AIR FLOW THROUGH AND ABOVE A FOREST OF WIDELY SPACED TREES.

by

STEVEN ROBERT GREEN
B.Sc (Physics), M.Sc. (Physics)

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to the
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DECLARATION

I certify that all the work contained in this thesis is entirely my own, except where stated otherwise, and that it has not been submitted in any previous application for a degree.

Signed ..............................................

Date ..................................................

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DEDICATION

This thesis is dedicated to my wife Leanne and to our two girls Rebecca and Kimberly. Thanks for being so patient and understanding.
ABSTRACT

Agroforestry systems are currently being advocated for the uplands of the UK, consisting of widely spaced trees on grassland utilized by grazing sheep or cattle. One of the aims of agroforestry is to provide wind shelter which will benefit the animals and plants and lead to overall increases in productivity. Practical information on various aspects of the canopy microclimate, such as air flow, is needed to design the optimum agroforestry system. This thesis reports on a series of field experiments, wind tunnel experiments and numerical experiments which were undertaken to examine and predict the properties of turbulent air flow through a forest of widely spaced trees.

The field experiment was carried out at Cloich farm forest, 32 km south of Edinburgh, in three stands of 8 m tall Sitka spruce trees (Picea sitchensis (Bong.) Carr) at spacings of 4 m, 6 m and 8 m between tree centres. Turbulent statistics associated with the air flow were measured using a vertical array of 3-component propeller anemometers, at heights of between 0.25h to 1.25h, h being the mean tree height. Mean wind speed in the forest trunk space increased with increasing tree spacing, and was 46% (8 m), 29% (6 m) and 16% (4m) of mean wind speed in an adjacent, open-paddock. Zero plane displacement, d, decreased with increasing tree spacing, and was 0.74h (8 m), 0.80h (6 m) and 0.87h (4 m) during daytime. Thermal stability acted to reduce turbulence velocities and momentum stresses at night by between 10% and 25%. Turbulence events within the widely spaced forest canopies were less extreme than reported elsewhere for closed forest stands. Slopes of the u-spectra in the trunk space were greater than -2/3 suggesting a bypass of the normal eddy cascade process.

The wind tunnel experiment was carried out in an open jet wind tunnel at the Civil Engineering Department, Edinburgh University, using 1:75 scale model forest made from 20 cm tall bottle-brush elements at spacings of 1/3h, 1/2h and 2/3h, extending a distance of 10h and 20h in the downwind dimension. The area densities matched approximately those of the Cloich forest study. Turbulence statistics were mapped from extensive measurements obtained using a 3-hot-wire probe. The wind tunnel study was successful in simulating many of the features of canopy flow identified in the field experiment. In addition, the experimental study resulted in a comprehensive set of measurements suitable for testing the predictions from the numerical experiment.
A numerical experiment was carried out in two-dimensions to predict turbulent flow in and above small forest placed in an otherwise undisturbed rural boundary layer flow. The computations were performed using a well-tested fluid dynamics program called PHOENICS. Equations governing the transport of momentum \( (U, W) \), turbulence energy \( (k) \) and the turbulence dissipation rate \( (\varepsilon) \) were solved using a standard two-equation, \( k-\varepsilon \) turbulence model. The canopy/airflow interactions were modelled using the spatially-averaged conservation equations for mean flow and turbulence kinetic energy as described by Raupach and Shaw (1982). An additional (unconventional) term was included in the \( k \)-equation to account for the energy transformation of shear-turbulence to wake-turbulence, and a similar semi-empirical term was added to the \( \varepsilon \)-equation.

Several computations were carried out to simulate the wind tunnel experiments. Very satisfactory agreement was reached between the predictions and observations of \( U \) and \( k \) for a four fold change in canopy density and a doubling of forest size, with minimal specification of an area density, \( A \), a drag coefficient \( C_d \), and suitable optimization of a single parameter, \( C_{de} \) in the \( \varepsilon \)-equation. Although no full-scale comparisons were made, it is concluded that the model presented in this thesis is potentially suitable for predicting turbulent air flow in a forest of widely spaced trees.
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LIST OF SYMBOLS

