Response to review by Ronald Queck

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.

General Comments

Representation of natural forest canopies within numerical models is an actual problem within the science community as it limits the accuracy and the applicability of their results.

The authors investigated the effect of changes in canopy structure using large-eddy simulations (LES). From the LES results they inferred statistical relationships between measurable canopy quantities and wind profile parameters (displacement height d and roughness length z_0). This approach is new and the well-defined changes within the canopy characteristics allow insight in the dependencies of the wind profile parameters.

Further, existing approaches for d and z_0 from literature where applied to calculate the wind profile parameters from canopy quantities.

The different d and z_0 estimates where then used within the logarithmic wind profile equation for the calculation of friction velocity (i.e. the momentum transport between surface and atmosphere) using measured wind speeds and stability parameters.

These calculations where again validated with direct measurements of the momentum transport.

We thank the reviewer for this supportive comment on our approach.

The authors found a dependence of the wind profile parameters on the maximum canopy height, leaf area index and gap fraction. However, changes of the vertical plant surface distribution resulted in an inconsistent variation of d and z_0 but also in incomprehensible changes of the simulated wind profiles.
As the authors state themselves, this is obviously caused by the interdependence between d and z_0.

Prodded by the reviewer's comments we put some additional work and analysis into this matter. As you will see in our response to the comment below fixing d and fitting only z0 to the resolved wind simulation results did not improve the relationships we find between z0 and canopy structure parameters, and in fact, it had very little difference altogether.
We no longer believe that the z_0-d tradeoffs are the only source of the problem of inconsistent z_0-canopy structure relationships. To understand this point, we conducted a sensitivity analysis by calculating the partial derivative of z_0 with respect to the mean wind speed ($<u>$), and the partial derivative the u_* with respect to z_0. The partial derivative is a direct measure of sensitivity of one

variable to errors in measurements or inference of another. We determine that at low mean winds (below 3 m/s) z_0 is extremely sensitive to variation in <u>, with the derivative (the rate of change in z_0 per change in <*u*>) being between 5 and 30 (see Figure 1, below). It means that for a variation of 0.1 m/s, the resulting z_0 (calculated from measurements at twice the canopy height) will change by 0.5-3 m which is a full range of the expected z_0 values for a 20 m canopy. At twice the canopy height <*u*> was less than 3 m/s roughly half of the time in our site in Michigan, and our simulations were set for <*u*> of 2.7 at that height. A variation in half-hourly mean wind speed at the order of 0.1 m/s can be a result of measurement errors, or local variations in the flow field due to topography (in reality) and canopy surface (in reality and the model) or even random large eddies that may affect the 30 minutes average at a specific half hour. However, and consistent with the results of our model inter-comparison section, $u*$ shows very little sensitivity to changes in z_0, when z_0 is above 0.5 m (assuming z0 ≈ 0.1*h*, the expected z0 for a canopy of *h*=22 m is around 2.2 m, well above 0.5 and well within the range where $u*$ is insensitive to z0). This explains why, despite the lack of a satisfying model for z_0 as a function of canopy structure, all the models we tested against observations showed high levels of precision in predicting $u*$.

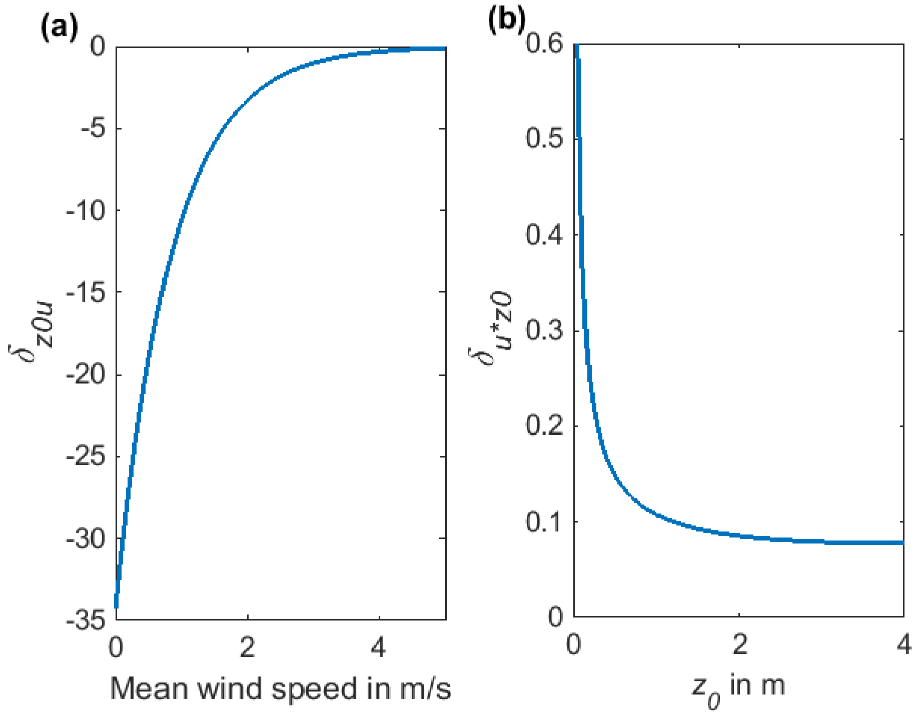

Figure 1. (a) Sensitivity analysis of z_0 *as a function of variation of the mean wind speed (*δ_{zou}*). We illustrate it here is a particular range of parameters, choosing a canopy height h=22 m (roughly the height we used in the simulation and observation site), displacement height d=0.67h, observation 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.*

Unfortunately, they did no deeper investigation of this problem. This may be caused by their indifferent consideration of d and z_0. Both of the parameters were named 'roughness parameters'. However, only z_0 represents the roughness of the canopy, differently, d is introduced in the wind profile to reduce the height above the ground z, as z is used as a scale for the mixing length $l=\kappa(z-d)$.
In many case the fitting of d and z_0 at the same time leads to tradeoffs. The determination of one parameter first, with an independent method, and calculation the other afterwards on the basis of the wind profile circumvents the problem. For example estimating d based on the canopy structure (i.e. depending on the canopy height or the gap width between the vegetation elements) would probably lead to a more reasonable behavior of z_0 within the presented work. If you want to use only wind measurements you can also use the methods described in Rotach (1994) or De Bruin and Verhoef (1997) to determine d.

We acknowledge the fact that setting *d* as a function of canopy height, and independent of z_0, is a common practice. We thank the reviewer for the suggestion of studying how z_0 changes when d is assumed fixed. We hoped that this analysis approach would allow us to improve the empirical model of z_0 as a function of canopy structure. We therefore followed the reviewer's recommendation and reanalyzed our results with an additional approach of fixed d. We set $d=0.67h$, and fitted the M-O equation for z_0 only, given <u>. The results, however, were disappointing, and were very similar to the results obtained with a variable *d* (see figure 2 below). This made us reevaluate our hypothesis that the tradeoff between z_0 and d drive the large variation in z0. As we show above, we find support for an alternative hypothesis: that the sensitivity of z_0 to <u> is responsible for the large variation in z_0 (see the results and explanation of the sensitivity analysis above). We will add the results of the sensitivity analysis to the discussion section in our revised manuscript as it shed further light on our findings, and on the prospects of finding an accurate empirical model for z_0. To add depth and interest, we also added the results of an additional simulation case – the Explicit-LES where we prescribed the canopy structure as observed by lidar and calculated the d and z_0 directly from the simulation results. We expanded the set of conditions and period over which we modeled u_* and the different approaches now show more differences in their ability to predict u_*. We rewrote the discussion section and the result sections completely, and are confident that the revised discussion holds more depth.

