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DIAGNOSING WIND VARIATION IN PERIODIC FOREST CLEARCUTS, IN RELATION TO TREE SWAY

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1. INTRODUCTION

Forest management trials in the bòreal mixedwoods near Manning (Northern Alberta), lead by Forestry Canada, are evaluating felling practises that, at the time of hardwood (Aspen) harvest, preserve the Spruce understory for later harvest . A concern is windthrow of the previously- sheltered remnant spruce, and the experimental and theoretical work reported here (and in the companion paper) is intended to interpret the observed *spatial variation* of tree windthrow, across a cutblock.

The mode of windthrow in the trial blocks at Manning is root upheaval. An assumption of our work is that the key factor in the *spatial variation* of treefall susceptibility (over the short term, at this site) is the wind forcing,- rather than any systematic variation in soil conditions, rooting depth, tree health, etc. Concentrating then on wind forcing and resultant sway, our approach to interpreting spatial variation of windthrow is to firstly calculate the spatial distribution of wind & gust statistics across cutblocks, by solving the momentum equations, then calculate "remnant" tree response to the wind statistics.

The link between tree sway statistics and wind statistics is discussed in a companion paper (Flesch & Wilson): briefly, treating the tree as a 2nd order vibrating system, we relate the variance σ_θ^2 of tree angular displacement (θ) to the power spectrum $S_{u|u|}$ of the instantaneous wind force $u|u|$ (notation w.r.t mean and fluctuating variables: instantaneous alongwind component $u=U+u'$), where $S_{u|u|}$ is observed not "**at**" the "subject" remnant tree, but merely, at the same *alongwind* location relative to the upwind edge of the cutblock.

The critical feature of the wind-force spectrum turns out to be the variance, which we can estimate from our calculated field of wind statistics:

$$\sigma^2_{u|u|} \approx \sigma^2_{uu} \equiv \sigma^4_u \left(Kt_u - 1 + 4\left(\frac{U}{\sigma_u}\right)^2 + 4\left(\frac{U}{\sigma_u}\right) Sk_u \right) \qquad (1)$$

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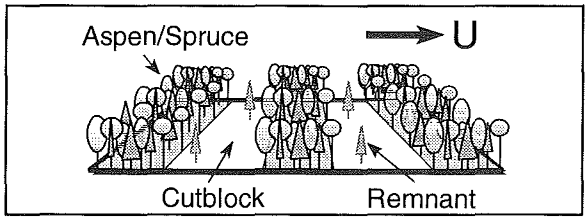

Within our framework then, the wind statistics governing tree sway are: mean U, variance σ_u^2, skewness Sk_u, and kurtosis Kt_u.

2. EXPERIMENTAL GUIDANCE

We instrumented towers across one of a sequence of cutblocks at Manning (widths of the cutblocks and intervening forest blocks $X_F=X_C=6h_c$, where h_c=25m is mean tree height), with cup and/or propellor anemometers (at height z=10m, ie. z/h_c=0.4). Tree sway sensors were placed on two remnant spruce within the cutblock. Time series of vector wind and tree sway were recorded, during periods of autumn (no-leaf) winds: an unattended data-logger, upon ascertaining that over the *previous* 15 min interval mean windspeed exceeded a specified threshold and that mean wind direction lay within 30° from the normal to the cutblock edges, proceeded to store signals (at sampling frequency 5 Hz) for the subsequent 15 min interval (storage capacity limitėd the number of such series we could obtain). Unfortunately few *consecutive* intervals satisfying the direction criterion occurred, so that we have had no choice but to estimate the higher-order statistics (Sk_u, Kt_u) from inadequately-long records.

3. WINDFLOW MODEL

We are experimenting with solutions of simplified U, W -momentum equations, that represent only what are (according to experience) the dominant terms (advection by the mean flow; pressure gradient; drag on trees; and divergence of the vertical turbulent momentum flux): in dimensionless form,

$$\frac{\partial}{\partial x}\left(U^2 - K_a\frac{\partial U}{\partial x}\right) + \frac{\partial}{\partial z}\left(UW - K\frac{\partial U}{\partial z}\right) = -\frac{\partial P}{\partial x} - c_d\, A\, h_c\, U\,|U|$$

$$\frac{\partial}{\partial x}\left(UW - K_a\frac{\partial W}{\partial x}\right) + \frac{\partial}{\partial z}\left(W^2 - K_a\frac{\partial W}{\partial z}\right) = -\frac{\partial P}{\partial z}$$

