3.7 TWO AND THREE DIMENSIONAL NUMERICAL AIRFLOW MODELLING ALONG FOREST EDGES

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1. INTRODUCTION

Cut block logging, in which a large area is completely logged, is a common harvesting method in British Columbia and most other provinces in Canada. Due to the displeasing aesthetic nature of clear cuts, there has been pressure for companies to attempt different methods of harvesting, from selective to strip and even trying smaller sizes of clear cuts. While all of these methods have their own distinct ecological values, they may promote either the structural or rooting failure of trees. Selective cutting removes structural support that is gained from neighbouring trees while both strip cuts and small cut blocks increase the edge to area ratio, thus potentially allowing a larger area of non wind firm trees to be exposed to wind.

Most of the numerical modelling that has been performed to date on forests, especially those investigating forest-clearing boundaries, have been performed using “in house code”. This study used a commercially available computation fluid dynamics (CFD) program to investigate flow above and through a forested environment. The CFD program utilised was FLUENT (Fluent Inc., Lebanon, New Hampshire).

Several other studies have used numerical methods to predict wind speed and turbulence in forested environments. Li et al. (1990) used numerical methods to investigate flow from a clearing into a forest. Miller et al. (1991) compared data from field locations upwind, inside and downwind of a small clearing. Green (1992) used a commercially available CFD package (Phoenics) to model a small stand of trees in a large domain. Liu et al. (1996) utilised a $\kappa-\epsilon$ turbulence model to predict airflow and turbulence at a forest – clearing boundary. In addition, there have been field and wind tunnel studies done, most recently Novak et al. (2001), Chen et al. (1995), Gash (1986), and Raynor (1971), which examined windthrow related to forest edge boundaries. Meroney (1968) chose a wind tunnel because of the expenses involved with setting up and gathering field data. Miller et al. (1991) were only able to validate their output from four points at three sites. Although wind tunnel studies can be less costly than field measurements, there are a limited number of industrial and academic institutions that have access to wind tunnels for such modelling.

High performance computing is becoming increasingly available at many institutions as their benefits expand and encompass many disciplines. Similarly, CFD software has many uses in a variety of fields. With these types of advances, the role of wind tunnels, which have very specialised applications, similar costs and are not as easily accessible can now be shared with CFD.

At the University of British Columbia (UBC), the biometeorology/soil physics group in the Faculty of Agricultural Sciences have been using the UBC Department of Mechanical Engineering wind tunnel to conduct airflow related research on forest clearings since 1992 (Chen et al. 1995, Novak et al. 2001). The objectives of this paper is to see whether CFD modelling has skill in replicating wind tunnel measurements of wind flow in forested areas with clearings.

2. METHODS

Measurements collected from wind tunnel experiments were compared against the output from FLUENT using different turbulence models. The geometries used in FLUENT are produced using an integrated program called Gambit that allows the user to build the necessary numerical geometries and generate meshes for use in FLUENT. FLUENT uses a finite volume approach to solve the equations of fluid dynamics, which are applied to the specified domain of the geometry being investigated.

2.1 *Wind Tunnel*

The wind tunnel that was used for Novak et al. (2001), is a open-return blow-through wind tunnel operated by the UBC Department of Mechanical Engineering, and is 25 m long, 2.4 m wide and 1.5 m high. Counihan spires (Counihan 1969) were used to generate large-scale turbulence. Bluff bodies were placed 0.5 m and 1.0 m down stream of the spires to produce intermediate turbulence. Large roughness elements were used to generate smaller-scale turbulence and were arranged in a diamond pattern with a density of approximately 21 m^{-2}. Six metres downwind from the spires, small roughness elements followed for 1.2 m with a density of 120 m^{-2}; these were used to help reduced the total length of the forested section. A detailed account of the setup is given by Chen et al. (1995).

The model forest constructed for the wind tunnel was based upon the Engelmann spruce at the Sicamous Creek research forest in southern British Columbia. The model trees were scaled down 200 times representing 30 m trees in a stand with 500 stem ha^{-1}. Each model tree was made from an artificial Christmas tree branch (Barcana, Granby, Quebec) with a length equal to 0.15 m. Each model tree consisted of a pair of twisted steel wires (0.0009 m) with flexible plastic strips 0.03 m in length and 0.001 m wide, angled at 40°, acting as the foliage (Chen et al. 1995). The bottom 0.015 m of the tree had the foliage removed and the top 0.045 m was trimmed to a point. The resulting model tree had a leaf area index of 6.3. The size of the clearing in the wind tunnel was 1.63 m by 1.63 m.

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2.2 *Numerical Wind Tunnel*

Both two and three dimensional wind tunnels were authored for use in numerical simulations. Gambit a CFD preprocessor was used to build the wind tunnel and generate the grid-cells/meshes. A flow domain very similar to the UBC set-up wind tunnel was reproduced using Gambit (Figure 1).

