction cases, canopy gaps were randomly created across the domain ranging from a single-pixel (25 m^2, tree-crown scale) to multi-pixel blocks (tens to hundreds m^2). A gap was described by shorter vegetation (h = 9 m) and a non-gap (closed canopy) was described by taller vegetation (h = 27 m). It should be noted that we introduced gaps in our horizontally homogenous canopy using holes of varying sizes and shapes, which was done to minimize the complexity of the prescribed "heterogeneity" treatment (*Appendix Figure 2*). The resulting gap-size distribution was arbitrary and may not have been well-representative of an actual, heterogeneous canopy environment with tree-fall gaps.

Empirical determination of roughness parameters from simulations results

To calculate flux and wind statistics, we first calculated the mean value of each model variable at each vertical model level over the entire horizontal domain at that height level, and over all 300 time snapshots. We then rotated the horizontal wind coordinates of each vertical level toward the downstream direction, such that the resulting mean rotated downstream velocity is:

$$\langle u_r \rangle_{xyt} = \left(\langle u \rangle_{xyt}^2 + \langle v \rangle_{xyt}^2 \right)^{1/2} \tag{8}$$

where $\langle \ \rangle_{xyt}$ marks an average of the simulation results over all voxels in the x (eastward) y (northward) and t (temporal, 300 snapshots) dimensions. Althought the wind forcing aloft is eastward, a rotation develops following the Ekman spiral and is further amplified by random x-y asymmetrices in the simulation domain. The rotation for the horizontal coordinate system of each horizontal layer is necessary to maintain a consistent downstream axis required for data analysis. After this rotation, we calculated the instantaneous perturbation of the velocity components from the $\langle \ \rangle_{xyt}$ average for each voxel in space and time along each horizontal layer, such that:

$$u_r' = u_r - \langle u_r \rangle_{xyt} \tag{9}$$

where the prime indicates an instantaneous perturbation from the mean value, in this example of the u_r (downstream) velocity component. Similar formulation applies to the vertical (w) and cross-stream (v_r) velocity components. Momentum flux at the down-steam direction was calculated as:

$$\langle u_r' w' \rangle_{xyt} = \left\langle \left(u_r - \langle u_r \rangle_{xyt} \right) \left(w - \langle w \rangle_{xyt} \right) \right\rangle_{xyt} \tag{10}$$

See Bohrer et al. (2009) for additional details on the calculation of wind statistics and momentum fluxes from RAFLES output.

We determined the effective aerodynamic canopy height, h_a, by identifying the height of the inflection point in the vertical wind-speed profile. This height marks the transition between the sub-canopy and above-canopy flow regimes (Thomas and Foken, 2007b). To find this point, we compiled a domain-averaged wind-speed profile using Eq. 8. Then, we determined h_a as the location where the second derivative of the horizontal wind profile crosses zero. We approximated this location within the vertical grid resolution using linear interpolation. We calculated the characteristic domain-averaged u_* for each simulation case by calculating the horizontal-temporal average u_* for each for each horizontal plane of grid cells within the 3-D virtual domain and further averaging these vertically over the range from 3.5-4.5h (u_* values are nearly invariable with height in that range). Obukhov length was calculated for each horizontal plane of grid cells within the 3-D virtual domain as a function of the characteristic u_*, surface heat flux (prescribed) and the mean potential virtual temperature at each horizontal plane of grid cells. Next, the vertical profile of horizontal mean wind speed from all grid layers above 1.5h_a and below 4.5h (95 m) above ground was fitted to Eq. 1 to determine d and z_0 using the characteristic friction velocity and the Obukhov length. The empirical fit was calculated using MATLAB's (version R2013b, The MathWorks, Inc., Natick, MA, USA) nonlinear, least-squares fit function: *fit*( ). We constrained the solution for the surface roughness parameters to a physically meaningful range by constraining d to be between 0 and h_a of the simulated forest and z_0 to be larger than 0.

Results

Virtual experiment to explore canopy-roughness relationships

We found that d was significantly affected by maximum canopy height ($h_{\max}$) (3-way ANOVA, Table 2). We also found that h_a and δ_e were significantly affected by $h_{\max}$, *LAI*, and gap fraction (*GF*) (Table 2). z_0 was not found to be significantly affected by any single aspect of canopy structure investigated within this study. As suggested by Thom (1971) and Nakai et al. (2008b) we checked the relationship between z_0 and ($h_a - d$) and found a significant relationship ($r^2 = 0.72$, $P < 0.001$). We found a positive relationship between d and $h_{\max}$ (fit forced through [0,0], Figure 1).

$$d = 0.69 h_{\max} \tag{11}$$

Surprisingly, canopy gaps showed little effect on d. A higher correlation existed between d and $h_{\max}$ ($r^2 = 0.78$) than between d and mean canopy height ($r^2 = 0.48$) across the gap fraction sensitivity analysis. There was little change to d with increasing gap fraction, except for the scenario with 50% gap fraction in the leaf-on simulations, which was significantly lower. Therefore, the relationship with $h_{\max}$ (which was constant as the number of gaps increased) was selected instead of mean canopy height (which decreased as the number of gaps increased). Seasonality (leaf-on vs. leaf-off) also showed surprisingly small differences in d as height was varied, which had previously been observed at US-UMB (Maurer et al., 2013).

We found positive h_a-$h_{\max}$ and h_a-*LAI* relationships and a negative h_a-gap fraction (*GF*) relationship (Figure 2). We note that a positive h_a-h relationship was previously observed at US-UMB using 12 years of meteorological data and tree-growth censuses (Maurer et al., 2013). By utilizing the suite of RAFLES simulations we empirically calculated a single canopy-h_a relationship as:

$$h_a = h_{\max} + aLAI + bGF + c \tag{12}$$

where $a = 0.06$ m, $b =$ (-)0.69 m, and $c =$ (-)0.11 m.

We found a negative δ_e-*LAI* relationship and positive δ_e-$h_{\max}$ and δ_e-*GF* relationships (Figure 3). As expected, we found δ_e to be consistently higher during leaf-off periods compared to leaf-on periods at corresponding heights and gap fractions as wind was better able to penetrate the sub-canopy. Increased *LAI* intensified the effect of gap fraction on δ_e as the slope of the leaf-on fit-line was larger than that of leaf-off periods.

Relationships were empirically determined using roughness parameters from each RAFLES simulation, except for those with 'unnatural' vertical LAD profiles (i.e., the 'Upper', 'Middle', and 'Lower' LAD cases) as no patterns were observed between any roughness parameters and vertical LAD profile. Maximum canopy height was used instead of mean canopy height because maximum canopy height was more tightly correlated with each roughness parameter than mean canopy height. The resulting roughness parameters for each simulation are listed in Table 1.

We calculated a 'Biometric' h_a using the relationship we found in the virtual experiment between h_a and *LAI*, gap fraction and h_{max} (Eq. 12). To simulate the conditions in our site at US-UMB, we assumed a gap fraction of 5%, which was found by calculating the percent area within the NCALM lidar scan domain with vegetation height less than 2 m. We used the peak growing season site-level mean *LAI* of 4.2 as measured from 2000-2011 (Maurer et al., 2013). A 'Biometric' *d* was then calculated using Eq. 10. Finally, a 'Biometric' z_0 was calculated as:

$$z_0 = \lambda(h_a - d) \qquad (13)$$

where $\lambda = 0.34$ was determined from Eq. 7 given the set of h_a, d and z_0 values from our simulations through the virtual sensitivity experiment.

