International Conference 'Wind Effects on Trees'
September 16-18, 2003, University of Karlsruhe, Germany

THE VENFOR PROJECT: THE ROLE OF FOREST EDGES IN THE PATTERNS OF TURBULENCE DEVELOPMENT – FINDINGS FROM A FIELD EXPERIMENT, WIND TUNNEL EXPERIMENT AND A LARGE EDDY SIMULATION MODEL EXPERIMENT

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Abstract

Wind damage often affects trees a few tree heights back from the edge. A series of airflow forest edge experiments, field and wind tunnel, and model simulation show a delay in the development of shear stress and streamwise variance downwind of the roughness change. Potentially tree damaging gusts only occur in the zone where the shear stress has been established. A good correspondence in turbulence development between all of the experiments is reported.

Introduction

Wind damage to forests rarely affects trees at the edge of the stand. Therefore, if we can understand how the flow regime at forest transitions creates this seemingly counter-intuitive damage pattern, we may be able to improve the stability of forest stands.

Few previous experiments have examined in detail the transition of airflow and turbulence development across a forest or other roughness change. Bradley 1968 investigated shear-stress adjustment and wind profiles across roughness transitions; Raynor 1971 measured mean wind speeds within and above a forest across a forest edge transition; Antonia and Luxton 1971 examined a smooth to rough change in a wind tunnel but across a very large change in roughness. More recent field, wind tunnel and modelling experiments have been undertaken across a variety of roughness transitions. Mulhearn 1978, Pendergrass and Ayra 1984 and Theurer et al 1992 worked on wind tunnel experiments measuring turbulence across roughness changes. More recently Flesch and Wilson 1999 reportd measurements in forest block cuts but they had limited measurements into the forest after the clearing. A series of shelterbelt experiments have taken place that may have some similarities in flow adjustment with block roughness transitions and these include Judd et al 1996 who undertook a comprehensive wind tunnel study and Patton et al 1998 who made investigations using a large eddy simulation.

This paper will review a series of recent experiments and modelling studies undertaken by the authors commenting on the strengths and limitations of each study. The experiments are a field study described by Irvine et al 1997, wind tunnel experiment using laser doppler anemometry (LDA) undertaken by Marshall et al 2002 and further analysis of both datasets were completed by Morse et al 2002, and Large Eddy Simulation (LES) of a forest Yang

2003. Most recently the experimental procedures of the LDA wind tunnel experiment have been repeated measuring the velocity field using a particle image velocimetry (PIV) system. Finally the results of a selection of velocity statistics for the above experiments will be presented.