Roman symbols

$A(z)$ canopy area density (m$^2$m$^{-3}$)
$A_r$ maximum area density (m$^2$m$^{-3}$)
$a'$ constant (0.04 m s$^{-1}$)
$a_E$ discretization coefficient for grid point E (similarly, W,N,S) (kg s$^{-1}$)
$b$ source term (kgϕ.s$^{-1}$)
$b'$ constant (0.8 m$^2$)
$C_\phi$ source term coefficient (kg s$^{-1}$ per $T$)
$C_d$ elemental drag coefficient
$C_{1e}$ turbulence model constant (1.44)
$C_{2e}$ turbulence model constant (1.92)
$C_{4e}$ turbulence model constant (1.5)
$C_\mu$ turbulence model constant (0.5478)
$C_D$ turbulence model constant (0.1643)
c transfer coefficient to parameterize sweeps (s$^{-1}$)
d zero plane displacement (m)
$E$ false time step
$F_x$ body force in the $x$ direction (m s$^{-2}$)
$F_e$ mass flow rate through cell face at $e$ (similarly $w,n,s$) (kg s$^{-1}$)
$H$ size of the hyperbolic-hole region
$h$ mean canopy height (m)
h average height of roughness element (m)
$I_i$ turbulence intensity of $u_i$ ($\sigma_i/U$)
$J_i$ total flux in the $ith$ direction (kgϕ.s$^{-1}$)
$k$ turbulence kinetic energy (m$^2$s$^2$)
$K_{E}$ turbulent diffusivity for water vapour (m$^2$s$^{-1}$)
$K_{H}$ turbulent diffusivity for heat (m$^2$s$^{-1}$)
$K_{M}$ turbulent diffusivity for momentum (m$^2$s$^{-1}$)
$K_{\rho}$ kurtosis factor for $u_i$
$L_E w$ Eulerian length scales for horizontal and vertical scales (m)
$L_r$ turbulence length scale (m)
$L_n$ total length of computational domain (m)
$l_h$ mixing length at top of canopy (m)
$l_m$ mixing length (m)
$n$ natural frequency (s)

number of samples

$P$ dynamic pressure (Pa)
$P$ static pressure (Pa)
$p$ pressure fluctuation (Pa)
$R$ residual source term (kg$\cdot$s$^{-1}$)

universal gas constant (287.04 J K$^{-1}$ kg$^{-1}$)

$R(t)$ autocorrelation coefficient

$r_{ij}$ linear correlation coefficient
$S$ source term (kg$\cdot$s$^{-1}$)

$S_L$ ground area per element (m$^2$)
$S_s$ average vertical cross-sectional area of element (m$^2$)
$S_{ijH}$ normalized conditional momentum stress in quadrant $i$, hole size $H$

$S_f(\omega)$ power spectral density of $u_j$ (m$^2$s$^{-1}$)

$Sk_i$ skewness factor for velocity component $u_i$

$s$ size of smallest grid cell (m)

skin friction factor (5.22)

$T$ PATCH multiplier depending on PATCH-type (see 5.15)
$T_{ijH}$ time fraction for events in quadrant $i$, hole size $H$
$\tau$ time (s)

$U$ mean streamwise velocity (m s$^{-1}$)
$U_i$ instantaneous velocity component in the direction $x_i$ (m s$^{-1}$)
$U_i$ mean velocity component in the direction $x_i$ (m s$^{-1}$)
$U_T$ velocity at canopy top height (m s$^{-1}$)
$U_x$ friction velocity, $U$-star (m s$^{-1}$)

$u$ streamwise velocity component (m s$^{-1}$)

$u_i$ fluctuating velocity component in the direction $x_i$ (m s$^{-1}$)

$uw$ tangential momentum stress (m$^2$s$^{-2}$)
$V$ mean tangential velocity (=0 m s$^{-1}$)
\( V \)  velocity scale (m s\(^{-1}\))
\( V_\phi \)  value of phi (\( \phi \))
\( v \)  tangential velocity component (=0 m s\(^{-1}\))
\( W \)  mean vertical velocity (m s\(^{-1}\))
\( w \)  vertical velocity component (m s\(^{-1}\))
\( x \)  horizontal cartesian coordinate aligned with the mean wind (m)
\( x_i \)  represents (\( x,y,z \)) for \( i = 1,2,3 \) (m)
\( y \)  horizontal cartesian coordinate aligned crosswind (m)
\( z \)  vertical cartesian coordinate (m)
\( z_0 \)  roughness parameter (m)