Testing empirical approaches that link roughness parameters to biometric measurements

The 'Biometric' approach, derived from our simulation results, provides relationships between easily measurable characteristics of the canopy (i.e., *LAI* and maximum canopy height) and *d* and z_0. In order to evaluate the potential improvement to estimates of u_* using this approach, we compared the accuracy and precision of modeled u_* values using the 'Biometric' approach with those of 5 alternative approaches. We evaluate the resulting friction velocities predicted by each of these six ('Biometric' and 5 alternatives) structure-driven parameterization approaches using 30-min observed values of u_*, canopy height and LAI over multiple years at US-UMB (2000-2011, at 34 m a.g.l). The 5 alternative approaches employed are:

(1) 'Classical' – fixed $d = 0.66h$ and $z_0 = 0.10h$, where we use $h = 22$ m;

(2) 'Explicit-LES' – fixed d = 0.67h and z_0 =0.094h as determined from the simulation results of the 'realistic' LES case;

(3) ‘Yearly Observed’ – a purely empirical approach, using the values of d and z_0 calculated from meteorological observations during each growing season at US-UMB from 2000-2011 (Maurer et al., 2013). In this approach, the values of d and z_0 vary each year according to observations. d and z_0 were calculated by fitting Eq. 1 to a seasonal set of half-hourly mean observations of wind speed and friction velocity at twice the canopy height (46 m a.g.l.) and only during neutral to slightly unstable atmospheric conditions during daytime. We also tested applicability of shorter-term observations of d and z_0 to long-term predictions of friction velocity. This test was motivated by the fact that there are only few sites around the world with more than a decade of data, while short observation campaigns are more common. We used the observed d and z_0 from each year to simulate the entire decadal time series of friction velocity. This resulted in 12 different 'Yearly' models. Anecdotally, the most accurate model was associate with observed d and z_0 from 2008, and the least accurate model with the yearly values from 2005.

Numerous past studies have attempted to derive relationships between roughness parameters and other canopy-structure statistics. We chose two in this study:

(4) Raupach (1994) calculated d and z_0 as functions of canopy area index (Λ), drag coefficient (c_d), and canopy height (h):

$$d = \left[1 - \frac{1 - \exp\left(-\sqrt{2c_d\Lambda}\right)}{\sqrt{2c_d\Lambda}}\right]h \qquad (14)$$

and

$$z_0 = \left[\left(1 - \frac{d}{h}\right)\exp\left(-\frac{\kappa \bar{u}}{u_*} - \eta_h\right)\right]h \qquad (15)$$

where c_d = 7.5, η_h = 0.193, and $\Lambda = 2nbh/A$, where n is the number of stems in a sample plot, b is the mean diameter at breast height, h is the mean tree height, and A is the total ground area within the canopy sampling area. Full plot censuses provided the data to calculate Λ. These were conducted in 2001 and 2010, and Λ values where linearly interpolated for the years between the censuses and extrapolated to 2011;

(5) Nakai et al. (2008a) calculated d and z_0 as functions of stand density (ρ_s), LAI, and h:

$$d = \left[1 - \left(\frac{1-\exp(-\alpha\rho_s)}{\alpha\rho_s}\right)\left(\frac{1-\exp(-\beta LAI)}{\beta LAI}\right)\right]h \tag{16}$$

and

$$z_0 = 0.264\left(1 - \frac{d}{h}\right)h \tag{17}$$

where α and β are 7.24x10^{-4} ha stems^{-1} and 0.273, respectively, and we used the US-UMB mean stand density of 750 stems ha^{-1}.

The values of d and z_0 as determined by each of the parameterization approaches are listed in Table 3. The range for yearly observed mean d values was 18.3-26.0 m and for z_0 0.99-1.99 m. The 'Classical' approximation based on h resulted in a significantly lower d = 14.0 m (outside the range of the inter-annual variability over 12 years), and a slightly above-range z_0 = 2.10 m. The 'Explicit-LES' resulted in a very similar d to the 'Classical' approach. The 'Biometric' approach predicted high but within-range d values (24.0-25.0 m) but extreme z_0 values (3.64-3.82 m). There was nearly no overlap between the values of z_0 from each of the approaches, indicating poor agreement between approaches for this parameter.

Improvements to estimates of friction velocity using canopy-structure-roughness relationships

Modeled u_* from all six approaches was regressed against observed u_*. The slope and intercept of the fit-line (estimates of accuracy), coefficient of determination (r^2), and root mean square error (estimates of precision) are reported in Table 3. Surprisingly, all parameterization approaches produced similar results, with coefficient of determinations between 0.56 and 0.61, near zero, but significantly negative intercepts between (-)0.052 and (-)0.072 (significant margin ±0.004). The most significant difference between the approaches was in their bias. All approaches (except the ‘Yearly Observed’ 2008 which was the only one that was not significantly biased) produced a significant positive bias, but the bias varied from near zero to 43% (slope of observed vs. modeled fit-line between 1.01 and 1.431, significant margin ±0.01). The results of all parameterization approaches are listed in Table 3. We found that the precision of the results obtained by using each of the 12 ‘Yearly Observed’ models over the entire 12-years period to be higher than the combined results of using the observation for each specific year during that year only. The bias of the prediction obtained with the observed *d* and z_0, applied to the entire 12-year period varied from no significant bias (using the 2008 parameters) to 1.38 (with the 2005 parameters). The combined (each year with its own parameters) produced an intermediate bias for the friction velocity estimates.

The 'Yearly Observed' method is dependent on long term observations of wind, temperature, heat flux and friction velocity, which are rarely available in forest sites. The other methods we tested do not require directly observed roughness parameters. Of these methods, the ‘Raupach 94’ approach had the highest precision and lowest bias (slope = 1.24, r^2 = 0.604), the 'Explicit LES approach ranked second and our ‘Biometric’ approach ranked third, although it performed similarly to the very simple 'Classical' approach. The ‘Nakai 08’ approach proved to be the least compatible with our site.

Discussion

Response of roughness parameters to canopy structure change

To date, despite a strong need by the modeling community, there is no single consensus approach that relates roughness length and displacement height to observable properties of canopy structure, such as LAI, height, leaf density and gap fraction. Furthermore, observations in our field site (Maurer et al 2013) and by others (Nakai et al., 2008a) have shown that the roughness parameters in forests and not easily constrained by leaf area or canopy height. Our underlying assumption in setting up this model-based experiment was that the lack of clear empirical relationship between roughness parameter and canopy structure was due to the complexity of canopy structure. We assumed that different characteristics of the canopy drive different effects on roughness length and displacement height. In real forests, many of the structural characteristics vary in time in different ways, resulting in interacting and sometimes conflicting effects on roughness length and displacement height. We set up a numerical experiment that was designed to separate the effects of different observable characteristics of canopy structure. We also hypothesized that, to some degree, the difficulty in identifying a clear effect of canopy structure on each of the roughness parameters is because roughness length and displacement height values may trade-off, such that similar solutions can be fitted either with low d and high z_0, or *vice versa* (Nakai et al., 2008a;Nakai et al., 2008b;Maurer et al., 2013).

By testing the independent effects of different characteristics of canopy structure through a set of controlled virtual experiments, we indeed found that different roughness parameters where sensitive to different structural characteristics. The aerodynamic canopy height (h_a) and eddy penetration depth (δ_e) were both sensitive to leaf area, canopy height and gap fraction (figure 2,3). In contrast, d was only significantly sensitive to canopy height, while z_0 did not show any significant relationships with any single canopy structure characteristic.

We found positive d-h_{max} and h_a-h_{max} relationships independent of *LAI*. A strong correlation had previously been reported between h_a and h (Nakai et al., 2008b;Bohrer et al., 2009;Maurer et al., 2013;Thomas and Foken, 2007b). As canopy height was the only canopy characteristic that varied among the 'canopy height variation' simulations (Table 1.c.), it is reasonable to assume that δ_e would be relatively constant, regardless of canopy height. However, as canopy height increased within our virtual domain, the constant mean site-level *LAI* was stretched further in the vertical direction. Therefore, the mean leaf density in the upper canopy was smaller for taller canopies resulting in an increased δ_e with canopy height (Figure 3b). In spite of increased δ_e, we also observed a positive d-h_{max} relationship. Indicating that the increased δ_e only partially compensated for the increase in canopy height, allowing for d to increase linearly with canopy height, but with a slope smaller than 1.