Experiments and Modelling

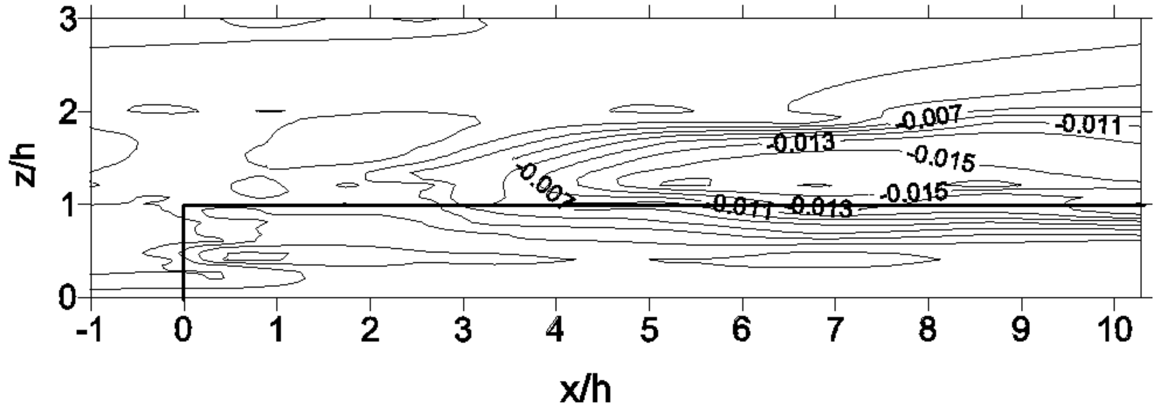
For any set of forest wind flow experiments and simulations, full field scale studies are the most important as they most closely describe the actual conditions in commercial and natural forests. Field experiments are always expensive to run, with finite equipment resources and therefore the experimental layout and equipment deployment is always a series of compromises. Our field experiment ran with four towers positioned across a forest edge at x/h=-6, x/h=0, x/h=3.5 and x/h=14.5, where h is the tree height. 3D anemometers were placed at three heights z/h=0.5, z/h=1 and z/h=2. Field experiments also depend on the ideal weather, particularly having a wind direction almost perpendicular to the forest edge. Most of these problems are overcome in a wind tunnel where you can have almost complete control over the experimental conditions and multiple model runs are relatively inexpensive. We describe here a wind tunnel experiment with LDA measurements which were made at one position and was then moved to other positions. In total there were 20 measurement points in the vertical at 11 horizontal locations across a forest edge of mechanically realistic trees, over an area equivalent to a little over 10 x 10 tree heights and a height equivalent to 6h. The single LDA approach does not allow the measurement of events simultaneously across the edge at a number of locations, so one cannot easily observe the evolution of gust events in an adjusting turbulent flow. The PIV wind tunnel experiment has recently been completed; it yielded the flow field within a limited window (approximately 200mm x 200mm, approximately1 x 1 tree heights, with 23 x 23 measurement points).

An LES can explicitly resolve the main energy containing eddies but all other scales including canopy processes have to be parameterised. The tree canopy was represented as a drag term in the model which has an x direction of 40h with half the distance made up of ‘trees’ and half of a ‘moorland’ drag surface. The LES model has an equivalent ‘height’ of 6h. The LES experiment is more like a forest block cut experiment due to the model’s periodic boundary conditions but this is only noticeable well above z/h=2. The LES is computationally expensive but allows the calculation of terms that are normally only available indirectly through experimentation by accounting for residuals in prognostic equations that represent turbulent flow. The PIV wind tunnel experiment has recently been completed; it allows the flow within a limited window (approximately 200mm x 200mm, in this experiment about 1 x 1 tree height, with 23 x 23 measurement points) to be investigated.

Results and Discussion

Figure 1 shows a contoured normalised stress plot from the wind tunnel. It is clear that the stress levels immediately downwind of the forest edge are very low. The shear stress only starts to develop after three to four tree heights downwind of the edge, eventually reaching a maximum between seven and eight tree heights distance downwind of the forest edge. The normalisation is made with a reference velocity within the wind tunnel, which is well above the forest. Similar patterns are seen in the development of both the streamwise and vertical velocity variance but with the vertical variance developing later than the streamwise variance, and further downwind of the edge. Morse et al 2002 examined this downwind shift and suggested that the delay in the vertical variance development is due to the dominance of the pressure redistribution term (of the prognostic equation for vertical velocity variance) over the shear production term; this pressure term is driven by some components in the prognostic equation for the streamwise variance. Thus, the stress development is shifted downwind until the turbulence starts to return to isotropy, the anisotropy being created by the air flowing over the forest edge itself. This idea was explored and confirmed through the LES studies and discussed by Morse et al 2001 and Yang 2002, 2003. This implies that trees damage associated with turbulent coherent gusts may occur only in the zone downwind of the forest edge where the stress has been re-established see Marshall et al 2002.