The alongwind (U) momentum equation includes a momentum sink $c_d.A.h_c\ U|U|$ representing the drag on trees,- c_d being the bulk drag coefficient of trees, and A being the area density ($m^2.m^{-3}$) of tree parts (variable through cutblocks and forest blocks). K_a is a small artificial diffusivity, included to ensure numerical stability, while K is the "true" eddy viscosity, which we estimate as

$$K = \lambda(x,z)\sqrt{c_e\ k(x,z)}$$

where λ(x,z) is an adaptive lengthscale, and k(x,z) is the TKE determined from the approximate TKE budget:

$$\frac{\partial}{\partial x}\left(U\,k - K_a\frac{\partial k}{\partial x}\right) + \frac{\partial}{\partial z}\left(W\,k - \mu\,K\frac{\partial k}{\partial z}\right) = \tau\frac{\partial U}{\partial z} - \epsilon$$

Details of the specification of the (crucial) lengthscale λ, and definitions of constants (such as μ, c_e above), are given in Wilson et al. (1995), where this closure was applied to the case of a uniform canopy on a ridge. The only deviance here is that, within cutblocks the lengthscale (here λ_C) is "relaxed" from the forest specification (there λ_F) toward the open flat plain limit, $k_v\ (z/h_c)$, where k_v is von Karman's constant; ie.

$$\lambda_C(x,z) = G\lambda_F(x_0,z) + (1-G)\,k_v z\ ,\ G = \exp\left(-\gamma\frac{x-x_0}{h_c}\right)$$

where x_0 denotes the leeward edge of the forest block lying upwind of the clearing in question.

3.1 Specifying adjustable constants

No change was made to the three "uniform canopy case" closure constants (c=α=1, μ=0.2), elsewhere optimised (Wilson et al., 1995) by matching equilibrium solutions of these equations to wind tunnel observations in and above a uniform model canopy. It remained in our present application of the closure to specify: the lengthscale adjustment parameter γ, the canopy area density A(z), and the drag coefficient c_d. We treated γ and the bulk parameter $C=c_d A\ h_c$ as free to be optimised. As will be shown, C=γ=½ gives good agreement of the model with observations. Varying C, we concluded that for this cutblock (when leafless), 0.1 << C < 1.

3.2 Boundary Conditions

The instrumented cutblock was the leeward member of an alongwind sequence of four such, upwind of which lay slight topographic variation and a wider block (12 h_c) of "control" forest. In modelling the flow we placed upstream from the model origin (x=0) a uniform forest, while downstream from x=0 were a sequence of five cutblocks, the last extending a distance $48h_c$ alongwind, and terminated by the outflow boundary, at $x=+96h_c$.

Inflow profiles (of U,k) at $x/h_c=-12$ were obtained as equilibrium (∂/∂x = 0) solutions of the equations. At the outflow boundary ($x/h_c=96$), ∂_x(U, k)=W=0. Along the top of the domain ($z/h_c=40$), W=0, and shear stress τ=1 (the disturbed canopy flow grows into a deep constant stress layer); and at both upper and lower boundaries, the vertical flux of TKE was specified to vanish.

3.3 Numerical Details

We used Patankar's (1980) Semi-Implicit Method for Pressure-Linked Equations to solve the momentum equations. Alongwind resolution was uniform at $0.2h_c$. Below h_c, vertical resolution was $0.22h_c$, while above, the grid was progressively stretched. Our constant stress layer up to $z=40h_c$ (=1 km) at the inflow is unrealistic, as might be our specification of non-disturbance at that height, even $96h_c$ (=2.4 km) downstream, by internal boundary-layers stemming from variations of drag at ground. Our solutions should therefore not be regarded as grid/domain-independent,- though we anticipate the deficiency is minor.

4. MODEL and OBSERVED WIND STATISTICS

The field experiment mismatches the model in that we do not have, upwind of the first cutblock, a region of uniform forest standing on flat terrain. Thus there is ambiguity in the choice of a scale with which to normalise the velocity statistics. We circumvented that minor difficulty by re-scaling model and observed wind statistics, so as to give unit value at the point $(x,z)=(5,0.4)h_c$.