We found a linear relationship between h_a and gap fraction. Eddy-penetration depth scaled with gap fraction as well. It was consistently larger during leaf-off periods compared to leaf-on periods, and the presence of higher *LAI* during the leaf-on periods resulted in a steeper linear slope of the relationship between δ_e and gap fraction (Figure 3c). Intuitively, increased gap fraction should lead to increased δ_e, as more canopy openings allow eddies to penetrate deeper into the canopy. These findings are not surprising, as Shaw et al. (1988) found deeper δ_e at lower *LAI*. For example, we found that increased gap fraction corresponded to increased momentum flux, turbulence, and horizontal wind speed inside the canopy (below 1h) (Figures 5, 6). This was likely due to the extension of turbulent eddy penetration deep into canopy gaps, indicated by elevated standard deviation of the vertical velocity, σ_w (a component of the turbulence kinetic energy) in canopy gaps (Figure 6a). Such locations of increased turbulent eddy penetration are less likely to occur in horizontally homogenous canopies (Figure 6b). However, the lack of any relationships between roughness length and gap fraction at all levels below 50% gap (Table 1) was surprising, as Bohrer et al., (2009) found increases to d, z_0, and h_a in patchier canopies (more gaps) during leaf-on conditions. The major difference between these two studies was that the scale of the gaps prescribed here – corresponding with 1-2 crown sizes – was typically smaller than those in the Bohrer et al., (2009) experiments.

We found no consistent correlations between roughness parameters and the mode of the vertical LAD profile, as the variability in roughness parameters over the range of LAD scenarios was extremely high (Table 1). Although the shape of the vertical profile of wind speed is apparently different between the 'Lower' and the 'Upper' LAD profiles (Figure 7) there was no consistent canopy-wind or canopy-turbulence relationships that could be predicted by the bias of the vertical LAD curve (Figure 7). LAD profiles may change in complex ways across the landscape and over many time scales (seasons, years, decades) due to disturbance or senescence. As our virtual experiment has shown, the effects of the vertical LAD profile are inconsistent with a simple representation of the vertical distribution of LAD using its vertical bias as a single descriptive characteristic. Our results indicate that site-level mean *LAI* and canopy height are easier to obtain and, in general, provide more reliable characteristics of canopy structure than the vertical profile of LAD.

Our simulations did not detect a continuous increase to d or z_0 with *LAI*, which was inconsistent with several previous wind tunnel or model studies (Choudhury and Monteith, 1988;Grimmond and Oke, 1999;Raupach, 1994;Shaw and Pereira, 1982). We also did not find significant relationships with any single property of canopy structure, except between displacement height and canopy height. To a limited degree, this was the result of tradeoffs between the two, as indicated by the fact that h_a, which combines d and z_0 through the slope of their tradeoff curve, λ, was better constrained than d or z_0 alone. However, this tradeoff cannot fully explain the lack of relationship, as we did not find a significant and consistent relationship between z_0 and different canopy structural characteristics even when we assumed a fixed displacement height and fitted only for z_0 (results not shown). Combined, our results indicate that both of our underlying hypotheses were at least partially false, and neither the structural complexity of the canopy, nor the tradeoffs between z_0 and d can fully explain the lack of clear relationship between canopy structure and d and z_0.

The lack of canopy structure effects on z_0 within the virtual sensitivity experiment, and in particular, the lack of consistent seasonal differences between leaf-on and leaf-off periods, may suggest that leaf area is not the primary driver of z_0. To further understand the drivers of z_0, we calculated the sensitivity of z_0 to changes in wind speed at a measurement height z above the canopy, δ_{z0u}. This can be done by solving Eq. 1 for z_0 assuming neutral conditions, and calculating the sensitivity as the partial derivative of z_0 with respect to $\bar{u}_z$:

$$\delta_{z0u} = \frac{\partial z_0}{\partial \bar{u}_z} = \frac{-\kappa(z-d)}{u_*}\exp\left(\frac{-\kappa \bar{u}_z}{u_*}\right) \quad (17)$$

We determine that at low to intermediate mean wind speeds (below 3 m/s), z_0 is extremely sensitive to variation in $\bar{u}$, with the derivative being between 5 and 30 (Figure 8). This indicates that, for an observed variation of 0.1 m/s measured at twice the canopy height the resulting z_0 will change by 0.5-3 m, which is a full range of the expected z_0 values for a 20 m tall canopy. At our site in Michigan, 3 m/s was approximatly the median wind speed and was therefore selected to drive the simulations. In reality, variations in half-hourly mean wind speed at the order of 0.1 m/s can be a result of local variations in the flow field due to topography, or measurement errors due to instrument placment and calibration. In both reality and LES, such variations in wind speed at a given measurement point could also be the result of effects of local modification to the flow field due to specific heterogeneous canopy-surface structures (which were determined to extend up to 5*h*, Raupach and Thom, 1981;Bohrer et al., 2009), and could also be driven by random large eddies that may affect the 30 minute average at a specific half hour. We hypothesize that this high sensitivity of z_0 may be inhibiting the attempts to empirically estimate its relationships with the canopy structural characteristic.

Integrating canopy-structure characteristics into models

Typically, surface roughness parameterization is used in models to directly or indirectly predict the friction velocity, which is further used in the surface flux calculations. To test the performance of different parameterization approaches, we used data from 12 years of wind, friction velocity, Obukhov length, and canopy structure observations in a forest site in Michigan. We compared six approaches that differ in whether they do (or do not) incorporate temporal variation to canopy structure, and in the source of data they require to determine z_0 and d. Surprisingly, but optimistically for the purpose of accurate modeling, all the surface roughness parameterization approaches we tested resulted in relatively high precision (r^2 = 0.58-0.61) in predicting the half-hourly friction velocity over 12 years. This is surprising because each of the approaches used a different set of values for z_0 and d, which in some cases, were very far from each other. For example The 'Biometric' and the 'Classical' approach performed rather similarly, but the 'Biometric' approach z_0 values were about 80% larger than the 'Classical'. To understand this discrepancy, we calculated the sensitivity of the friction velocity to variation in z_0, δ_{u*z0}.

$$\delta_{u*z0} = \frac{\partial u_*}{\partial z_0} = \frac{\kappa \bar{u}_z}{z_0}\left[\ln\left(\frac{(z-d)}{z_0}\right)\right]^2 \quad (18)$$

For a case similar to the one we simulated, with a canopy at 22 m and mean wind speed of 3 m/s, we found that the friction velocity is not sensitive to changes in roughness length when roughness length is higher than 0.6 m (Figure 8). As a general approximation (following the 'Classical' approach), for a forest canopy higher than 10 m, roughness length is expected to be larger than $0.1h$ = 1 m. Therefore, while the value of the roughness length parameter is highly sensitive to changes in the half-hourly mean wind speed (Equation 17, Figure 8, Table 1), the resulting friction velocity may not be greatly affected from this variation in the parameter's value.

The best performing approach for parameterization of roughness length and displacement height, was obtained using the annually observed values of these parameters. The 'Yearly Observed' model demonstrated ~7% less error than the fixed-in-time 'Classical' canopy-roughness relationships. The combined 'Yearly Observed' approach used the z_0 and d values for each year to predict friction velocity values in the same years. This method performed better than when applying the data observed during a single year to the entire time period. However, the roughness parameters observed during 2011 provided a more accurate and precise model for the entire 12-year time series, than the combined approach. The z_0 and d values observed during 2005 provided the worst model, but still performed better than the 'Classical' approach. It is rather intuitive that when observations of z_0 and d exist, they will provide the best approach for modeling of friction velocity (Table 3). Our results indicate that the inter-annual variability of canopy structure that affects roughness length has only a very small effect on the resulting friction velocity. Annual growing-season averages of z_0 and d from any single year can provide a suitable approximation to the decadal time series of roughness length parameter values. However, the low spatial coverage by flux networks over the globe limits the use of this method across large spatial domains.