**Greek symbols**
\( \alpha \)  attenuation coefficient of exponential wind profile
\( \alpha_\phi \)  under-relaxation factor for \( \phi \)
\( \Gamma \)  diffusion coefficient (kg m\(^2\) s\(^{-1}\))
\( \delta \)  height of disturbed boundary layer (m)
\( \delta_{ij} \)  kronecker delta
\( \delta_0 \)  height of undisturbed boundary layer (m)
\( \partial \)  partial derivative
\( \Delta \)  difference
\( \Delta\delta' \)  thickness of inner boundary layer
\( \epsilon \)  dissipation rate for turbulence energy (m\(^2\) s\(^{-3}\))
\( \epsilon_{T_d} \)  dissipation of shear-turbulence (m\(^2\) s\(^{-3}\))
\( \theta \)  wind angle (degrees)
\( \kappa \)  the von Karman constant (0.4)
\( \mu \)  dynamic viscosity (1.789 \( \times 10^{-5} \) kg m\(^{-1}\) s\(^{-1}\))
\( \nu \)  kinematic molecular viscosity (1.461 \( \times 10^{-5} \) m\(^2\) s\(^{-1}\))
\( \nu_t \)  eddy viscosity
\( \rho \)  density (kg m\(^{-3}\))
\( \sigma_i \)  turbulence velocity for component in the \( x_i \) direction (m s\(^{-1}\))
\( \sigma_k \)  turbulent Prandtl number for \( k \) (=1.0)
\( \sigma_\epsilon \)  turbulent Prandtl number for \( \epsilon \) (=1.3)
\( \tau \)  tangential momentum flux (kg m\(^{-1}\) s\(^{-1}\))
\( \phi \)  general dependent variable standing for \( P,U,V,W,k \) of \( \epsilon \)
$\phi_E$ empirical stability function for water vapour (s m$^2$)
$\phi_H$ empirical stability function for heat (s m$^2$)
$\phi_M$ empirical stability function for momentum (s m$^2$)
$\chi$ shelter integral (m$^3$ s$^{-1}$)
$\omega$ wave period (s)
1.1 INTRODUCTION AND BACKGROUND

In recent years the study of air flow within and above plant canopies has become a subject of increasing interest. The major scientific motivation has been to gain an understanding of the processes of momentum, heat and mass exchange between a plant canopy and the atmosphere. Since these exchanges are regulated by wind distributions in and above the canopy, the wind flow exerts a controlling influence on canopy microclimate. Efforts to understand canopy/air flow interactions, and therefore perhaps to modify canopy microclimate beneficially, depend on being able to predict the nature of turbulent flow through the vegetation.

Early studies in plant canopies concentrated on the measurement and prediction of the vertical distribution of various mean quantities (e.g. Penman and Long, 1960; Denmead, 1964). Some of the early measurements of wind speed in plant canopies (e.g. Oliver, 1975) may have suffered serious errors by using cup anemometers which overestimate mean wind speed in gusty conditions by between 10% to 15% (Wyngaard, 1981). With the advent of more sophisticated and faster-response instrumentation such as sonic anemometers, researchers have been able to measure velocity fluctuations and corresponding fluxes due to the turbulent motions.

Much experimental work has been carried out towards gaining a better understanding of crop aerodynamics (e.g. Uchijima and Wright, 1964; Shaw et al, 1974; Bache and Unsworth, 1977; Wilson et al, 1982, Shaw and McCartney, 1985), and the effect of wind flow on other aspects of the crop canopy microclimate, such as the transport of sensible heat (Maitani and Ohtaki, 1987), latent heat (Maitani and Seo, 1985) and carbon dioxide (Desjardins et al, 1978; Anderson and Verma, 1985) and the waving motions of plants (Maitani, 1979; Finnigan, 1979).

Many full-scale experimental studies of the aerodynamics of tree canopies have been carried out (e.g. Allen, 1968; Garrett, 1978; Dolman, 1986; Baldocchi and Hutchison, 1987; Baldocchi and Meyers, 1988). Similarly, many studies have examined the effect of wind flow on aspects of the microclimate, such as the transport of sensible heat (Grant et al, 1986), latent heat (Denmead and Bradley, 1985), and carbon dioxide (Verma et al, 1986, Denmead and Bradley, 1989).
The traditional approach in most studies has been to take measurements at one tower or location, the measurement point being located well away from the boundaries of the canopy domain so as to minimise advective edge effects. The distance of uniform surface over which the wind travels is termed the *fetch*, and the wind is usually considered to be 90% or more equilibrated with the new surface to heights of 0.01 x fetch. In this case, the flow can be treated using a one dimensional framework, so that vertical transport predominates and advective transport is negligible.