With regards to the collective naming of d and z_0 as roughness parameters: to some degree, one may argue that z_0 and d are two shape parameters of a single curve. Observations in the real world have shown that they tend to trade off, even when obtained as the distinct (and independent) solutions from observations at multiple heights (see Nakai et al 2008 and we have similar observations in our site). Nonetheless, we agree with the reviewer that they may be considered separately. We will revise the language in our manuscript to better distinguish them and clarify that they are not one exchangeable entity.

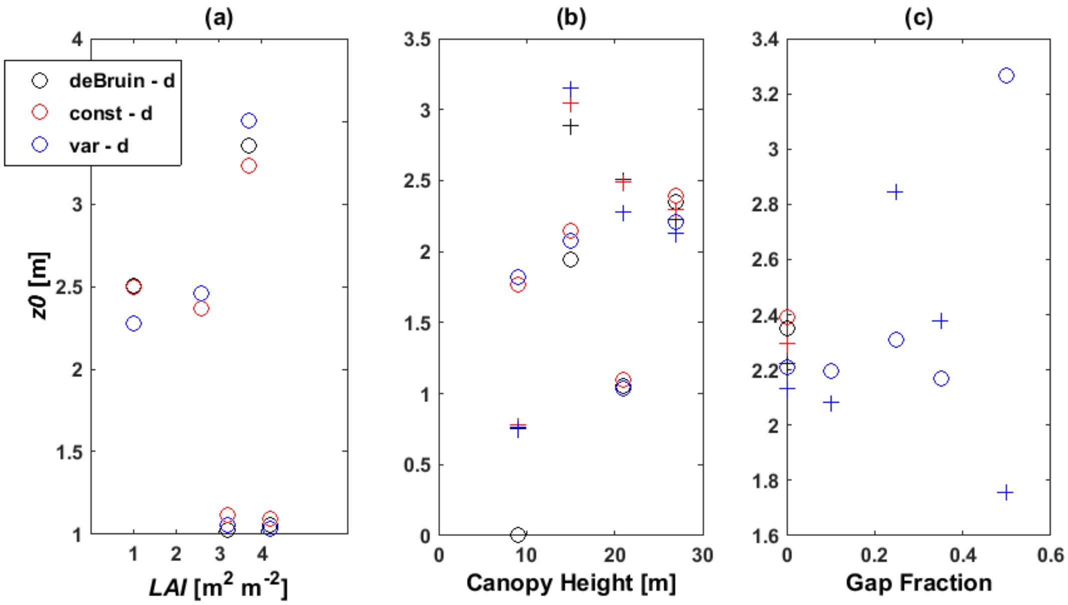

Figure 2. The relationships between z0 and canopy structure characteristics ((a) LAI, (b) Canopy Height, (c) Gap Fraction). Z0 was calculated in 3 ways – (1) 'var –d' – is the one presented in the manuscript and done by fitting MOST to the wind profile; (2) const-d'- following the reviewer's suggestion, fixing d at the 'Classic' 0.67h and fitting MOST to find z0 only; (3) 'deBruin-d' – also following the reviewer recommendation, using the approach by deBruin to determine d, independently of z0, and then fitting MOST to find z0. Crosses mark the results of leaf-off simulations and circles are the leaf-on simulations.

The wind profiles in Figures 4-6 are not easy to compare, as they were not normalized with the wind speed at the top of the canopy or the wind speed at a reference height within the inertial sub-layer. Moreover, the figures indicate a different wind speeds within the inertial sub-layer far above the canopy. Thus, the different LES are probably not really comparable.

The LES is forced by nudging the mean wind speed high above the canopy (from the model to about 5*h*) to a prescribed velocity that was the same for all simulations. Any differences in the wind profile below that forced layer height is the result of differences in surface roughness. All simulation cases are directly comparable, and in fact, we are confident that the approach we took for forcing and canopy description in the model made special considerations not to introduce any implicit or explicit assumptions of roughness length, such that any conclusion of roughness length differences between the models is an outcome of the canopy structure and not a by-product of the forcing. We chose the height of the forcing layer to be high enough such that the forcing will not directly affect the results. The exact height of the inertial sub layer is not easy to define, and as Raupach and Thom (1981) suggested (and Bohrer et al (2009) confirmed with LES simulations) may extend up 5 times the canopy height.
As the reviewer points out, we did make a mistake in the presentation of the profiles by not normalizing them. We now present the wind speed profiles and the $\langle u_r'w'\rangle$ profiles normalized by u_* or u_*^2, respectively, and by extending the height up to which we show the profile. As you

can see in the revised manuscript figure 4 (which is copied to this response document as Figure 3, below), this has collapsed the curves and made the results of different simulations directly comparable. We also revised the color scheme to be consistent (low-to-high) across all canopy structure variables in figures 4-6 in the manuscript.

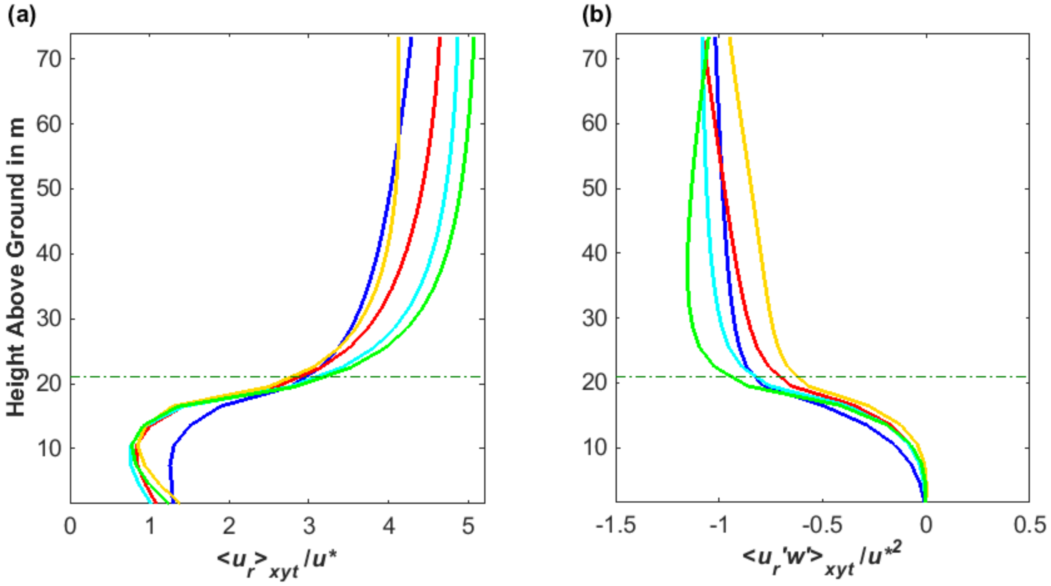

Figure 4. Vertical profiles of: ***(a)*** *mean downstream horizontal wind speed* $<u_r>_{xyt}$ *normalized by u* and* ***(b)*** *momentum flux normalized by* u^{*2}*; for* $LAI=1.0m^2m^{-2}$ *(blue),* $LAI=2.6m^2m^{-2}$ *(cyan),* $LAI=3.2m^2m^{-2}$ *(green),* $LAI=3.7m^2m^{-2}$ *(orange), and* $LAI=4.2m^2m^{-2}$ *(red). Canopy height shown as horizontal dashed dark green line.*

The conclusions of the authors are not very productive. The authors state 'consistent relationships between roughness parameters and LAI, maximum height, and gap fraction' (p16371L9). Which is, at least partly, contrary to statements within the document (p16368L3: However, the lack of any relationships between roughness parameters and gap fraction was surprising).