LES with an explicit, prescribed canopy structure based on lidar observations of the canopy at a site can generate a surrogate virtual observations from which to evaluate the roughness parameters. However, these type of simulations are limited in their temporal domain (just a few hours as a representative of an entire decade). They are also dependent on high resolution canopy lidar observations that, to date, are not common. Parameterization approaches which rely on biometric observations, rather than on wind observations, may be the most reliable and broadly available method to estimate long-term roughness parameters. Our ability to estimate canopy structure characteristics such as *LAI*, canopy height, and gap fraction over a broad range of spatial and temporal scales is continuously improving through the use of on-site biometric measurements, and airborne and satellite remote sensing observations (Chen et al., 2002;Jonckheere et al., 2004;Zheng and Moskal, 2009).

As an indication for the potential of biometric approaches, the approach suggested by Raupach (1994) performed even better than the combined 'Yearly Observed' approach (Table 3). However, this approach relies on stem census observations. While such records are more common than flux sites, there is still no broad global coverage for this type of observation. We tested two biometric approaches that only required more commonly observable canopy characteristics. The approach by Nakai et al (2008a) and the approach derived by the virtual experiments in this study (the 'Biometric' approach) require LAI, canopy height and gap fraction or stand density to determine z_0 and d. Of the two, our 'Biometric' approach performed relatively well, and provided slightly better estimates than the 'Classical' approach. Variable success by the three biometric methods may not be surprising – a study by Grimmond and Oke (1999) determined that careful consideration must be given to higher-order structural features of the surface than the ones represented in this study and include in the biometric approaches. Examples of such higher-order structural characteristics include the complexity of organization, and density of roughness elements. Similar reasoning could provide insight towards the poor performance of the method of Nakai et al. (2008a) at US-UMB, which is less dense, taller, and has higher *LAI* than those sites used to parameterize the 'Nakai 08' method.

The ‘Biometric’ method presented in this study is essentially a variant of the ‘Classical’ method, with the major difference being the use of maximum canopy height as opposed to mean canopy height, and adding small perturbations to displacement height based on *LAI* and gap fraction. The limited success of this method can be attributed to some degree to the limited effect of inter-annual variability of canopy structure. However, a decade of observations in a site represents only a very narrow range of potential canopy structures. We predict that this method will significantly improve the prediction of friction velocity when applied to situations where canopy structural variability is larger, such as after significant disturbance events.

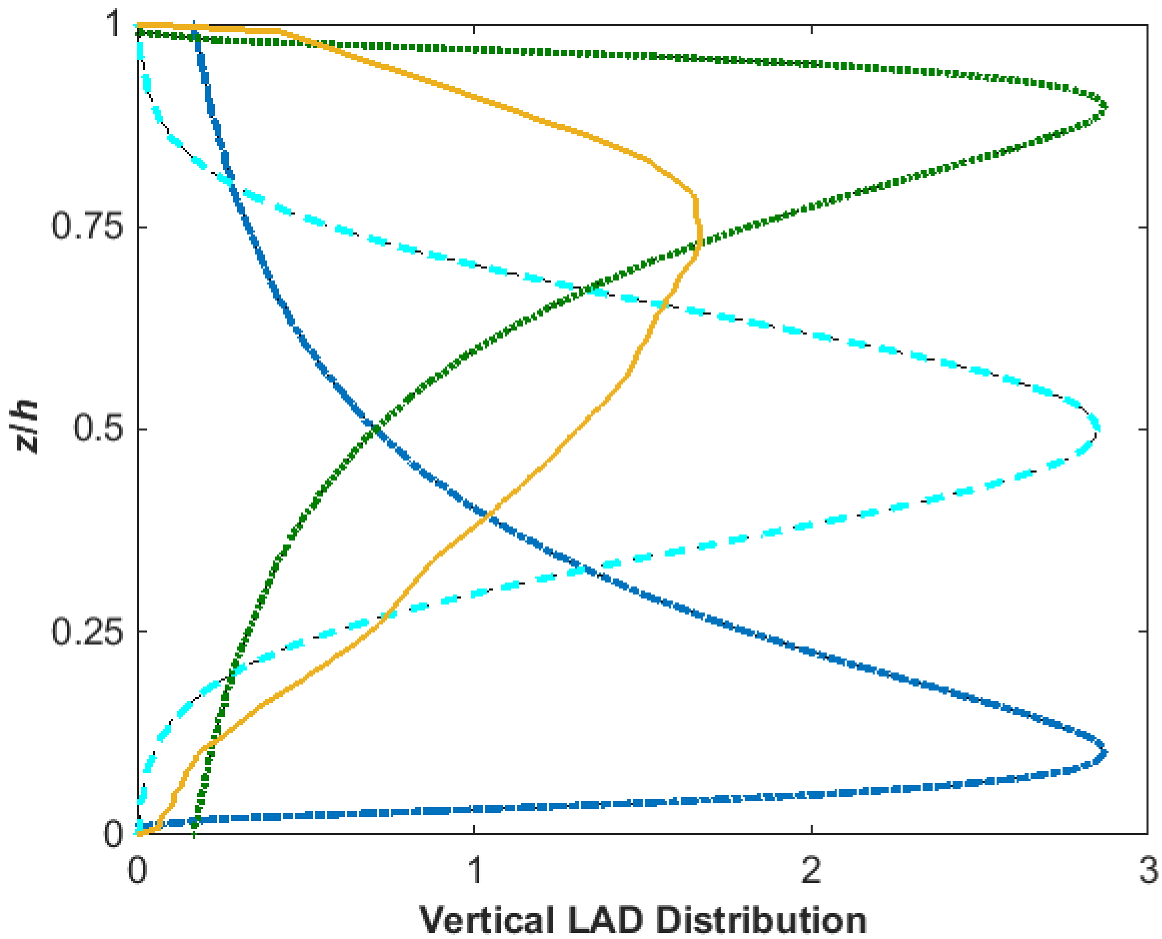
Conclusions

In this study we used an LES, long-term meteorological observations, and remote sensing of the canopy to explore the effects of canopy structure on surface roughness parameters in a forest site. We performed a virtual experiment to test the sensitivity of roughness parameters with respect to four axes of variation in canopy structure: (1) leaf area index, (2) the mode of the vertical profile of LAD, (3) canopy height, and (4) gap fraction. We found consistent relationships between the aerodynamic canopy height and *LAI*, maximum height, and gap fraction and between d and maximal canopy height. We found that the predicted values of friction velocity are not sensitive to roughness length. As a result, most of the roughness-based approaches we tested for simulating friction velocity performed similarly well. This is despite having very different approaches for determining the values of z_0 and d, and having large differences in the range of z_0 and d values. This is good news for modelers, because it limits the error from using the current approaches that do not vary in time and do not incorporate canopy structure.

Nonetheless, most of the approaches we tested which used annually variable z_0 and d and that incorporated canopy structure provided better approximation for friction velocity than the 'Classical', time-invariable method. Many easily obtainable metrics of canopy-structure characteristics are available through a suite of measurements, such as on-site meteorological and biometric observations or satellite-derived site characteristics. Additionally, many ecosystem models and ecosystem modules within earth system models resolve the growth of the forest and accurately predict canopy height and *LAI*. Some models, such as the Ecosystem Demography model (Medvigy et al., 2009) even resolve the distribution of stem sizes. Such demographic models could readily incorporate the approach by Raupach (1994) for a significant improvement in surface roughness parameterization. For other models that resolve, or are forced by observed leaf area and vegetation height, our LES-derived 'Biometric' approach could offer an easy way to dynamically affect the roughness-length parameterization. This could provide an improvement of surface flux modeling, especially when canopy structure variations are large. Due to limited spatial coverage by direct meteorological measurements, remote sensed structure statistics, and stand inventories, we suggest utilizing site- and time-specific biometric measurements of canopy structure to estimate site-level d and z_0. The effectivity of these model improvements will, of course, be dependent upon the quality, quantity, and resolution of the datasets available at the forest of interest.