The form of the mean wind profile is central to a large number of canopy transport problems, and is often represented by a simple mathematical expression. The three most commonly used canopy wind profile models are those of Cionco (1965), Cowan (1968), and Landsberg and James (1971). These models adopt so-called K-theory, where fluxes of momentum, and other scalars, are related to gradients in the mean variables. Velocity profiles predicted from these models decrease monotonically with depth into the canopy.

These simple models have been used widely to predict the effect of a change in canopy geometry on the profiles of mean velocity within a plant canopy (Seginer, 1974; Kondo and Kawanaka, 1986). However, the assumptions underlying K-theory models are often violated in the canopy domain (Corrsin, 1974; Legg and Long, 1975). More sophisticated models of canopy flow have been developed (Wilson and Shaw, 1977; Wilson, 1988; Meyers and Paw U, 1987) to overcome some of the deficiencies of K-theory, but testing of these models still remains largely one dimensional.

The general character of the wind over natural surfaces can be satisfactorily reproduced over scale models in a wind tunnel. In addition, a wind tunnel is a convenient facility in which to study air flow through canopy elements and to investigate the two-dimensional nature of the flow near the edges of the canopy domain. Extensive measurements have been conducted in wind tunnels using a variety of stylized canopies consisting of rods and pegs (Kawatani and Meroney, 1970; Marshall, 1970; Thom, 1971; Wooding *et al*, 1973; Seginer, 1975; Seginer *et al*, 1976; Seginer and Mulhearn, 1978), flexible strips (Plate and Quraishi, 1965), nylon filaments (Finnigan and Mulhearn, 1978), miniature plastic trees (Meroney, 1968, 1970; Sadeh and Kawatani, 1979; Papesch, 1984), porous foam blocks (Argent, 1990) and rigid rectangular elements (Raupach *et al*, 1986).
Considerable advances have been made in the understanding of turbulent flow in plant canopies from many experimental observations covering a wide variety of crop and tree canopies, both at full- and model-scale. It is now recognised that canopy turbulence has a number of important universal characteristics which are relatively independent of the precise structure of the canopy. Evidence is emerging that $h$ (mean canopy height) is the dominant length scale, $U_*$ (friction velocity) is the dominant velocity scale, and that transfer processes near to and within the canopy are dominated by large scale, intermittent downsweep motions (Raupach, 1988a).

Excellent reviews by Raupach and Thom (1981), and more recently by Raupach (1988a) summarise our knowledge of canopy aerodynamics and the way in which turbulence transfers scalar quantities such as temperature, water vapour and carbon dioxide between the canopy and the atmosphere.

However, much of our current knowledge has been gained from one-dimensional, vertical profile studies in relatively closed canopies. In a recent review of canopy transport processes, it was concluded that 'another area ripe for development is that of advection, edge effects and changes in surface type' (Raupach, 1988a). Few full-scale experimental studies have been made in relatively open, or sparse canopies. Orchards are a good example of sparse canopies and several aerodynamic studies have been commissioned (Randall, 1969; Weiss and Allen, 1976; Baldocchi and Hutchison, 1987). But to date, much our knowledge of air flow through widely spaced tree canopies is rudimentary and speculative.

Understanding the aerodynamics of widely spaced tree canopies is of increasing importance to the UK where agroforestry practices are currently being advocated. The most probable system for adoption in the uplands of the UK is a sylvopastural system consisting of widely spaced trees on grassland which is utilized by grazing sheep or cattle (Alcock and Thomas, 1986).

One of the aims of the sylvopastural system is to provide shelter which will benefit the animals and plants and lead to overall increases in productivity. Heat loss from an animal may be a function of tree spacing as this determines both radiative and convective coupling of the animal to its environment (Mount and Brown, 1982). Preliminary research findings in New Zealand show that significant reductions in ground level wind run (greater than 50%) and rises in grass minimum temperature of between 0.1 °C to 1.0 °C could be obtained in stands of *Pinus Radiata* at wide spacings (100 stems per ha) (Percival *et al*, 1984).
Practical information on various aspects of canopy microclimate, like the turbulent air flow, will assist in designing the optimum agroforestry system. More work both experimental and theoretical is therefore needed to establish the shelter likely in different canopies and at different densities.