The two dimensional (2D) domain was a total of 12.59 m in length and 1.5 m in height. Buff bodies were authored with the same dimensions (two dimension equivalent) as the wind tunnel. In the two dimensional domain the large and small roughness elements had twice the spacing of the wind tunnel. The roughness elements in the wind tunnel were positioned in a diamond pattern, so the two dimensional domain represents the wind tunnel along a plane at the centre of the wind tunnel. Trees were designed to have a similar shape to those in the wind tunnel (Figure 1). Tree density in the wind tunnel was attempted to be reproduced in the two dimensional domain by arranging trees so that they were spaced at the same distance apart as the rows were in the wind tunnel. This setup allowed 53 trees to be authored after the small roughness elements, followed by a 1.63 m clearing and another 22 trees for a total of 75 trees. Initial simulations did not have the additional clearing (0.60 m) after the second stand of trees, but was added to improve solution convergence, after reverse flows developed at the outflow. Due to the two dimensional layout of the domain, Counihan spires were not able to be located within the numerical wind tunnel.

The three dimensional numerical wind tunnel was set up with parameters more similar to those in the wind tunnel. The width of the three dimensional domain was authored to a width of 0.09 m. This allowed for three complete trees and two half trees (those along the domain boundary) to be authored every two rows. The first row included a complete tree that was between two half trees and the second row had two complete trees, repeating this configuration produce a diamond shaped pattern. Due to the limited width of the domain, the Counihan spires were not able to be authored. The sides of the domain were identified as symmetrical boundary conditions, which acts much like a mirror to predict flow out and into the domain but keeping a zero flux across the boundary. The densities of the large and small roughness elements were achieved in diamond shaped staggered patterns. This was also true for the layout of the trees. The dimensions of the tree used in the three dimensional simulations was also 0.15 m in height. The diameter of the model trees authored were 0.04 m as they needed to fit into diamond shapped pattern, with a density of 500 stems ha^{-1}. The lower 0.015 m, represented the stem/trunk of the tree and was 0.001 m in diameter. The angled lower foliage, was 0.02 m in vertical height with an angle of 45°. This was increases from 40° due to the necessity to keep the diameter of the trees at 0.04 m to satisfy the density requirements. The main section was 0.07 m followed by the crown which was the top 0.045 m of the tree that was trimmed to a conical shape.

The mesh generated throughout the domain

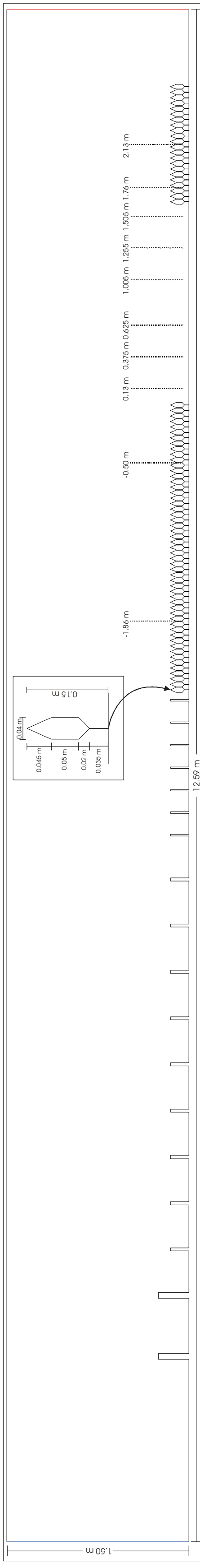

Figure 1: Geometry authored for CFD simulations was closely based upon the wind tunnel at UBC, from which measured data were compared to simulated output. In order to simulate a fully developed turbulent flow of a real wind tunnel, bluff bodies and two sizes of roughness elements were produced to help recreate the setup of the UBC wind tunnel. Simulated output at the ten locations indicated, were compared to the 29 points along each location in the wind tunnel. Locations shown include distance from forest – clearing edge.

for both the two and three dimensional simulations were non-conformal. An irregular triangular scheme was utilised in face meshing, while volume meshing was accomplished using a four-node tetrahedral approach. The largest distance between nodes was set at 1/10 tree height (0.015 m) within the canopy, growing to 0.3 m at the ceiling.

The porous jump boundary condition was used to impose a porous canopy on the model. The porosity of the canopy was designated as 0.18 based upon a leaf area density that was initially set at 25 m^2 m^{-3}, using an index developed by Gross (1993). Novak et al. (2001) had determined for their model trees in the wind tunnel that the the drag coefficient (C_d) = 1.