Appendix A: Simulation setup details

Appendix Figure 1: ‘Lower’ (-·-) blue; ‘Middle’ (---) cyan; ‘Upper’ (···) green; and ‘Natural’ (solid line) yellow (mean observed in the US-UMB forest plot), vertical LAD profiles used in virtual canopies for RAFLES simulations.



Appendix Figure 2: Height maps for varied plot-level gap fractions: (a) 100%, (b) 50%, (c) 35%, (d) 25%, (e) 10%, and (f) 0%. Here, gap fraction refers to the percentage of the canopy described by h_L (h = 9 m, blue) as opposed to h_H (h = 27 m, green). Distance along the simulation domain is in meters.

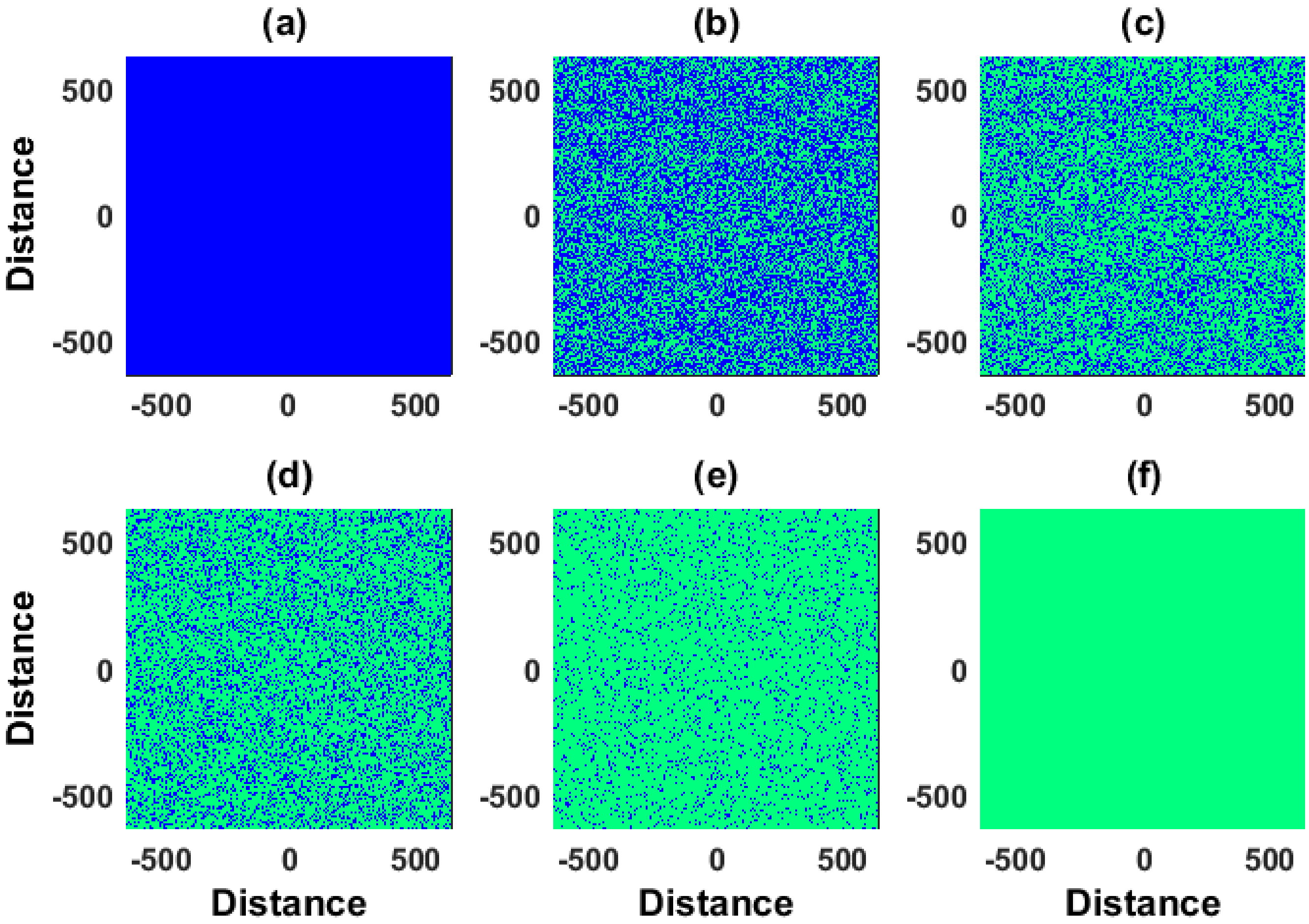


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Table 1: Description of simulation cases used for sensitivity analysis of roughness parameters derived from an LES over variable canopy layouts, and the resulting roughness parameters for each simulation case. Canopy structure was varied along four axes: (a) *LAI*, (b) vertical LAD profile, (c) canopy height, (d) gap fraction and (e) realistic.

Experiment	LAI ($m^2\ m^{-2}$)	LAD ($m^2\ m^{-3}$)	Height (m)	Gap Fraction	*d* (m)	z_0 (m)	*d/h*	z_0/h	λ	h_a (m)	δ_e (m)
(a) LAI variation	1.0	Natural	21	0%	14.2	2.6	0.67	0.12	0.38	20.9	13.1
	2.6				13.7	3.1	0.65	0.15	0.41	21.1	11.0
	3.2				16.5	1.3	0.79	0.06	0.27	21.1	10.7
	3.7				7.6	4.0	0.36	0.19	0.29	21.2	9.9
	4.2				16.0	1.2	0.76	0.06	0.24	21.1	10.2
(b) LAD profile variation	4.2	Lower	21	0%	13.6	1.7	0.65	0.08	0.24	20.7	12.6
		Middle			8.8	5.7	0.42	0.27	0.55	19.1	8.2
		Natural			16.0	1.2	0.76	0.06	0.24	21.1	10.2
		Upper			13.8	2.8	0.66	0.14	0.38	21.2	10.2
(c) Canopy height variation	1.0	Natural	9	0%	4.4	0.8	0.49	0.09	0.17	9.3	7.1
			15		3.6	3.5	0.24	0.23	0.31	15.0	10.1
			21		14.2	2.6	0.67	0.12	0.38	20.9	13.1
			27		20.1	2.5	0.74	0.09	0.36	26.9	15.8
	4.2	Natural	9	0%	3.7	2.0	0.41	0.22	0.35	9.4	6.3
			15		8.7	2.5	0.58	0.17	0.38	15.2	7.9
			21		16.0	1.2	0.76	0.06	0.24	21.1	10.2
			27		20.1	2.9	0.75	0.11	0.41	27.1	11.9
(d) Gap fraction variation	1.0	Natural	27	0%	20.1	2.5	0.74	0.09	0.36	26.9	15.8
				10%	19.8	2.2	0.73	0.08	0.31	26.8	17.5
				25%	18.5	3.2	0.69	0.12	0.39	26.8	18.2
				35%	17.9	2.4	0.66	0.09	0.27	26.7	19.2
				50%	18.7	1.8	0.69	0.07	0.23	26.7	20.2
	4.2	Natural	27	0%	20.1	2.9	0.75	0.11	0.41	27.1	11.9
				10%	20.4	2.7	0.76	0.10	0.42	27.0	13.0
				25%	18.7	2.8	0.69	0.11	0.34	27.0	14.4
				35%	19.1	2.4	0.71	0.09	0.30	26.9	15.8
				50%	14.4	4.0	0.53	0.15	0.32	26.9	17.3
(e) Realistic	4.2	Natural	27	5%	14.2	0.9	0.67	0.05	0.43	16.7	10.3

Table 2. Results of a 3-way ANOVA to test any significance maximum canopy height (h_{max}), leaf area index (*LAI*), and gap fraction (*GF*) have on displacement height (*d*), roughness length (z_0), aerodynamic canopy height (h_a), or eddy-penetration depth (δ_e). *P*-values listed in **bold** font indicate a significant effect.