This research attempts to further our understanding of plant canopy aerodynamics by addressing the problem of air flow through and above a small, isolated forest of widely spaced trees. To achieve this goal, a series of field and wind tunnel experiments were initiated to examine the effect of tree/element spacing on the air flow, and a numerical simulation model was used to predict the turbulent flow field. The wind tunnel and numerical experiments were conducted in two-dimensions in order to examine and predict air flow through forest edges. An overview of some the basic features to the problem is given in the following section.

1.2 BASIC CONCEPTS

There are basically three regions of the flow that we need to consider in order to address the problem of air flow through and above an extensive forest. These regions can be roughly divided into (a) established flow above the canopy, (b) established flow within the canopy, and (c) the flow transition through the forest edges. Regions (a) and (b) occur at distances well away from the influence of the forest edges and will be important in extensive forest canopies. Region (c) is particularly relevant to the present study of flow through small forests. The basic concepts of turbulent air flow through and over a forest canopy are discussed below.

1.2.1 Equilibrium wind profiles above uniform plant canopies

For simplicity, we begin by considering steady-state, neutral conditions above an extensive, uniform, level canopy, so that advection is negligible and vertical transport predominates. In this case, a well developed turbulent boundary layer develops above the canopy consisting of an outer layer and a surface layer in which vertical fluxes of momentum do not vary significantly with height (Fig. 1.1). Very close to the roughness elements of the canopy the turbulent structure is influenced by the wakes generated by the elements, establishing a roughness sublayer (Raupach and Legg, 1974). In the inertial sublayer (Fig. 1.1) the following local flux-gradient relationship applies
\[ \tau(z) = K_M \frac{dU}{dz} = U_*^2 \quad ; \quad K_M = \frac{\kappa U_* (z-d)}{\phi_M} \] (1.1)

where \( \tau(z) \) is the momentum flux (a shear stress) at height \( z \), \( K_M \) is the height-dependent turbulent diffusivity for momentum, \( U \) is the mean horizontal velocity, \( U_* \) is the friction velocity, \( d \) is the zero plane displacement height, \( \phi_M \) is an empirical function related to the stability of the atmosphere, and is universal over bare ground and low vegetation (Dyer, 1974), and \( \kappa \) is the von Karman constant (0.4).

The friction velocity is a scaling parameter determined from the shear stress, \( \tau \), by the relation \( \tau = \rho u w = \rho U_*^2 \), where \( \rho \) is the mean air density, and \( u \) and \( w \) are the turbulent fluctuations about the mean for the horizontal and vertical wind components, respectively. The shear stress equates to a vertical flux of horizontal momentum. Provided the vertical flux is constant with height above the surface, which is strictly true only in the inertial sublayer, \( \tau \) is a measure of the drag force on the surface per unit ground area. In neutral conditions \( \phi_M \) equals 1 and Eq. 1.1 integrates to the semi-logarithmic wind profile given by

\[ U(z) = \frac{U_*}{\kappa} \ln \left( \frac{z-d}{z_0} \right) \] (1.2)

where \( z_o \) is the roughness length. The semi-logarithmic wind profile gives rise to two aerodynamic properties describing the canopy, namely \( d \) and \( z_0 \), which must be determined from wind profile measurements in the inertial sublayer.

Fig. 1.1. Constant flux layer and its sublayers over an homogeneous plant canopy (from Raupach and Legg, 1984).

![Diagram of wind profile layers](image-url)
The zero plane displacement is usually thought of as the level to which the effective surface must be raised to make the neutral wind profile in the inertial sublayer obey the semi-logarithmic law, and the roughness length is the level where \( U \) is extrapolated to zero. Physically, \( d \) is defined as the mean level of momentum absorption by the canopy (Thom, 1971) and can be calculated from measurements of the shear stress profile within the canopy. A graphical procedure to determine \( d \) and \( z_0 \) from measured wind speed profiles is illustrated in Thom (1975).

For dense agricultural crops, \( d \) appears to be a simple function of crop height, \( h \), given approximately by \( d=0.64h \) (Campbell, 1977). For a range of coniferous forests, Jarvis et al. (1976) found \( d \) to be in the range 0.61\( h \) to 0.92\( h \) with a mean of 0.79\( h \). In general \( d \) will be mainly influenced by the density of the roughness elements and will increase monotonically with increasing element density, as demonstrated in the numerical experiments of Shaw and Pereira (1982).