Figure (1) compares the modelled pattern of mean wind variation U(x) across the cutblocks (at

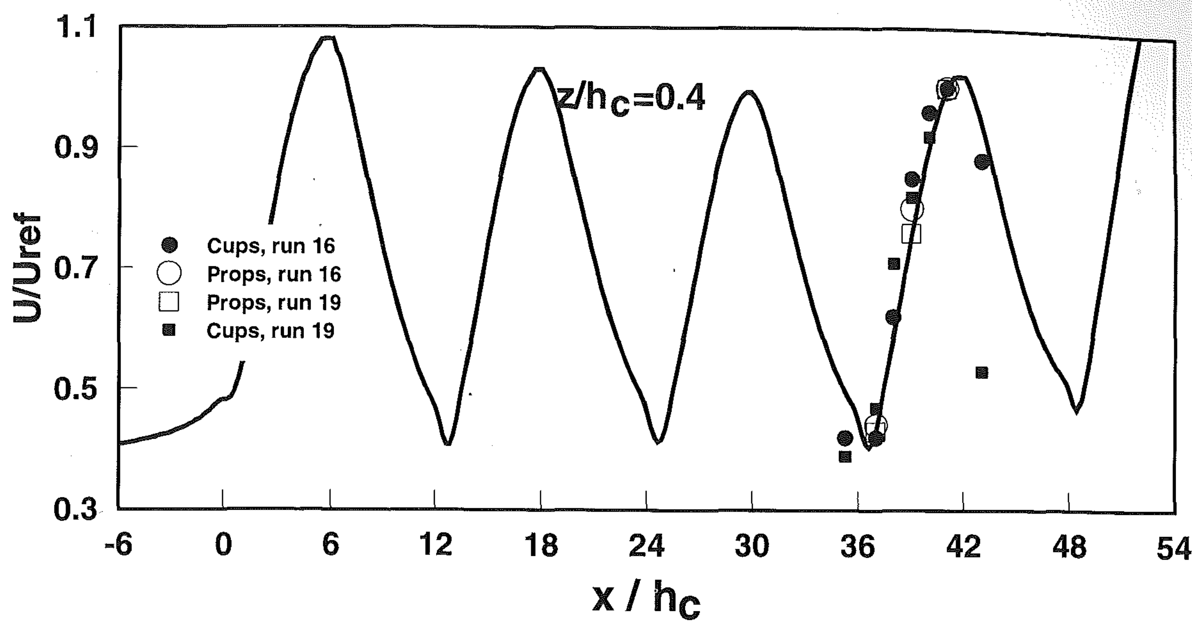

Figure 1. Mean windspeed across periodic cutblocks

z/h_c=0.4), with observations from two 15 min intervals. These two (of the six available autumn) runs are most suitable for comparison with our 2-d model flow, according to the criteria of constancy (along x) and normality (with respect to forest/cutblock edges) of the mean wind direction (β). Wind directions, determined by the 3-d propellor anemometers mounted at distances (1,3,5) h_c from the upstream edge of the cutblock, were:

Run 16:	β=	-20°	-12°	-10°
Run 19:	β=	+10°	+29°	+36°

Agreement in Fig (1) between the modelled and the observed modulation of the mean wind across the cutblock is striking. This is surprising (to us), for this was a *real* forest, visibly tending more to the inhomogeneous than the homogeneous as regards constancy (even within uncut blocks) of tree height, spacing, and species-mix; and furthermore standing on not entirely flat ground. Surely our simple flow model, whatever the deficiencies of its closure, has captured the dominant factor driving the spatial variation - presumably advection due to the gross x-wise variation in forest drag-force. Admittedly one could take the cynical view that only an insane model would fail to predict speedup in cutblocks; and so with a coefficient C available to vary the depth of the modulation curve, and another, γ, to adjust its shape, there is no achievement here.

Declining further comment as to whether there is "model skill," we note that (according to the model) there is little variation from one cutblock to the next in the amplitude of the wind-modulation; indeed, even extreme values differ only modestly from one cutblock to the next (consistent with findings of Raupach et al., 1987, for a clearing within a wind-tunnel model canopy). We conclude our instrumented cutblock ought to be "typical" of its neighbours, and that a periodic boundary-condition might be used in the modelling.

Figure (2) shows that the numerical simulation also matches quite adequately our (sparse) observations of the turbulent kinetic energy (measured by propellor anemometers[2] at 1,3,5 h_c from the upwind cutblock-edge). TKE increased sharply over the upwind half of the cutblock, and less quickly (if at all) over the downwind half.