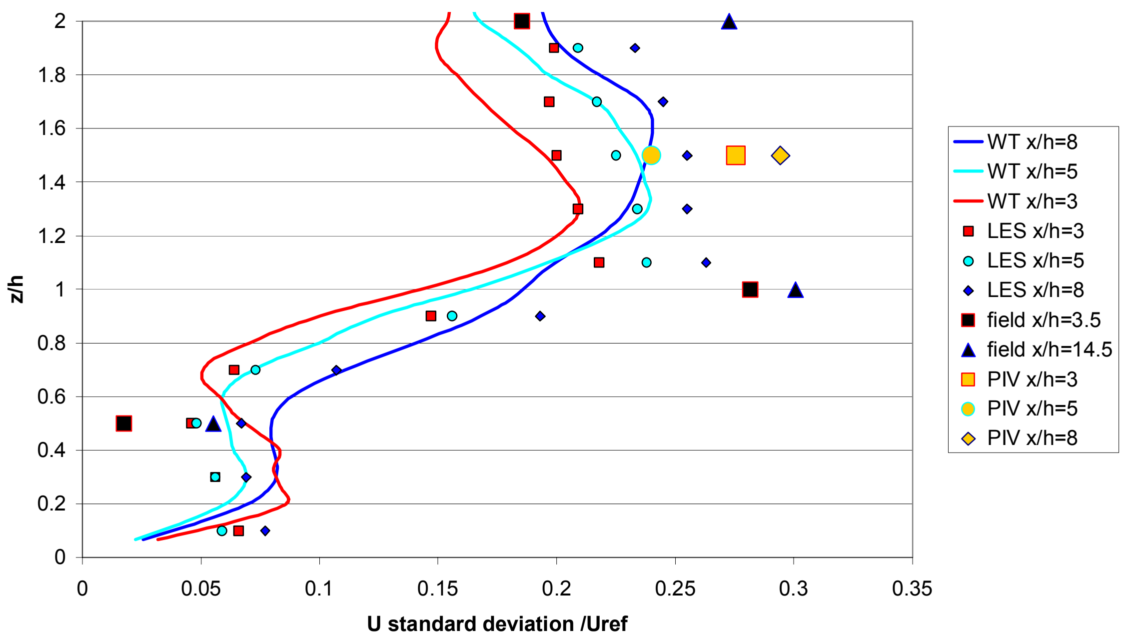
Fig. 1: Contour plot of kinematic shear stress normalised to reference velocity from the LDA wind tunnel experiment



To use the wind tunnel experiments and LES studies for stand management advice, we need to show that they have a good correspondence with field scale turbulence development features.

Figures 2 and 3 show data from all of the experiments as normalised vertical profiles at positions x/h=3, x/h=5 and x/h=8 downwind of the forest edge plotted in the vertical between z/h=0 and z/h=2. Figure 2 shows the normalised streamwise standard deviation profiles and figure 3 the normalised kinematic shear stress profiles. Normalisation for the LDA and PIV experiments are made as in Figure 1 and for the field and LES studies a reference velocity at x/h=–6.1 (upwind of the forest edge) was used.

Fig. 2: Normalised streamwise standard deviation profiles from all experiments



All experiments show an increase in the streamwise standard deviation downwind of the edge (see Figure 2). The data points from all of the experiments lie within a small range, for a given normalised height, within the canopy, with values from the field experiment a little lower than the laboratory experiments. Above the canopy the scatter is greater with the values being greatest from the field and PIV experiments. The field experiment at x/h=14.5 shows that the layer between z/h=1 and z/h=2 has a small change with height, indicating that the adjustment of streamwise variance is almost complete, when compared with the field data from x/h=3.5. This is not seen to the same extent in the wind tunnel LDA data or LES study. However, the general pattern of development is very similar between the experiments.