2.3 *Simulation*

Fluid was numerically simulated using the Navier-Stokes equations. Turbulence models were used to determine effects of turbulence on the flow. The two dimensional simulations utilised Reynolds Averaged Navier-Stokes (RANS) turbulence models: standard (std) $\kappa-\epsilon$, realizable (Real) $\kappa-\epsilon$, and Renormalized Group (RNG) $\kappa-\epsilon$. The three dimensional simulations used both RANS and Large Eddy Simulation methods.

All simulations were performed on a SGI Origin 3400 compute server at the University of Northern British Columbia. The inlet velocity of the simulation was 8.7 m s^{-1}, to match the wind tunnel velocity. Each of the models were run to produce 1.51 seconds of simulated flow (unsteady simulation). To produce this, flow in the domain was simulated at a rate of 10 000 Hz. These calculations took approximately two hours on eight processors for the two dimensional simulations and approximately 48 hours on eight processors for three dimensional simulations.

3. RESULTS

Streamwise velocity output were extracted from all two dimensional turbulence models and compared to UBC wind tunnel data. Ten locations (Figure 1) were selected from the wind tunnel, two up and downwind of the clearing and six within the clearing; each location had 29 vertical points ranging from 0.03 m to 0.59 m. These data were compared to the output calculated at the same points from all models. Four points in the wind tunnel were not sampled, so the total number of points available for statistical analysis was 286. Three dimensional model output and analysis was still in the preliminary stages at manuscript submission time.

Root-mean-square error (RMSE) and Willmott d were performed from the 286 points of both wind tunnel data and model output. Willmott d (Willmott 1981, 1982) is a statistic used as an index of agreement for model performance, with 1 being perfect, indicating a total agreement. All of the turbulence models agreed reasonably well with the wind tunnel, for horizontal velocity. Of the three turbulence models, the standard $\kappa-\epsilon$ agreed best (Table 1).

Table 1: Quantitative measures of model performance (std - standard $\kappa-\epsilon$, Real - realizable $\kappa-\epsilon$, and RNG - Renormalized Group $\kappa-\epsilon$) for horizontal wind speed from the two dimensional domain. Measures include mean and standard deviations of observed ($\overline{O}$, s_o) and predicted ($\overline{P}$, s_p) values, slope and y-intercept (a and b respectively), mean absolute error (MAE), root-mean-square error (RMSE) including systematic ($RMSE_s$) and unsystematic ($RMSE_u$), and the Willmott d statistic (d).

$\kappa-\epsilon$	$\overline{O}$	$\overline{P}$	s_o	s_p	N	a	b	MAE	$RMSE$	$RMSE_s$	$RMSE_u$	d
std	5.17	5.23	2.12	2.91	286	-1.70	1.37	0.829	0.984	1.92	1.00	0.961
Real	5.17	5.35	2.12	2.98	286	-1.75	1.34	0.882	1.04	2.12	1.14	0.958
RNG	5.17	5.71	2.12	3.20	286	-1.99	1.49	1.14	1.31	3.03	1.76	0.939

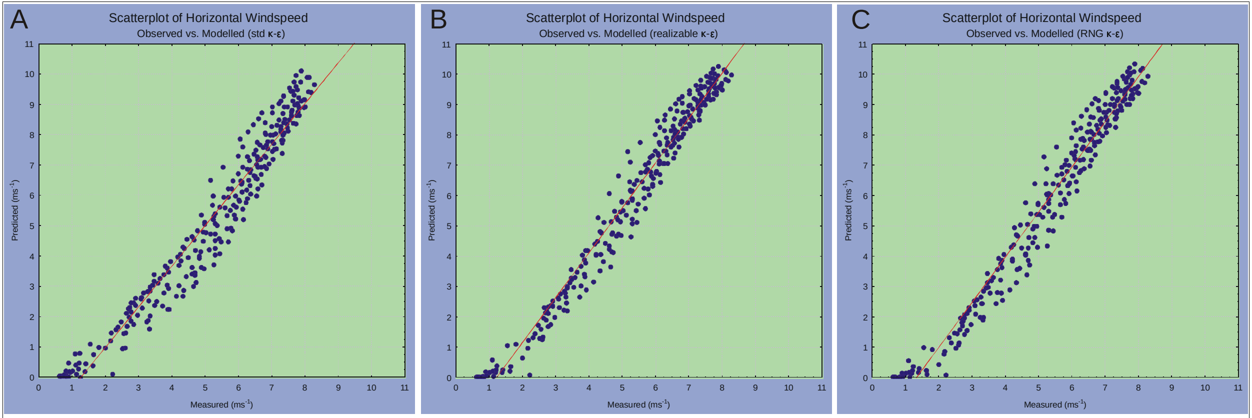

Figure 2: Scatterplots (A, B and C) for turbulence models, from the two dimensional domain, show that the realizable $\kappa-\epsilon$ and RNG $\kappa-\epsilon$ indicate a slightly tighter clustering of the results.