Despite the improvement of the correlation between d and canopy height by the use of the maximum tree height instead of the mean tree height, the general performance of the inferred statistical relationships was not better than the approaches from literature (Raupach 1994). The inclusion of the vertical plant area distribution seems to produce also no improvements. Thus, the main conclusion which remains is: It is very difficult to determine the influence of canopy structure on the wind profile parameter.

The revised results and discussion sections include better explanation of the advantages and disadvantages of each method and provides more constructive conclusions. While 'Raupach 94' came out the most accurate method, it requires full plot censuses which are not available over wide spatial coverage and, therefore, could not be implemented in a general global modeling approach. Our approach requires only LAI and gap fraction which are available world-wide from satellite datasets such as LANDSAT and MODIS, and canopy height, which is commonly predicted by models, can be measured by lidar and is already the source of roughness length estimates. We also show that the model results for u_* (and therefore, surface fluxes) are not very sensitive to interannual variation in canopy characteristics, which is an important and surprising conclusion.

Some of the methods and the results are poorly described. For example it is not clear how the 'Yearly Observed' method works and how the results are gained. The calculated d and z_0 of the 'Raupach 94' and 'Nakai 08' approaches are not reported.

We re-wrote the entire results section to better explain what we did, and how these methods compare to each other. Except the 'Classical' and 'yearly Observed' of specific years, all other approaches (including 'Raupach94' and 'Nakai08') produce variable z_0 and d that are dependent on the observed properties of the canopy at different times throughout each season and year. Therefore, in the previous version we chose not to provide a single value. We have now revised the table to provide the decadal mean, and extremes of z_0 and d for all the parameterization approaches and explain that in the table's caption.
The revised section that explains the different methods is now section 3.2 in the 'Results', just after the derivation of the 'Biometric' approach from the simulation results is explained.

The language of the manuscript could be improved by the use of shorter sentences, often different statements are linked together without break (e.g. P354L15-20, P360L20-23 and P363L3-10). Several parts need a revision with respect to concise and precise use of formulations (e.g. P16362L1, where the authors compare an improvement of something with a result of something).

We have revised the language of the manuscript, with specific focus on breaking long sentences to short ones and creating a clearer and more concise narrative. A language editor (Ashley Matheny) has read and proofed the revised version of the manuscript. A great resource for this revisions are the suggestions of both reviewers, which will be implemented in full. We will revise the formulation to be more precise and better explained (see our response to reviewer #2, as to clarifications of the formulation used to measure the mean properties in the simulation domain, such as u_r, and $w'u_r'$).

The content of subsections 2.6 and 2.7 belong either to subsections "Theory" or "Results" (the statistical methods must not be listed explicitly as far as they are standard methods).

We have removed section 2.6, and list the relevant information from there in the results section. We have moved section 2.7 to the "Results" section (new section 3.2).

Title/Abstract

P350L21: 'We compared it with three other semi-empirical models …'. Is LES a semi-empirical model?

We removed the term 'semi-empirical'

P350L23: 'fixed representations of roughness' please clarify what is meant by that phrase, or better reformulate the last two sentences.

We revised this to 'temporally invariable'

1 Introduction

The introduction could be written more concise and focused.
P352L4: The displacement height d is not a 'surface roughness parameter for momentum'
P354L15-20: Split the sentence.

We shortened the introduction by removing several redundant sections, and split this sentence, and many others.

2 Materials and methods

2.1 Theory

P356L21-22: Up to this line it is not clear how ha, d and z0 will be determined. The reader does not know what is 'simulation-specific'. "the horizontal wind profile": presumably the "vertical profile of the horizontal wind speed" is meant (see also P360L21, …).

We revised to: "In simulation results, where the detailed 3-D wind field is known, we can 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."

*P356L3: Check the indices (uw = 0.1 * uw_ha ?)*

We removed this formulation and replaced it by the sentence: "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 only 10% of its value at h_a (Nepf et al., 2007)."

2.2 Site description

2.3 Large eddy simulations

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

*P359L24: '**these** structural characteristics' Which? Please describe or name them.*

Done

P359L24: ‘surface-aerodynamic properties’ → ‘aerodynamic properties of the surface’

Done

P359L27: ‘that describe such canopy structure.’ → delete or exchange with ‘that characterize such canopy structure’

Exchanged to 'that describe such canopy structure'.

P360L1-6: Combine both of the lists (maybe as table)

We combined the lists, reduced the values to a range, and refer to the full list in Table 1.

P360L15: ‘Changes along the four canopy-structure axes yielded twenty permutation cases.’ - The permutation gives 400 cases!

We added an explanation that: "Based on the available computing resources, we selected twenty combinations of the structural characteristics listed above."

2.5 Empirical determination of roughness parameters from simulations results

P360L20-23: split sentence in two or shorten to: ‘To find this point we compiled a domain averaged wind-speed profile using Eq 2.’

Done

P360L22: ‘h_r’→’u_r’

Done

P360L22: ‘vertical layer’ - layer or column?

Layer. We revised the description of how we calculated u_r. See the revised section 2.5. We think it is clearer now.

P360L20-23: ‘As RAFLES was able to estimate wind statistics across a large domain,’ - delete or explain the function within this sentence.

We removed this sentence.

P360L24: ‘we fit the wind profile in space’ - delete ‘in space’

Done

P360L26: How did you interpolate between the profile functions? Did you use linear interpolation, spline or … (that is important for the position of inflection point.

New explanation reads: "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. "

P360L27: 'found the height above the ground' → 'determined h_a*'*

Done

P361L6: 'vertical layer' - layer or column?

Layer. However, we call them vertical layers, and they are, in fact, horizontal layers. We revised throughout.

2.6 Surface roughness parameters: forest structure effects → Sources of variation of wind profile parameter

P361L6: 'LAD position' → 'LAD distribution'

P361L6: 'chaotic' → 'not explainable'

P361L17-20: These are results which do not belong in 'Materials and methods'

We removed this section

2.7 Testing empirical models linking roughness parameters to biometric measurements

Please write clearly and in an easy accessible manner which models and methods did you apply.

P361L25: How did you evaluate the potential improvement of the surface flux estimates? The '(a)' belongs presumably to a 'not easy to follow' list which is continued at P362L5. Please use a clearer structure. Reformulate and split the sentence. One cannot compare an improvement of something with a result of something.

P362L5-18: This part shout be shifted to subsection 'Theory'.

P363L0-10: Reformulate and split the sentences into shorter ones.

*P363L4: What are the "**four** other direct empirical methods"?*

P363L7: Describe the "Yearly Observed" method.

P363L11: Did you force the regression trough zero? Otherwise report the offset values.