Fig. 3: Normalised kinematic shear stress profiles from all experiments

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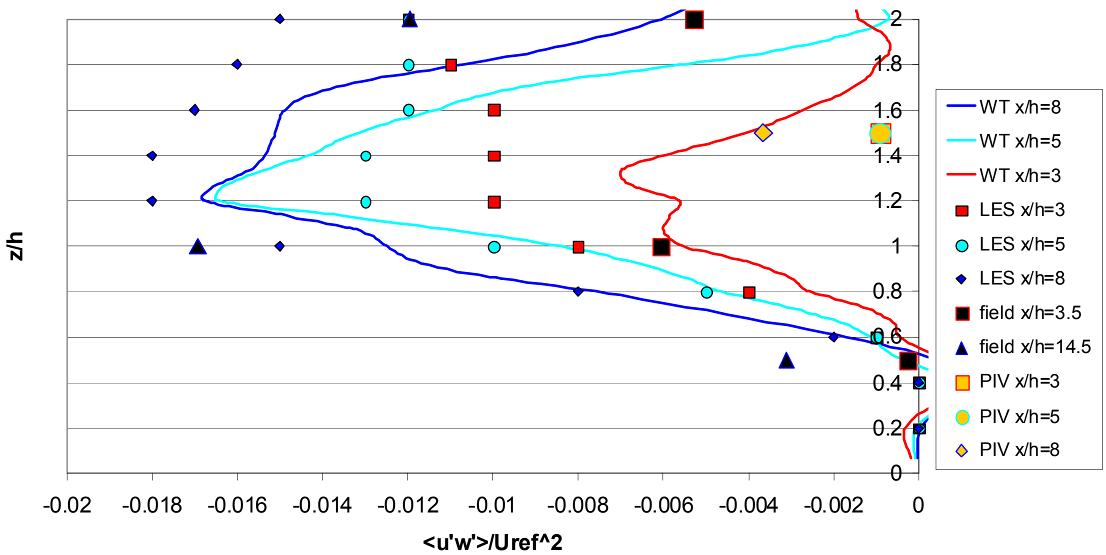

Increasing levels of shear stress downwind from the edge can be seen (Figure 3) and the vertical profiles from all of the experiments relate closely to the contour plot in Figure 1 from the LDA wind tunnel experiments. Unlike the streamwise variance there is no evidence that the adjusted layer extends over any more than a small proportion of the total z/h=1 to z/h=2 layer depth. Normalised values between experiments are similar but are more scattered than those for the streamwise variance. The main differences are the low values seen from the PIV wind tunnel experiment. Other PIV data for a continuous forest model in a wind tunnel, show normalised stress values only reached about -0.007 which is a similar value to those in Figure 3 just downwind of x/h=3 in the other experiments. Work is continuing to understand why these PIV data are so low given that the PIV produces comparable values with the other experiments for the mean flow (not shown) and standard deviation in both the streamwise velocity variance and vertical velocity variance (not shown).

Overall we can see that the comparison between the experiments is good and that the results are to a large extent interchangeable. The wind tunnel and LES both have ‘lids’ and are not coupled to a full atmospheric boundary layer but this does not seem to lead to difference in the flow development. All of the data in the experiments are run as neutrally stable, however, from limited field data, Morse et al 2002, we know that in stable conditions, at night, the pattern of development is completely different. The wind tunnel used in this experiment is neutral only and currently the LES is unable to simulate stable conditions. If we are only interested in wind damage and not for example night-time effluxes then neutral stability only experiments will suffice.

Conclusions and Further Work

The adjustment of a boundary layer is shifted downwind by the anisotropy created as the air flows over the forest edge. Once the turbulence in the flow starts to return to isotropic conditions the vertical velocity variance and shear stress start to approach full development in the flow above the forest. Once the shear stress is established coherent gusts can form and it is likely that a quick succession of these gusts may lead to damage that is observed downwind of forest edges.

Future work should include a field experiment with additional measurement points and the measurement of scalar fluxes across a forest edge. It is hoped that the PIV data will allow us some further insight into the development of shear stress and the change from anisotropic to isotropic conditions and subsequent gust development.

Acknowledgements

Martin Hill for the field data logging system and Rex Belcher for the wind tunnel experiments.

Funding from The U.K. Forestry Commission, NERC, EPSRC, The Scottish Forestry Trust, GIP Ecofor for support for the VENFOR project, British Council/Ministère des Affaires etangères en France: Alliance Programme, U.S. National Science Foundation grants ATM-95211586 and 0071377, NCAR Scientific Computing Division.

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