Variable	**3-way ANOVA *p-value***		
	h_{max}	***LAI***	***GF***
D	**<0.001**	0.065	0.370
z_0	0.290	0.227	0.918
h_a	**<0.001**	**<0.001**	**0.007**
δ_e	**<0.001**	**0.001**	**0.004**

Table 3. 30-min block-averaged friction velocity (u_*) model evaluation against measured u_* for displacement height (d) and roughness length (z_0) calculated from various methods – 'Classical', 'Yearly Observed', 'Biometric', 'Raupach 94', and 'Nakai 08' - at US-UMB spanning the 2000-2011 growing seasons. We show the slope and intercept of the linear fit, which are measures of the accuracy of the models, the coefficient of determination (r^2), which is a measure of precision, and the root mean square error (RMSE) between modeled and observed u_*, which is indicative of both precision and accuracy.

Method		***d*** **(m)**	***z₀*** **(m)**	**Slope**	**Intercept**	***r²***	**RMSE**
Classical		14.0	2.10	1.41	-0.05	0.584	0.212
Explicit-LES		14.2	0.94	1.31	-0.06	0.597	0.194
Yearly Obs.	Combined (2000-2011)	23.1 (18.3-26.0)	1.40 (0.99-1.99)	1.11	-0.04	0.564	0.187
	2008 (lowest bias)	26.0	0.99	1.01	-0.06	0.593	0.188
	2011 (highest r^2)	25.0	1.17	1.19	-0.07	0.607	0.179
	2005 (worst)	18.3	1.99	1.38	-0.06	0.588	0.207
Biometric		24.5 (24.0-25.0)	3.74 (3.67-3.82)	1.41	-0.05	0.585	0.212
Raupach 94		17.2 (16.6-17.9)	0.89 (0.88-0.91)	1.24	-0.07	0.604	0.183
Nakai 08		11.5 (11.1-12.0)	2.59 (2.40-2.86)	1.43	-0.05	0.582	0.216

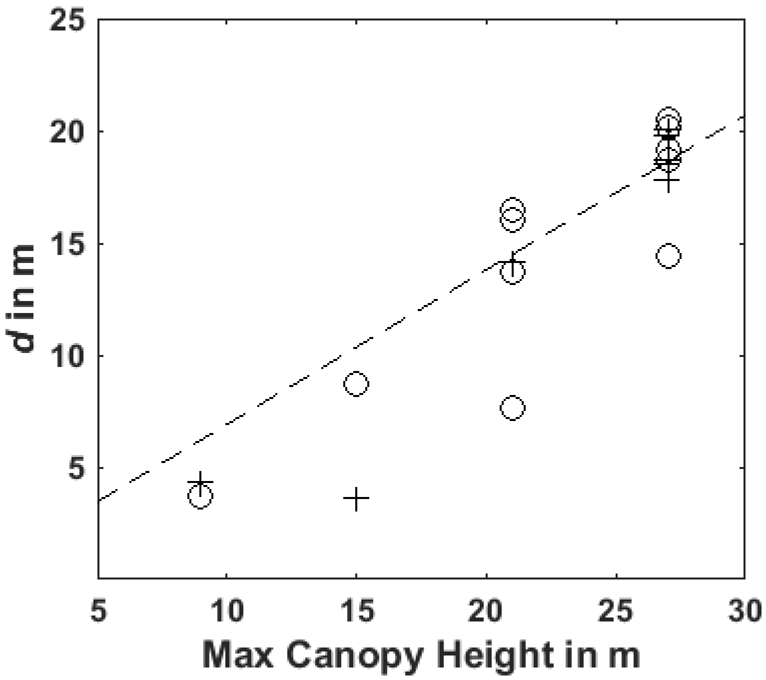

Figure 1. LES domain-averaged *d* vs. maximum canopy height. Crosses and circles correspond to leaf-off ($LAI = 1.0$ m^2 m^{-2}) and leaf-on ($LAI > 1.0$ m^2 m^{-2}) conditions, respectively. Best-fit line (forced through [0,0]) shown as dashed line ($d = 0.69h_{max}$).

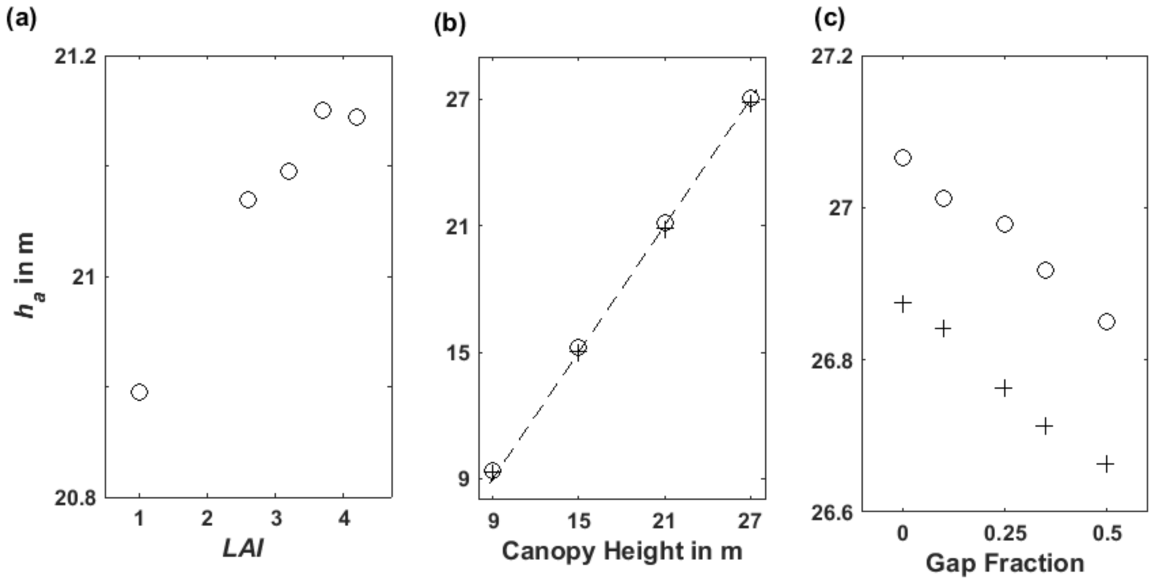

Figure 2. LES domain-averaged aerodynamic canopy height (h_a) vs. (a) leaf area index (*LAI*), (b) canopy height (h_{max}), and (c) gap fraction (*GF*). For (b) and (c), crosses and circles correspond to leaf-off and peak-*LAI* conditions, respectively.

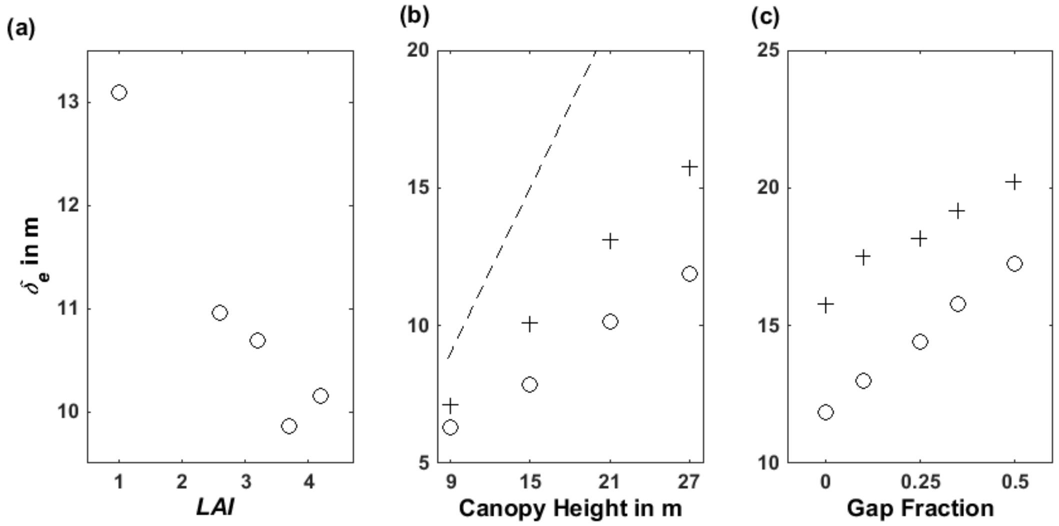

Figure 3. LES domain-averaged eddy-penetration depth (δ_e) vs. (a) leaf area index (*LAI*), (b) canopy height (h_{max}) and (c) gap fraction (*GF*). For (b) and (c), crosses and circles correspond to leaf-off and peak-*LAI* conditions, respectively. The dashed line in panel (b) represents the 1:1 line.