P363L17: I assume you did apply the yearly parameterizations of the "Yearly Observed" on the whole data set (all 10 years). Why did you use the parameters of structure-driven methods only for one year (P363L20)? This is inconsistent. Further, it would be interesting how long the parameters, which are gained from biometric measurements, can be used.

P363L19: Delete 'Sect. 2.7,' as this is Section 2.7.

We completely rewrote this section and moved it to the results, section 3.4. We also revised table 3, and report the intercepts of the regression lines.

3 Results

3.1 Virtual experiment to explore canopy-roughness relationships

P364L9: write '$d = 0.69h_{max}$' in Equation stile, thus you can refer on this result later on.

Done

P364L12: 'There was little change to d with increasing gap fraction'? Table A1 showed an decrease of d of almost 30 % (from 20.1 m to 14.4 m) as a result of the 50 % increase of the gab fraction.

We revised to: "There was little change to *d* with increasing gap fraction, except with 50% gap fraction in the leaf-on simulations, which was significantly lower. "

3.2 Canopy-roughness improvements to surface flux models

What are 'Canopy-roughness improvements'?

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

P365L7: 'fit' → 'fitted

Corrected throughout

P365L13: As far as I understood the setup, the h-h_{max} relationship is not 'found from the virtual experiment' it is given by the virtual canopies with h_{max} and GF.

We revised and cleaned up this section. It now reads: "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), we calculated the 'Biometric' h_a. 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 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 the Eq. 10. Finally, a 'Biometric' z_0 was calculated as:

$$z_0 = \lambda(h_a - d) \tag{13}$$

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.

P365L13: 'we empirically fit' → 'we calculated'

Done

P365L13: 'Eq. (11)' → 'Eq. (12)'

We revised equation references throughout.

P365L13-17: These lines are not comprehensible.
P365L20: Regard comment on P365L9, delete Eq. 14 and refer to 'd = 0.69hmax' as well as to Eq. 7 for z_0.
P365L21: How did you exactly determine λ.

See revised section above that addresses all these issues.

P366L3: SD is not introduced.

We removed this part and completely rewrote section 3.3

P366L9: 'Eqs. 11, …' →'Eqs. 12, …'. What influence has Eq. 13?

We revised equation references throughout.

4 Discussion

4.1 Response of roughness parameters to canopy structure change

P366L15-16: Emphasize that this are model results gained by the use of artificial canopies. Different relationships of h_a are possible for real canopies. Contrary to your statement, Table A1 shows that h_a is rarely sensitive to canopy structure, i.e. LAD profile variation (lower: h_a=20.7 m to upper: h_a=21.2 m).

We revised the discussion section thoroughly. Please check the revised version. It answers all of the comments and concerns indicated here. Specifically for the statement above, ha was sensitive to all canopy structure characteristics, other than LAD. We revised this sentence (now in the second paragraph of section 4.1 to read "By testing the independent effects of different characteristics of canopy structure through a set of controlled virtual experiment, 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) where both sensitive to some of the characteristics of canopy structure and linearly scaled with 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. "

P367L10: d and z_0 are canopy parameters; they do not change with meteorological conditions, *at least as long as the properties of the canopy are not influenced. However, the estimation of d and z_0 might depend on the meteorological conditions.*

We agree and removed this paragraph.

P367L22: 'roughness-height'? Did you mean 'roughness-canopy height' (i.e. z_0-h)?

We revised to "As canopy height was the only canopy characteristic that varied among the 'canopy height variation' simulations (Table 1.c.), it is reasonable to assume…"

P367L28: How does the eddy-penetration depth influence the determination of d?

It brings fast eddies lower into the canopy. By definition, *d* is the height were mixing with the air above has only negligible effect on momentum flux.

P368L3-4: Table A1 shows a clear relationship between GF and d or d+z_0 (see comment on P364L12)

We restricted this claim to z_0 only, and the effect of GF is only apparent at the extreme point of the GF continuum (50%). No effect until then. We revised to: "However, the lack of any relationships between roughness length and gap fraction at all levels below 50% gap (*Table 1*) was surprising"

P368L15-18: Repetition of P367L1..

Fixed

P368L21: I cannot identify a 'weaker above-canopy turbulence and horizontal wind speed' within Fig. 5a and b. This might be caused by different wind speeds within the higher model layers.

We removed this statement

P368L24-27: This statement is very general, i.e. trivial.

We removed it.

P368L18-21: Please, reformulate this sentence.

Revised to: "For example, we found that increased gap fraction corresponded to increased momentum flux, turbulence, and horizontal wind speed inside the canopy (below 1*h*) (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)."

P368L18-24: This is a conclusion, which is not so clearly stated within section 'conclusions' *(shift it).*

We removed it.

4.2 Integrating canopy-structure characteristics into flux models

P370L1-9: As the ''Yearly Observed' model' is not described these statements cannot be evaluated.

Section 3.2 now provides clear and detailed explanation of all parameterization approaches.

P370L12: What is meant by 'surface height, complexity, and density'(especially by the last to terms)

Revised to "complexity of organization, and density of roughness elements"

P370L10-19: What do you want to say exactly within this paragraph? Especially by the sentence: 'In their urban study of building heterogeneity, Grimmond and Oke (1999) suggested the method of Raupach (1994) for random building arrangements, which may provide insight towards its success in this study over our heterogeneous forest canopy.'

We removed this section.

P370L25: 'used' → 'taken'
P370L26: 'each' → 'any'

Fixed

5 Conclusions

P371L11-22: Those are general statements but not unique conclusions from your work.

The conclusions section was rewritten, in light of the analytic sensitivity analysis results, and the new approach for the discussion. It is now more interesting and meaningful.

Tables

Table 1 is not necessary, it is part of Table A1.

We removed table A1 and used it to replace table 1.

Table 3: Why has the coefficient of determination always the value 0.8?

Bug. We fixed it. See new table 3.

Figures

The axis labels of the kind ‘d [m]’ are common but mathematical incorrect. Please write ‘d in m’ or ‘d /m’ or ‘d m^{-1}’. Variables should be written in the same style as in the text (kursiv, …)

We revised to the format: 'd in m'.

Fig. 1: Please add a 1:1 line
Fig. 2: Please add a 1:1 line in Fig. 2b
Done.

Fig. 3: y-axis label: ‘d_e‘, use the Greek letter or write ‘eddy-penetration depth’, please add a 1:1 line in Fig. 3b
Done

Fig. 4: Use the same order of the colours in Fig. 4 and Fig. 5

Done

Fig. 5: Explain in the figure caption, what is exactly shown in 5c, d, e and f? If 5d shows the case with GF = 0 % then use the same colour as in 5a and 5b or better leave it out. SD is not introduced. The x-labels of 5b are not readable

Fig 5 was split to 2 figures and the 4-panel part was merged to 2.
Caption and labels were revised. We hope it's clearer now.

Fig. 6: Use the same colours like in Fig A1.

Done (all color schemes were made uniform)

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:

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

where $\overline{u}_z$ 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, $\overline{u}$ and $\overline{v}$, $\overline{u}_z$ is rotated toward the wind direction such that:

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

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:

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

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:

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

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:

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

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:

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

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).

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

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:

$$z_0 = \lambda(h_a - d) \tag{13}$$

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

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

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 $\bar{u}_z$:

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

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}.

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

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.

