WIND AND WIND FORCES IN A PLANTATION SPRUCE FOREST

B. A. GARDINER
Forestry Commission, Northern Research Station, Roslin, Midlothian, Scotland

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Abstract. Observations have been made of the turbulent structure within and above a dense (LAI = 10.2) plantation spruce forest along with measurements of the movement of individual trees. The mean statistics of the turbulence and the turbulence spectra are compared with observations in other crops and complementary wind-tunnel studies using 1:75 scale plastic trees. The measurements show that momentum transport and the subsequent motion of the trees is dominated by intermittent sweep/ejection events associated with 'honami' waves moving across the forest. The trees themselves act as forced damped harmonic oscillators and appear to short circuit the normal turbulent energy dissipation process by efficiently absorbing energy at their resonant frequencies. It is argued that understanding the nature and formation of 'bonami' waves over forests and crops is a crucial problem in agricultural and forest meteorology because of their important role both in turbulent transport and in causing wind damage.

1. Introduction

1.1. Wind damage to forests

Strong winds associated with Atlantic depressions cause considerable damage to forests in northern Europe every year. In Great Britain and Eire, trees are, in general, completely uprooted from the ground (windthrow) and the problem is exacerbated by shallow rooting in waterlogged soils (Miller, 1985). In an attempt to reduce damage and to predict better the likelihood of windthrow, a series of experiments has been carried out to understand the physical processes of windthrow and the nature of airflow in forests.

Two experiments were conducted to measure the airflow characteristics in and above a dense forest along with the response of the trees to wind loading. This paper presents the results from full-scale experiments in a commercial spruce forest in south-west Scotland. A second paper by Stacey et al. (1994), hereafter referred to as 'Paper II', discusses experiments in a 1:75 scale model forest composed of 12,000 dynamically correct plastic trees. Comparison of results from the two experiments indicates that the model forest closely simulates full-scale and allows confidence to be placed in the results from the model forest that could not be replicated at full-scale (edge effects, flow in clearings, effects of planting density, etc.).

1.2. Canopy airflow and aeromechanics

A substantial body of work exists on the nature of airflow within the canopies of forests and agricultural crops; see Raupach (1988) for an excellent review. He
shows that the vertical distributions of mean turbulence statistics are very similar for all canopies provided that the data are normalised by crop height. However, as Finnigan (1979a) pointed out, such information does not provide details of the unsteady aspect of the flow, which is a general feature of all wall-bounded turbulent shear flows. Momentum transfer is found to be intermittent in time and space and appears to be dominated by ‘large’, coherent structures which show up as waves in cereal crops, named ‘honami’ by Inoue (1955a). Recently great effort has gone into understanding the nature of the intermittent transport process because of the failure of flux/gradient theories to explain turbulent transport in canopies (Raupach, 1988). Finnigan (1979b) has made a detailed study of the structure of momentum transfer in wheat and various workers including Gao et al. (1989), Zhang et al. (1991) and Bergström and Högström (1989) have identified organised structures in forest and orchard canopies. These organised structures, also called sweep/ejection events, account for more than 60% of the fluxes of momentum, heat, water vapour and CO₂ (Zhang et al., 1991). However, the exact nature of these coherent structures and their formation is not yet fully understood. Finnigan and Mulhearn (1978) suggested that they formed in the outer part of the boundary layer whereas more recently it has been argued that they are created within the high shear region just above the canopy (Raupach et al., 1989).

Several workers have also investigated the relationship between airflow and the aeromechanical behaviour of crops (Inoue, 1955b; Finnigan and Mulhearn, 1978; Finnigan, 1979a; Maitani, 1979; Holbo et al., 1980; Mayer, 1987). Holbo et al. (1980), Mayer (1987) and Gardiner (1992) have compared the windspeed spectra and the displacement spectra of trees to obtain a mechanical transfer function for trees. They showed that, to first order, conifer trees can be regarded as cantilever beams with a lumped mass near the centre of the canopy, a similar conclusion to that reached by Finnigan and Mulhearn (1978) for wheat.

The first part of this paper presents the mean turbulence statistics of a dense spruce forest and these are compared with observations from other studies and from the wind-tunnel. Then, an examination is made of the intermittency of turbulent transport within the canopy and the detailed structure of sweep/ejection events. Finally, the interaction of the airflow and trees is discussed and comparison made of the wind loading on full-scale and model trees.

2. Experimental Arrangement

2.1. Site Description

The study area was located in the Rivox Forest, Nithsdale District near Moffat in southwest Scotland (55°19.5′ N, 3°33′ W). The site is gently sloping (approximately 6°) within a valley basin at an altitude of 360 m. The forest consists of Sitka spruce planted at 3584 stems/ha in 1962. The median height \( h_m \) of a sample of 476 trees