For uniform vegetative surfaces, the roughness length is empirically related to the height of the canopy and is given by \( z_0=0.13h \) (Campbell, 1977). For more complex surfaces (sparse vegetation for example) the form and spacing of the elements must be considered. Lettau (1969) suggested a method for estimating \( z_0 \) based on the average height of the roughness elements, \( h \), the average vertical cross sectional area of each element, \( S_S \), and the ground area per element, \( S_L \), as \( z_0=0.5h(S_S/S_L) \). Such a simple relationship was considered valid only for surfaces composed of fairly isolated roughness elements. Shaw and Pereira (1982) demonstrate that in increasing the density of a sparse array, the roughness length initially increases with increasing canopy density, reaches a peak, and then declines.

The semi-logarithmic law can be used to derive basic information about air flow above the canopy, such as the vertical momentum fluxes and the aerodynamic drag acting on the surface. However, the semi-logarithmic law is not completely applicable in the roughness sublayer over very rough surfaces, such as forests (Garratt, 1980). Wind tunnel measurements above a model forest by Raupach et al. (1986) showed a well defined roughness sublayer that extends to a height of about 1.5\( h \). Therefore we might expect the semi-logarithmic law not to apply to forest canopies below a height of about 1.5\( h \). The semi-logarithmic law gives no information of the distribution of winds deep within the canopy, although this is the zone which farmers and foresters may be particularly interested in. Nevertheless, the concepts of \( d \) and \( z_0 \)
are widely used to characterize the aerodynamic properties of plant canopies (Dolman, 1986; Hatfield, 1989).

The concepts of gradient-diffusion implicit in Eq. 1.1 have often been used to describe the transport of heat and water vapour over rough surfaces. It is generally accepted that in neutral conditions over bare ground or low vegetation, the stability functions are the same for heat ($\phi_H$) and water vapour ($\phi_E$) and equal to the stability functions for momentum ($\phi_M$) given by Dyer (1974). In this case, gradients in the vertical profiles of air temperature and humidity, multiplied by the turbulent diffusivity, can be used to calculate fluxes of sensible and latent heat. However, there are anomalies in using this approach over forests. Raupach (1979) found that the behaviour of $K_M$ (or $1/\phi_M$) was fairly close to that expected, but values of $K_H$ and $K_E$ (standing for the turbulent diffusivity for heat and water vapour, respectively) were between 2 and 4 times larger than values suggested from the empirical functions of Dyer (1974). There are also anomalies to this approach under conditions of regional sensible heat advection, when the ratio $K_H/K_E$ is then greater than unity (Motha et al., 1979).

1.2.2 Equilibrium wind profiles within uniform plant canopies

In a horizontally uniform canopy, subject to stationary flow, and in neutral conditions, the vertical gradient in the shear stress through the canopy is related approximately to the aerodynamic drag of the canopy elements by the relationship

$$\frac{d}{dz} \tau(z) = \frac{1}{2} C_d A(z) U^2(z)$$  \hspace{1cm} (1.3)

where $C_d$ is an effective drag coefficient and $A(z)$ is the frontal surface area exposed to the wind per unit canopy volume. Thom (1971) introduced the concept of a shelter factor of between 0.2 and 0.5 to account for the fact that the effective drag coefficient of a sheltered element is reduced below that of a single, unsheltered element.

Several simple analytic models have been developed to predict the vertical distribution of mean velocity, by adopting flux-gradient or K-theory whereby fluxes of momentum, $\tau(z)$, are related to the gradient in the mean velocity according to Eq. 1.1. Combining Eqs. 1.3 and 1.1 results in a second order partial differential equation in $U(z)$ which can be solved only when $C_d$ and $A(z)$ are known, and the boundary
conditions for $U$, namely $U(h)$ and $U(0)$ are specified. Also $K_M$ must be related to the other variables in the equation.