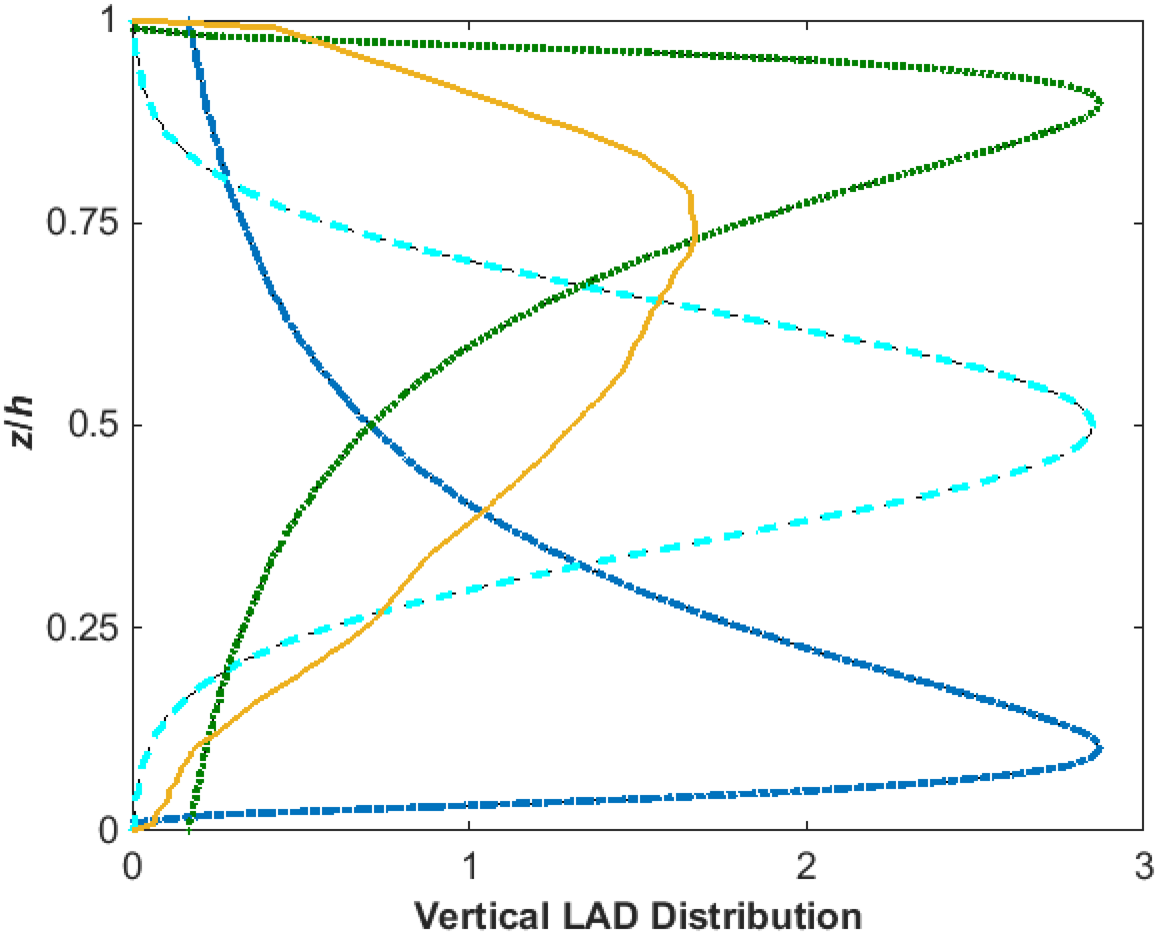
Conclusions

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.

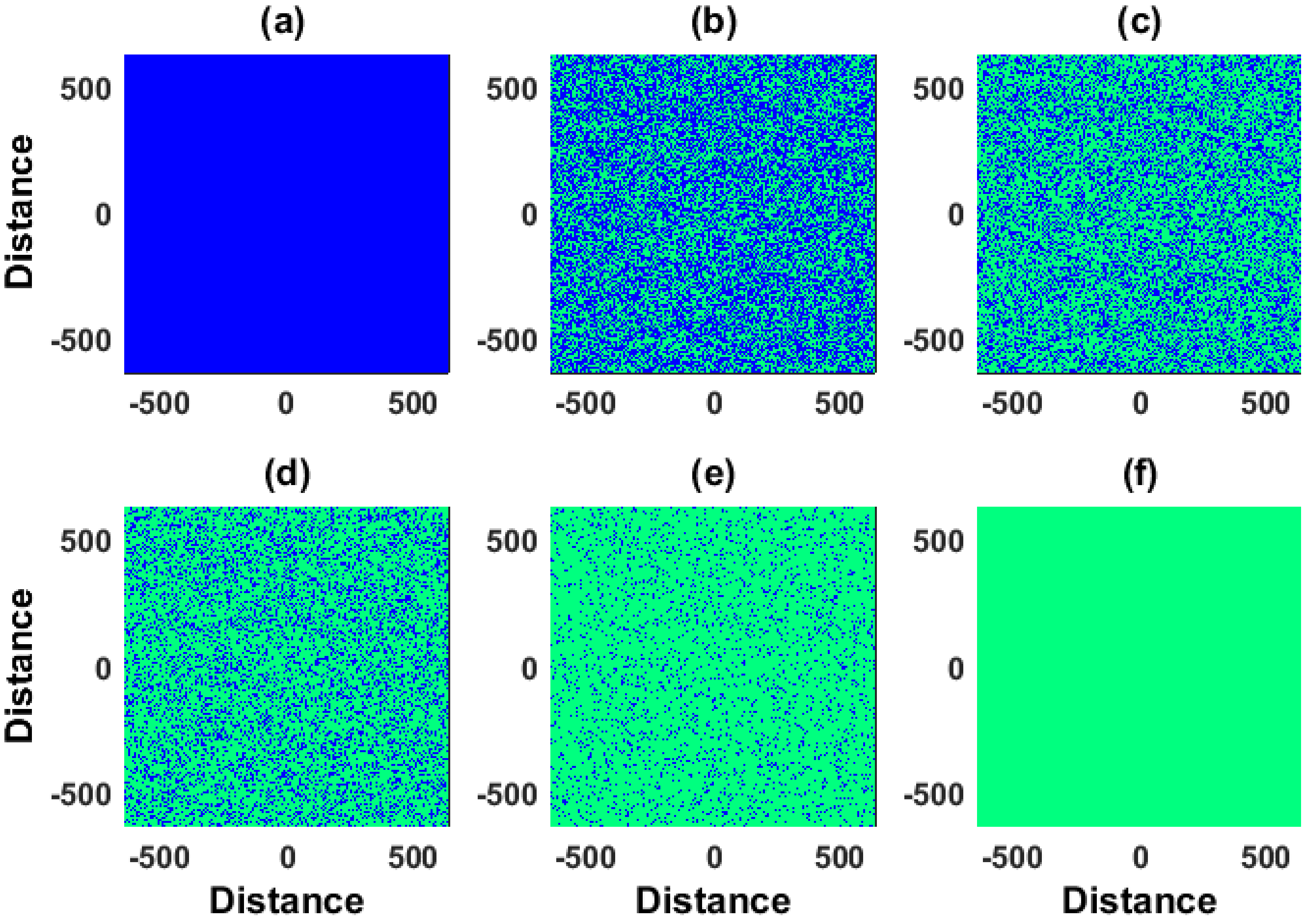


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Table 1: Description of simulation cases used for sensitivity analysis of roughness parameters derived from an LES over variable canopy layouts, and the resulting roughness parameters for each simulation case. Canopy structure was varied along four 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)**	**z_0 (m)**	**Slope**	**Intercept**	**r^2**	**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