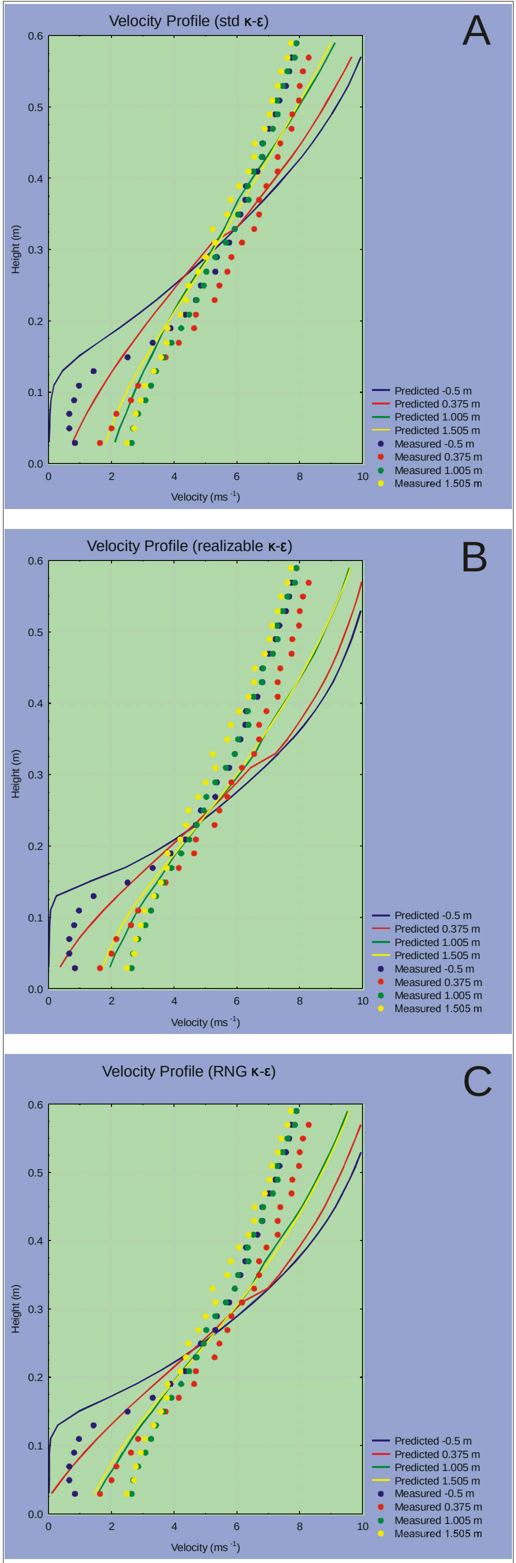

Figure 3: Vertical velocity profiles at indicated locations (from forest – clearing edge) for each model (2D domain) show the general trend of the horizontal wind speed. Graphs A, B and C show the under-prediction of wind close to the ground and over-prediction towards the top.

Scatterplots of the observed wind tunnel values and simulated output show wind speed was over predicted for all turbulence models used (Figure 2).

Vertical velocity profiles of select vertical locations, showed that the models were likely to under predict values close to the ground and over predict those in the middle of the domain (Figure 3).

4. DISCUSSION

General velocity trends are well represented in all simulations quantitatively. The models all over-predict the higher speeds and under-predict the lower speeds. Wind speed at stem level, within canopies, would be lower in the two dimensional domain as stems were designated as solid and the air was not able to flow around the stem as in the three dimensional domain and wind tunnel. Improved results may also be achieved by refining grid cells along the ground to resolve the under-prediction of airflow.

Although porosity was set higher than Lui et al. (1996), allowing more flow through the canopy, a reduced velocity was predicted within the canopy. The two sampling locations downwind of the clearing do show that lower wind speeds were simulated compared to the wind tunnel but they also indicate that the porous canopy does have an effect on the airflow as there is a 68 % drop in horizontal wind speed at the second location (h = 0.09 m). Isolating and a more detailed analysis of the two sampling locations in the stand downwind of the clearing may help improve canopy porosity characteristics.

Only two dimensional simulations were analysed for this extended abstract. Preliminary analysis of the three dimensional simulations, which do not have porous tree canopies, do show better agreement to wind tunnel measurements than the two dimensional simulations.

5. CONCLUSION

Computational fluid dynamics have been extensively used to study environmental problems at the landscape level. While those studies have been successful predicting airflow around buildings, our study shows that FLUENT has skill in replicating the airflow in a wind tunnel model of a forest-clearing. To our knowledge no other study has attempted to reproduce a forest-clearing on such a large scale with as much detail using numerical methods. Forthcoming work will focus on three dimensional models with Large Eddy Simulation turbulence treatments and improved porous canopy treatments.

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