We gained but a poor picture of the variation across the cutblock of higher-order statistics (Sk_u, Kt_u), owing to run-run variability[3] (probable causes: inadequate sampling duration and, run-run variablity

[2] Propellor anemometers will have underestimated the TKE, but that error is partially corrected by our focus on *relative* TKE.

[3] These run-run variations (in Sk_u, particularly) account for much of the run-run variation in $\sigma^2_{u|u|}$, and thus in tree sway variance!

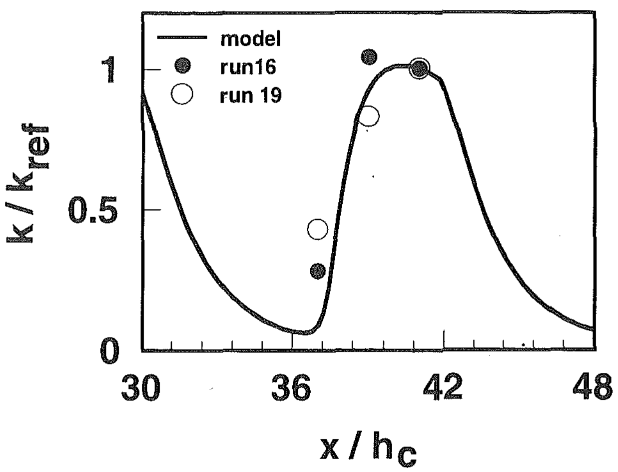

Figure 2. TKE across cutblock

in overall wind direction). We can only report that: (**a**) run-run scatter in Sk_u was greatest at the upwind tower ($1h_c$ leeward of the forest block), least at the downwind tower ($1h_c$ upstream from the transition back to forest); and (**b**), Sk_u decreased slightly with increasing downwind distance across the cutblock, a trend consistent in sign with that reported by Raupach et al.

Regarding *prediction* of $Sk_u(x,z)$, run-run variations cannot be explained within the scope of a 2-d flow model, even should we include the (suitably simplified) budget equation for Sk_u. Disregarding possible 3-dimensionality of the flow, we might hope to model the trend (with x) in population skewness (estimated inadequately from our too-short samples). To do so, rather than (at once) add the Sk_u-budget, we wondered whether Sk_u might be *diagnosed* from the mean wind profile. Qualitatively, Sk_u has to do with asymmetry of gusts relative to lulls. Then perhaps Sk_u might be related to *curvature* of the wind profile, but estimated *non-locally* (say, using the Laplacian operator, which compares U(z) with the average of "neighbouring" values from above and below). For example,

$$Sk_u(z) = 2\, U_\infty^{-1} \left(U_\infty + 0 - 2\, U(z) \right)$$

(U_∞ the free stream velocity) resembles the variation across a boundary-layer (not too close to the free stream, nor *within* the canopy). We are attempting on such lines to diagnose Sk_u within the canopy, and its alongstream variation in a disturbed flow. As yet we have nothing worthy of reporting, and are impeded in our progression (through Eqn 1) from modelled wind statistics to resultant tree sway.

It is unfortunate that we were unable to measure turbulence within the bracketing forest blocks. Raupach et al. reported an "enhanced gust zone," at the leading edge of the canopy block downwind of their clearing, wherein U and $\sigma_{u,v,w}$ were not markedly different from their values in the uniform canopy, but Sk_u was increased about threefold. This is the region where, according to Raupach et al., the forestry literature indicates windthrow is most likely to occur ("near, but not at, the upwind edge").

5. CONCLUSIONS

This may be the first attempt to combine high-resolution (order 1m) calculation of wind statistics, and tree dynamics, to infer statistics of tree sway. We do not claim the wind model as very novel; this is a simple closure. It is our attitude that, if a flow can be well-simulated within the compass of a closure that entails few empirical coefficients, and especially if those coefficients prove able to be left constant across somewhat differing experimental flows, then, there is no point in going to the complexity (and more numerous coefficients) of a higher-order scheme. Thus we *calibrate* a flow model against observations; and, in faith that the model is inherently "true," we expect it should remain useful over *modest* variations of the experimental situation (eg. wider/narrower cutblocks). If so, we have a means to interpret or anticipate, the patterns of windthrow.

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