The most commonly used canopy wind profile model is that of Cionco (1965) in which $K_M$ is derived from a mixing length model, $K_M = \frac{P dU}{dz}$ and the mixing length, $l$, is assumed to be constant. These assumptions yield the exponential wind profile given by

$$U(z) = U(h) e^{-\alpha(1-z/h)}$$

(1.4)

in which the attenuation coefficient $\alpha$ varies in the range 0.3 to 4 as area density is increases (Cionco, 1972). The upper part of the velocity profile in many plant canopies is approximated fairly well by the exponential wind profile where the coefficient $\alpha$ tends to increase broadly with foliage density (Raupach, 1988a). However deep within the canopy the characteristic 'S' shaped or nearly constant velocity distribution is observed in many plant canopies (Shaw, 1977). This phenomenon cannot be reproduced by simple K-theory.

The failure of K-theory inside the plant canopy stems from the basic hypothesis that the length scale of the turbulence is much smaller than the length scale over which mean gradients change appreciably, which is not valid within the plant canopy (Legg and Long, 1975). Denmead and Bradley (1985), working in Pinus ponderosa which is a fairly low density canopy, but horizontally homogeneous, provided the first experimental evidence of the existence of counter gradient fluxes occurring in the canopy. This is a phenomenon which K-theory is unable to predict. As a consequence, Denmead and Bradley (1985) concluded that 'measurements and models based on the classical notions of gradient-diffusion in the canopy are not well founded.' In general, gradient diffusion theories and the associated flux-gradient relationships become progressively less reliable as a rough surface is approached, and they often fail completely within the plant canopy, where negative turbulent diffusivities are often predicted.

Increasingly sophisticated turbulence models have been developed (Wilson and Shaw, 1977; Wilson, 1988; Meyers and Paw U, 1987) to overcome some of the deficiencies of K-theory, such as the inability to predict counter gradient fluxes and sub-canopy wind speed maxima. Rather than specifying the turbulent flux per se, these so called higher-order models solve additional equations for the momentum flux, and other second order moments appearing in the governing equations. Such models (e.g
Wilson and Shaw, 1977) require several length scales and constants that are usually determined by forcing the model to reproduce the observed flow characteristics in the free, neutral surface layer. When compared to observations in a wide range of plant canopies these more sophisticated turbulence models produce realistic secondary wind speed maxima near the ground, and realistic turbulence velocity and shear stress profiles. Testing of these models remains largely one dimensional, the extension to two and three dimensions having been rarely tried nor rigorously tested in plant canopies.

In a recent review of canopy transport processes, Raupach (1988a) compiled high quality turbulence data from seven comprehensive experiments on canopy flow: three in wind-tunnel model canopies (denoted by WT), two in crop canopies and two in forest canopies (Moga and Uriarra, respectively) (Fig. 1.2).

![Graphs showing vertical distribution of mean velocity, tangential momentum stress, longitudinal turbulence velocity, and vertical turbulence velocity in plant canopies](image)

Fig. 1.2. Vertical distribution of (a) mean velocity, (b) tangential momentum stress, (c) longitudinal turbulence velocity and (d) vertical turbulence velocity in plant canopies (from Raupach 1988a).
Despite the wide range of canopy types, the measurements shared some common features. Importantly, it was shown that $h$ and $U_*$ provided an approximate collapse of the data in canopies where $h$ varied by a factor of 400 and $U_*$ by a factor of 10 or more. It was concluded that $h$ is the dominant length scale and $U_*$ is the dominant velocity scale for the turbulence in the canopy. Two of these data sets, WT strips (Raupach et al, 1986) and the Moga forest (Raupach et al, unpublished) are particularly relevant to the present study (the solid lines in Fig. 1.2) because they were obtained in sparse canopies.

1.2.3 Wind characteristics above forest/grass boundaries and abrupt changes in roughness

Departures from the idealized equilibrium profiles presented above, may occur because of the presence of either obstacles in the flow (e.g. hills) or changes in roughness near the edges of the forest domain. Although it is quite likely that both influences occur simultaneously, these effects are generally considered independently. Typical changes in vertical profiles of mean velocity over a low isolated hill are shown in a recent review paper by Finnigan (1988). In the present discussion we bypass the effects of topography and consider air flow over a sudden step change in roughness on an otherwise flat, level terrain. This situation is depicted in Fig. 1.3.

![](fig13.png)

**Fig. 1.3.** Development of a new equilibrium boundary layer as air flows from open country over a forest wall (not to scale) (from Shin, 1971).
Upstream of the forest edge, the 'open country' boundary layer roughness is low. At the interface of the forest edge, a step change in roughness produces a disturbance in the velocity and shear stress profiles. In this region, the wind variations are changed by the geometry of the leading edge, with its higher roughness and change in height, displacing the wind vectors vertically and increasing the turbulent mixing.