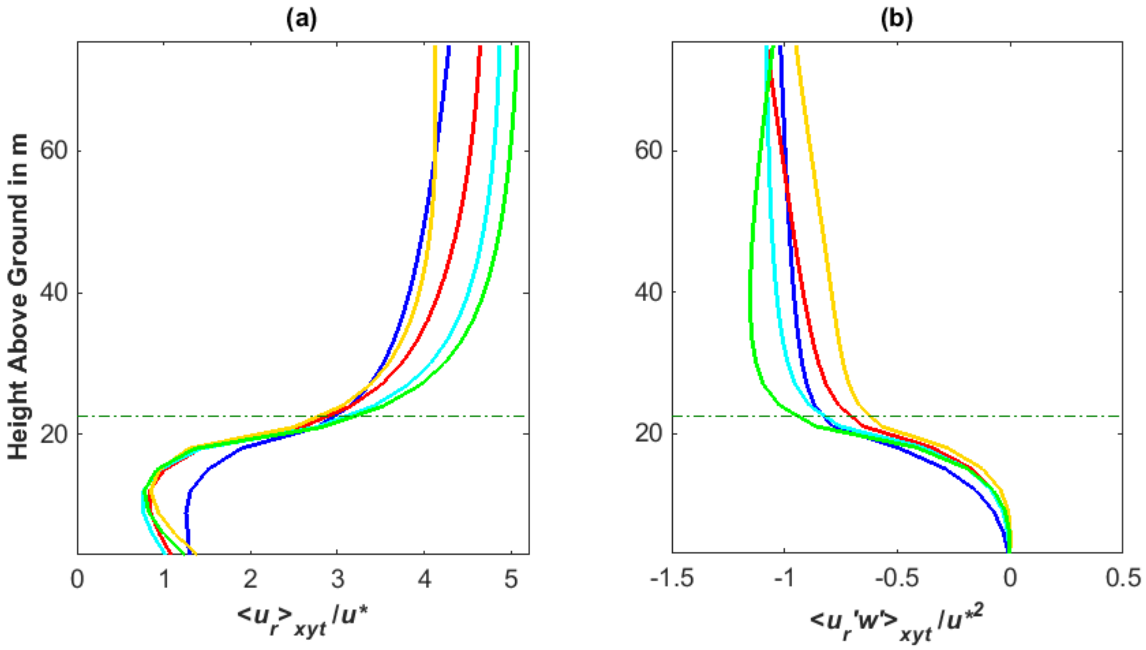

Figure 4. Vertical profiles of (a) Horizontal wind normalized by friction velocity, and (b) momentum flux normalized by the square of friction velocity for *LAI* = 1.0 m^2 m^{-2} (blue), *LAI* = 2.6 m^2 m^{-2} (cyan), *LAI* = 3.2 m^2 m^{-2} (green), *LAI* = 3.7 m^2 m^{-2} (orange), and *LAI* = 4.2 m^2 m^{-2} (red). Canopy height shown as horizontal dashed green line.

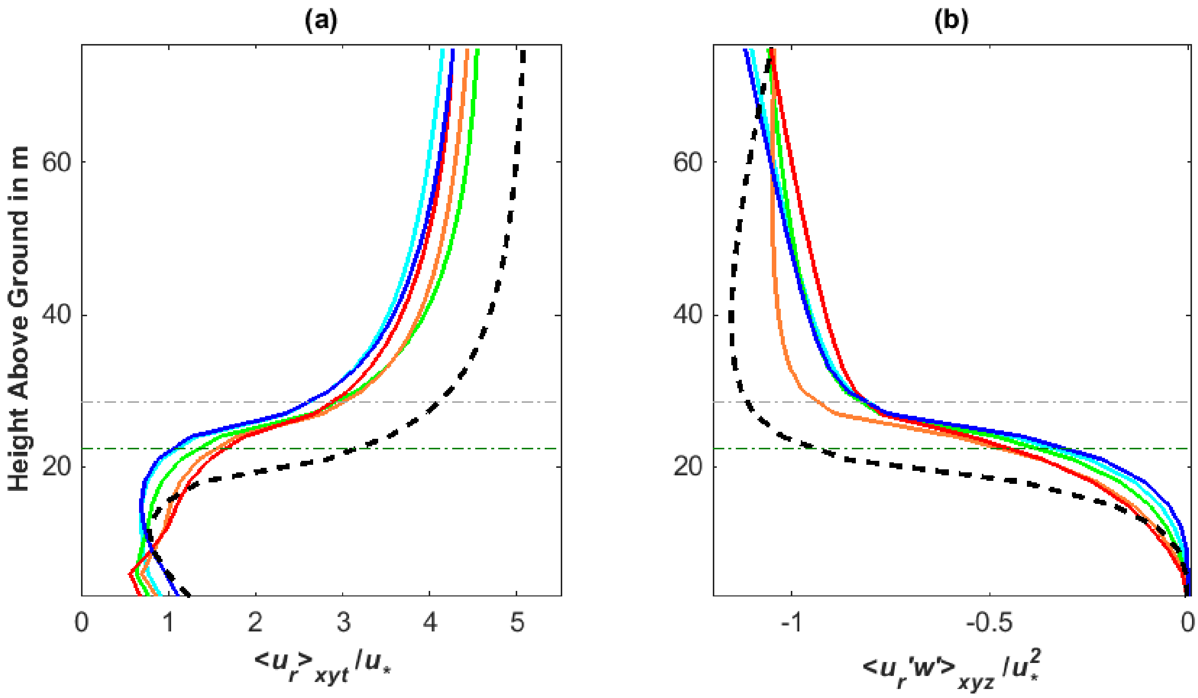

Figure 5. Vertical profiles of (a) Horizontal wind normalized by friction velocity, and (b) momentum flux normalized by the square of friction velocity in a 27 m tall canopy with gap fractions of 0% (blue), 10% (cyan), 25% (green), 35% (orange), and 50% (red); and in a continuous 21 m tall canopy (dashed back). Canopy height for the tall and short canopies is shown as dashed horizontal gray and green lines, respectively.