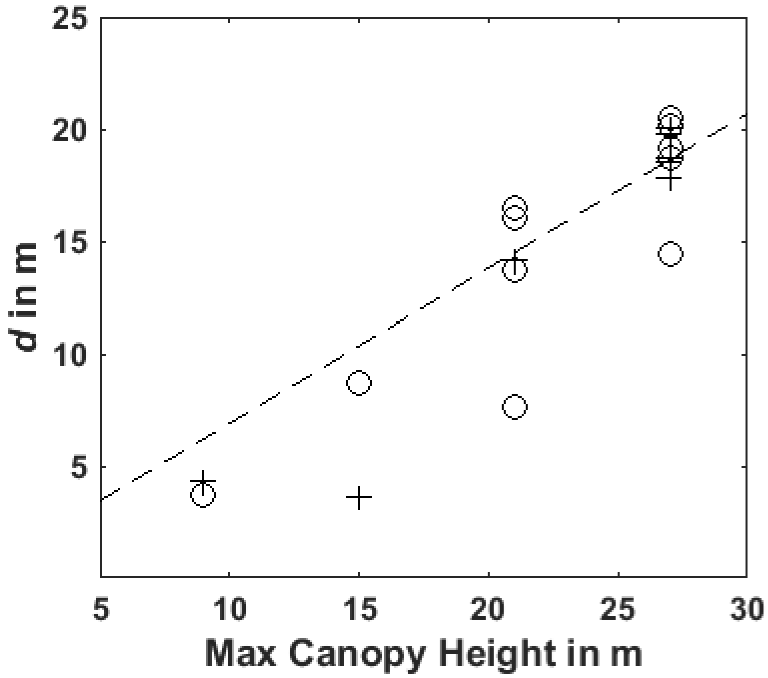

Figure 1. LES domain-averaged *d* vs. maximum canopy height. Crosses and circles correspond to leaf-off ($LAI = 1.0$ m^2 m^{-2}) and leaf-on ($LAI > 1.0$ m^2 m^{-2}) conditions, respectively. Best-fit line (forced through [0,0]) shown as dashed line ($d = 0.69h_{\mathrm{max}}$).

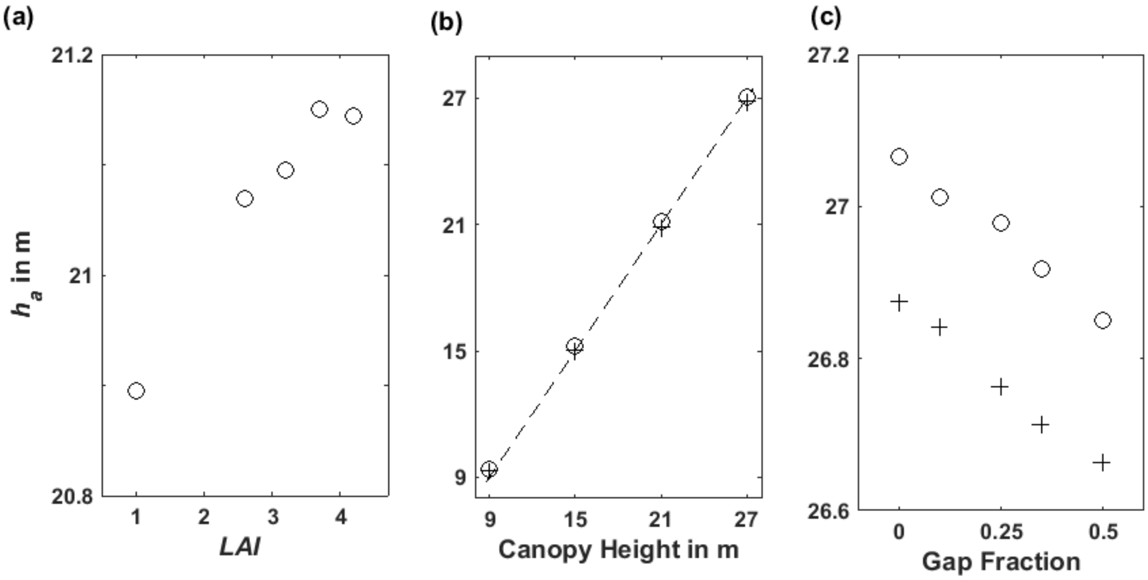

Figure 2. LES domain-averaged aerodynamic canopy height (h_a) vs. (a) leaf area index (*LAI*), (b) canopy height (h_{max}), and (c) gap fraction (*GF*). For (b) and (c), crosses and circles correspond to leaf-off and peak-*LAI* conditions, respectively.

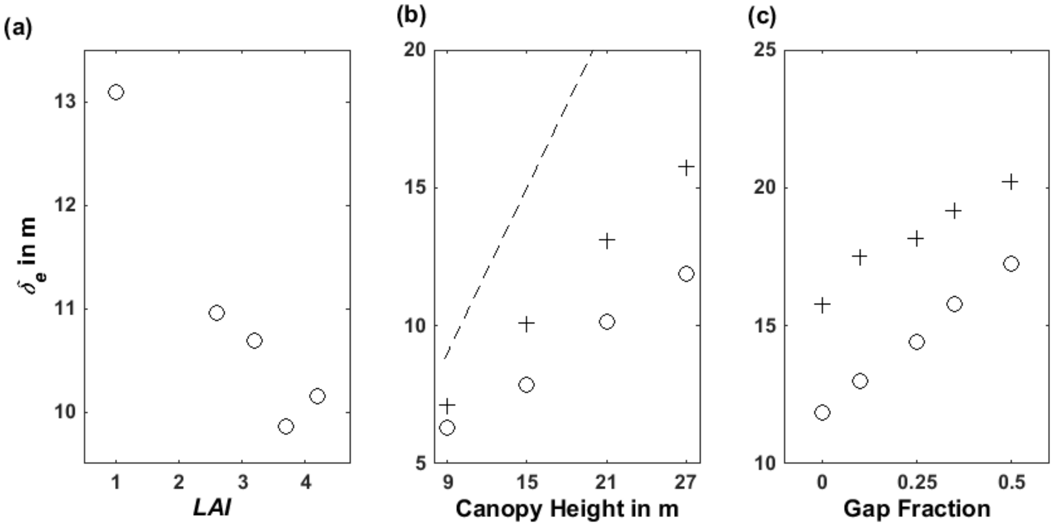

Figure 3. LES domain-averaged eddy-penetration depth (δ_e) vs. (a) leaf area index (*LAI*), (b) canopy height (h_{max}) and (c) gap fraction (*GF*). For (b) and (c), crosses and circles correspond to leaf-off and peak-*LAI* conditions, respectively. The dashed line in panel (b) represents the 1:1 line.

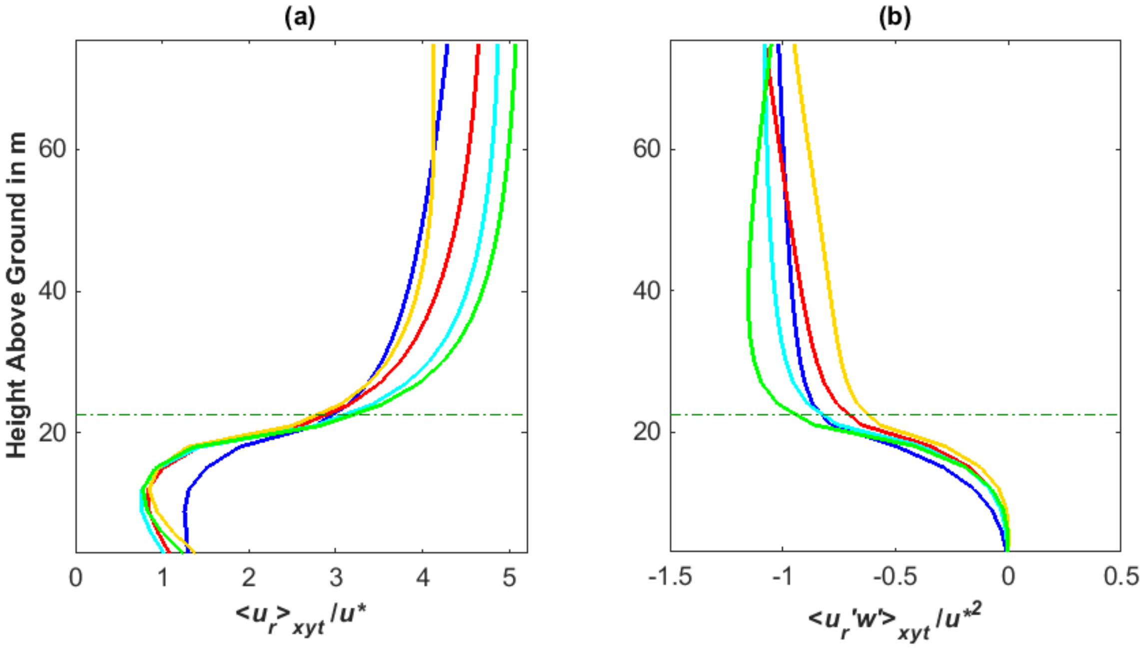

Figure 4. Vertical profiles of (a) Horizontal wind normalized by friction velocity, and (b) momentum flux normalized by the square of friction velocity for *LAI* = 1.0 m^2 m^{-2} (blue), *LAI* = 2.6 m^2 m^{-2} (cyan), *LAI* = 3.2 m^2 m^{-2} (green), *LAI* = 3.7 m^2 m^{-2} (orange), and *LAI* = 4.2 m^2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

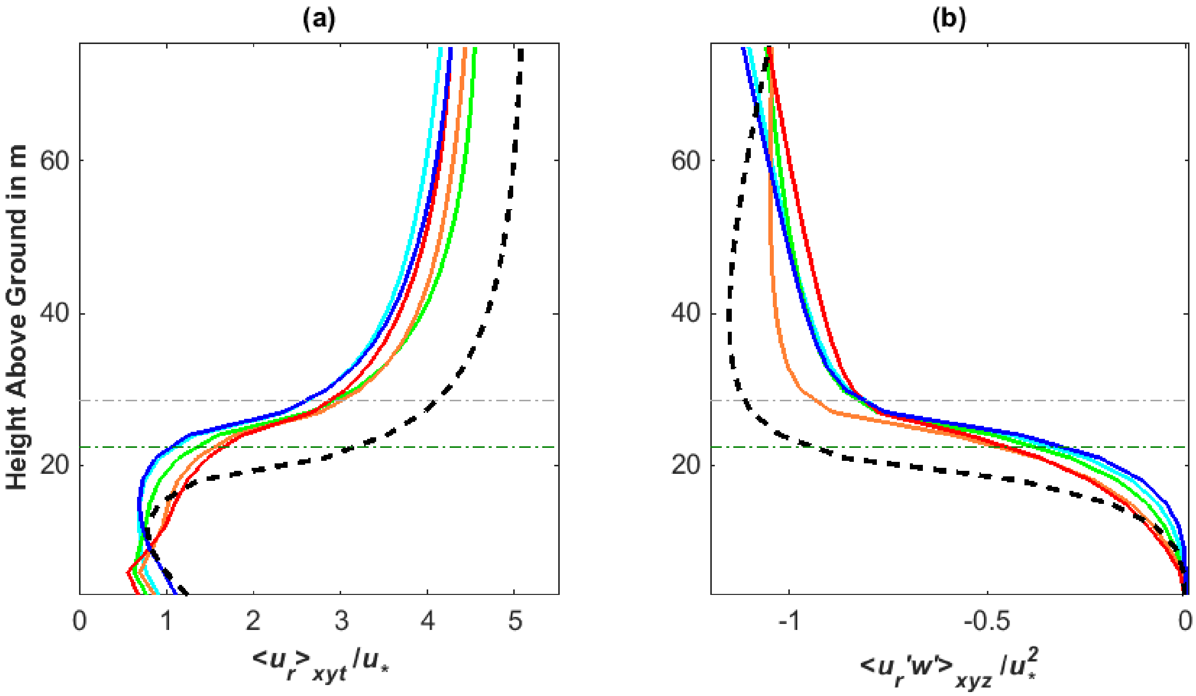

Figure 5. Vertical profiles of (a) Horizontal wind normalized by friction velocity, and (b) momentum flux normalized by the square of friction velocity in a 27 m tall canopy with gap fractions of 0% (blue), 10% (cyan), 25% (green), 35% (orange), and 50% (red); and in a continuous 21 m tall canopy (dashed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