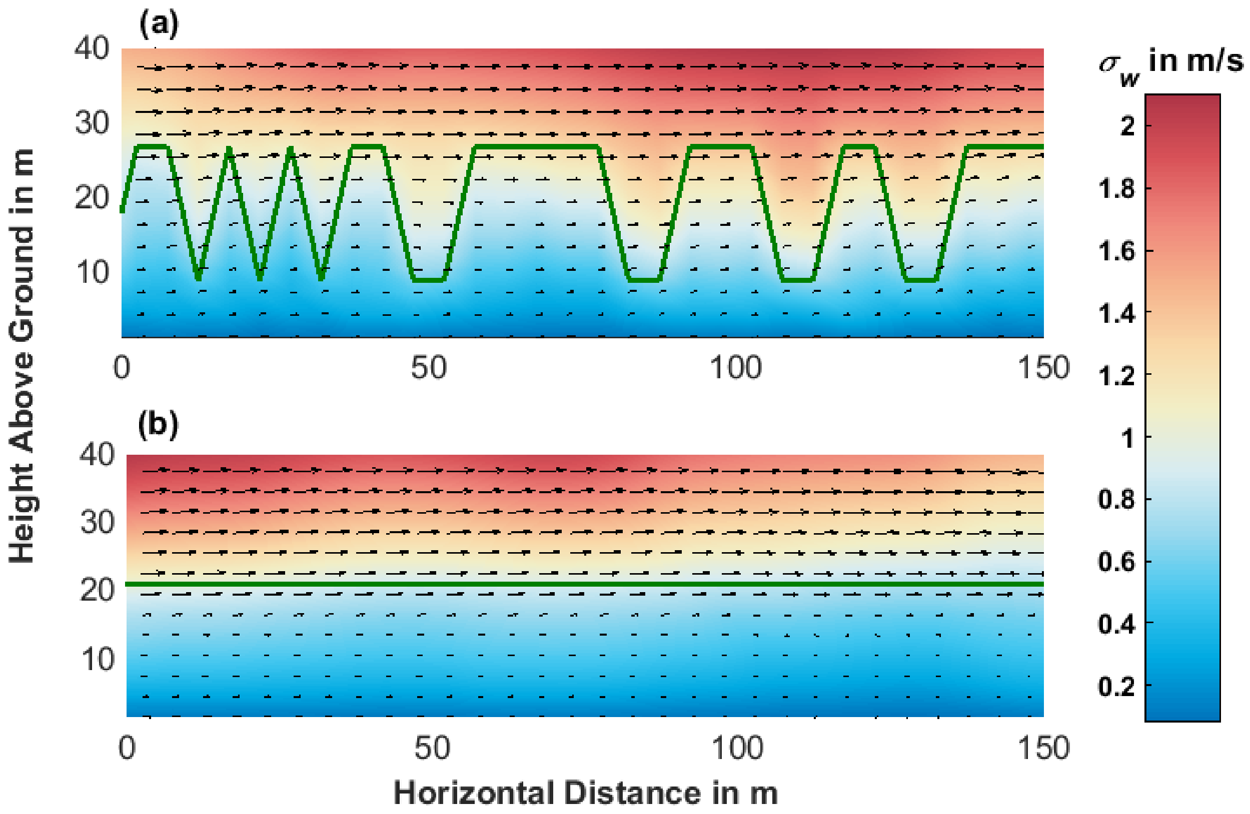

Figure 6. Vertical cross-section through the simulation results of (a) a 27 m tall canopy with 25% gap fraction and (b) homogeneous 21 m tall canopy. 30-minutes mean wind speed and direction are illustrated using black arrows, the standard deviation of vertical velocity (an indication of turbulence intensity) is plotted using a colormap. Canopy top in each simulation is illustrated by a solid green line.

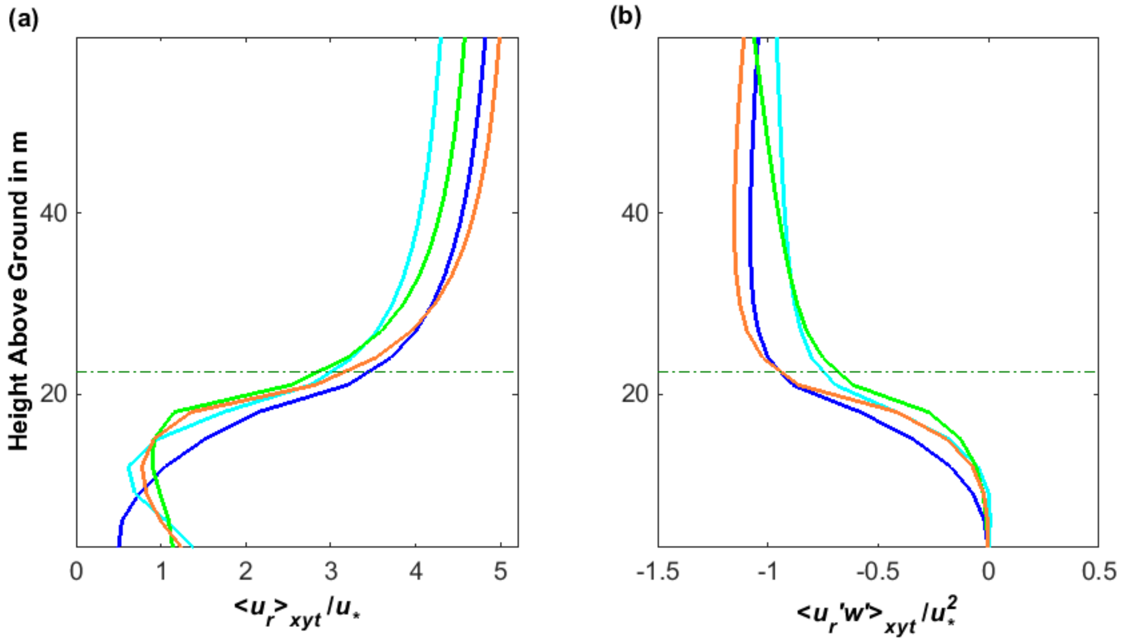

Figure 7. Vertical profiles of (a) Horizontal wind normalized by friction velocity, and (b) momentum flux normalized by the square of friction velocity for 'Lower' (blue), 'Middle' (cyan), 'Upper' (green), and 'Natural' (orange) LAD profiles. Canopy height shown as dashed horizontal green line.

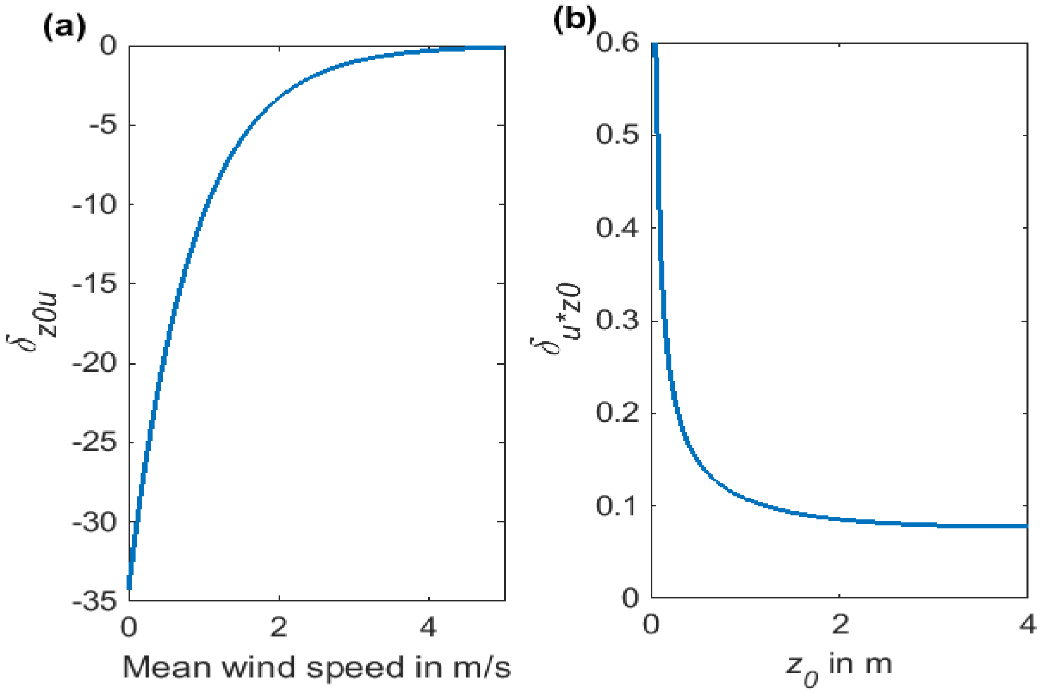

Figure 8. (a) Sensitivity analysis of z_0 as a function of variation of the mean wind speed (δ_{zou}). We illustrate it here is a particular range of parameters, choosing a canopy height h=22 m (roughly the height we used in the simulation and observation site), displacement height d=0.67h, observation height of 2h (the recommended observation height for a flux tower) and u_* of 0.35 m/s. The results are similar for other canopy heights and u_* values. (b) Sensitivity of u_* to variation in z_0 (δ_{u*z0}). We plotted the response curve over the same parametric range expected for z_0 values, wind speed at the center range of 3 m/s. u_* is relatively insensitive (δ_{u*z0} < 0.15) for any z_0 above 0.5 m.