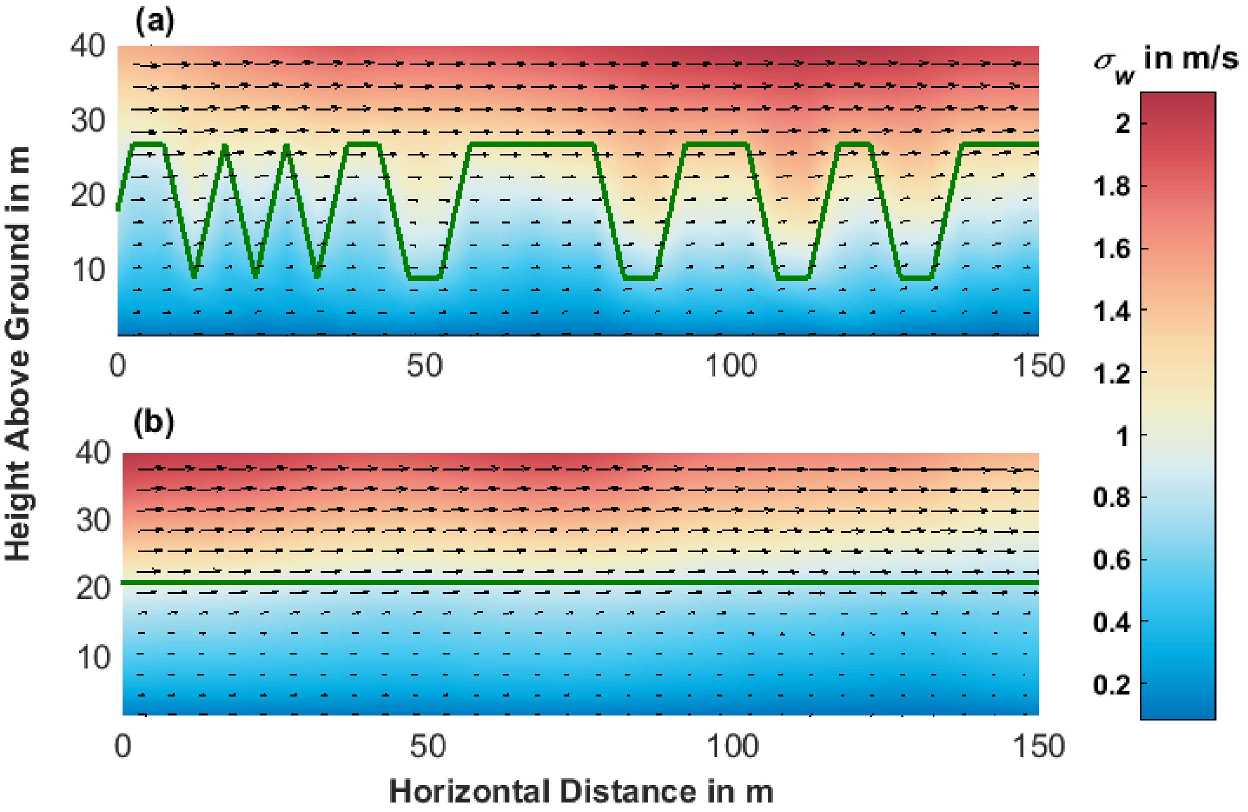

Figure 6. Vertical cross-section through the simulation results of (a) a 27 m tall canopy with 25% gap fraction and (b) homogeneous 21 m tall canopy. 30-minutes mean wind speed and direction are illustrated using black arrows, the standard deviation of vertical velocity (an indication of turbulence intensity)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

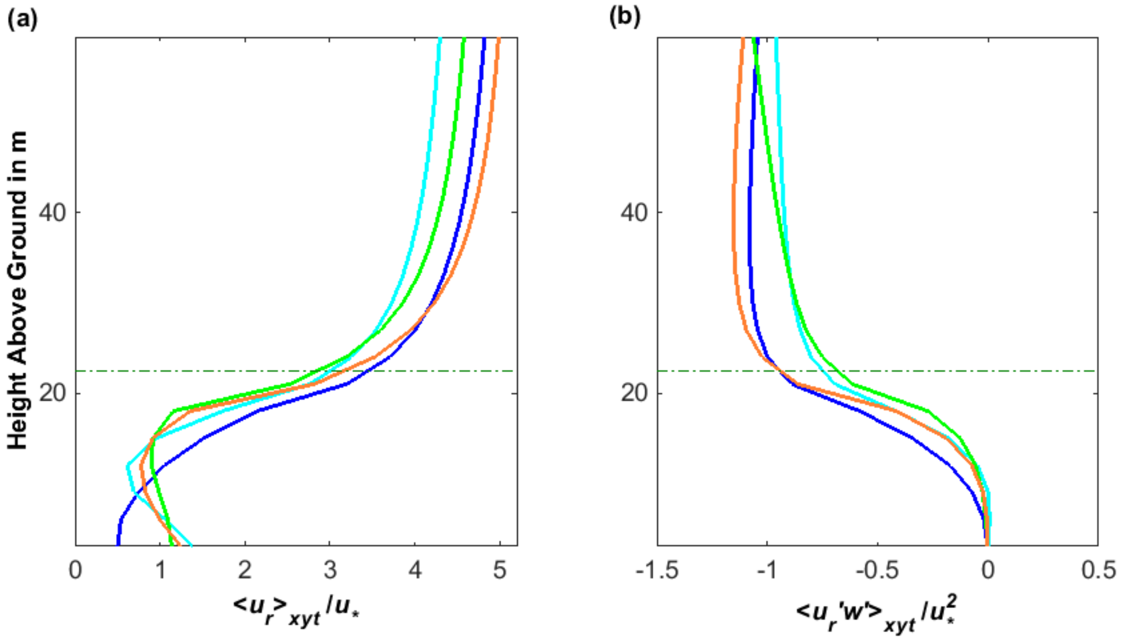

Figure 7. Vertical profiles of (a) Horizontal wind normalized by friction velocity, and (b) momentum flux normalized by the square of friction velocity for ‘Lower’ (blue), ‘Middle’ (cyan), ‘Upper’ (green), and ‘Natural’ (orange) LAD profiles. Canopy height shown as dashed horizontal green line.

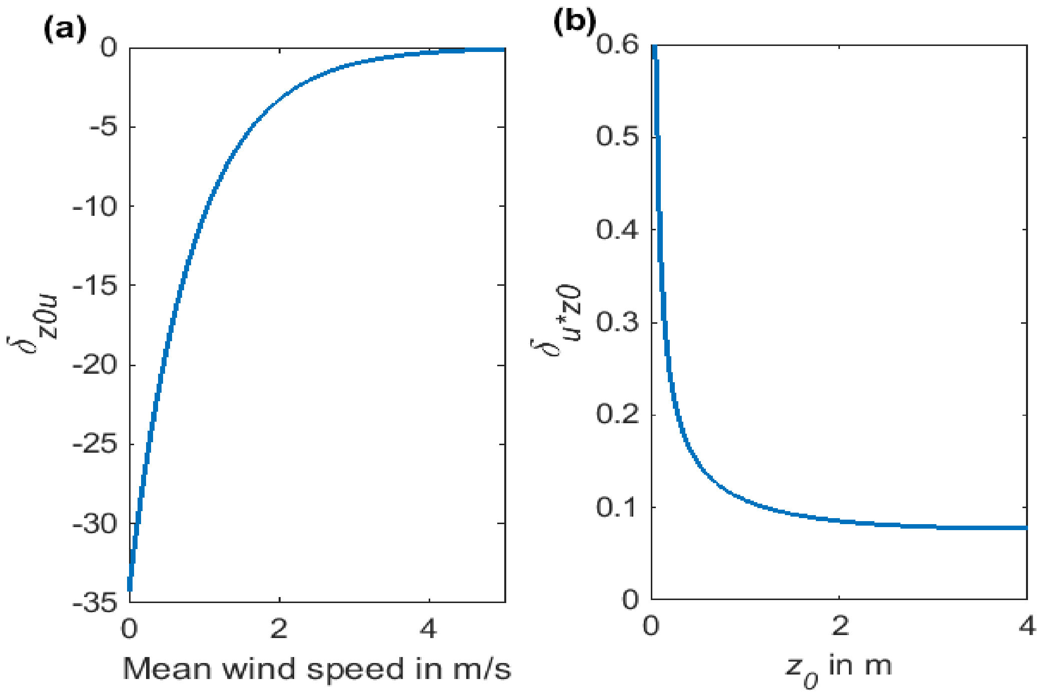

Figure 8. (a) Sensitivity analysis of z_0 as a function of variation of the mean wind speed (δ_{zou}). We illustrate it here is a particular range of parameters, choosing a canopy height h=22 m (roughly the height we used in the simulation and observation site), displacement height d=0.67h, observation 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 ($\delta_{u*z0} < 0.15$) for any z_0 above 0.5 m.