Most studies of the response of the boundary layer to changes in surface roughness have been directed largely at the growth of the envelope containing the disturbed boundary layer (Rao et al., 1974). The increased roughness, due to a forest edge for example, exerts a substantially larger drag on the air flow than existed upwind, so the air is decelerated as it moves from the smoother to the rougher surface and a corresponding increase in shear stress and turbulence energy is observed above the canopy. The undisturbed surface boundary layer, $\delta_0$, upwind of the forest wall changes to a disturbed boundary layer, $\delta$, which increases in the vertical direction, $z$, for increasing fetch or distance $x$, downwind from the change in surface features. The growth of the disturbed boundary layer is often considered proportional to the $4/5$th power of the fetch (Rao et al., 1974).

An inner layer develops below the disturbed layer, which is characteristic of the new roughness and in which turbulent fluxes are approximately constant. When equilibrium is reached well downwind from the change in surface features, this inner layer corresponds to the surface layer pictured in Fig. 1.1. Some controversy surrounds the height-to-fetch ratio for the development of the inner layer. For example, Shin (1971) collated early measurements of flow over forest borders and estimated $\Delta\delta' = 0.08x$, whereas more recent measurements by Gash (1986) for a heath (0.25 m) to forest (10 m) transition gave $\Delta\delta' = 0.03x$. Both results show the commonly applied height-to-fetch ratio of 1/100 gives over-conservative estimates of the distance required for the development of a new equilibrium layer over a forest. This study shows that differences in the behaviour of $\Delta\delta'$ are possibly due to different forest densities. It is essential to take measurements below the height of the inner layer in order that they are characteristic of the underlying surface and not of the surface roughness upwind.
1.2.4 Wind characteristics through forest edges

Our understanding of within-canopy air flow through forest edges is largely empirical (McNaughton, 1989) and can be visualized in the following manner. If a substantial trunk space region exists, then the adjustment of the wind through the forest wall follows two pathways. The airflow separates and is either forced to rise above the canopy, behaving in the manner described above, or is forced down into the canopy trunk space.

Miller (1980) observed the behaviour of air flow through forest edges using smoke tracers. Smoke released upwind of the forest edge, at the height of the trees, rose above the top of the canopy and did not penetrate the forest edge, but smoke released in the trunk space generally moved well into the stand. An intermittent recirculating eddy (a rotor) was sometimes observed at the leading edge with the wind blowing into the stand at low windspeed. When smoke was released at midcanopy at the forest edge, the smoke tracer dissipated and diffused upwards leaving the canopy before a distance of \(2h\).

Reifsnyder (1955) measured wind profiles at the leading edge of a small forest and found a 60% reduction in mean wind speed in the crown compared to upstream values. Maximum velocity reduction generally occurs at the level of greatest foliage density, giving rise to a local minimum in velocity near mid-canopy, and a local secondary maximum in velocity in the trunk space. This so called sub-canopy jet reduces with increasing distance into the forest.

Nageli (1953) found trunk level wind speed reached an equilibrium value at \(8.5h\) in spruce, Reifsnyder (1955) concluded equilibrium was reached at about \(7h\) in pine, Raynor (1971) found it to be \(6h\) in a much denser stand of pine and Meroney (1968) found it to be between \(15-20h\) in the wind tunnel with model trees.

Shin (1971) proposed a semi-empirical model for the adjustment of mean velocity in the trunk space, hypothesizing an exponential decrease in velocity with distance from the forest edge. Changes in forest density were not considered, although the influence of forest density will obviously be important when comparing flow through relatively open canopies with flow through much denser forest borders. A more open forest edge might allow the wind flow to penetrate to a much greater distance as a sub canopy jet. The penetration of air flow through leading and trailing forest edges is different (Fig. 1.4).
Fig. 1.4. Wind speed isotachs at the edge of a coniferous forest (from Raynor, 1971).

Forest density influences air flow through the trailing edge of the forest by allowing the wind to penetrate downwards into the canopy a little distance from the edge. Raynor (1971) recorded very little acceleration of the wind beneath the canopy right to the edge of a pine plantation with a very dense forest wall, whereas Fritschen et al (1969 as cited in Fritschen, 1985) observed an acceleration in wind speed over the last few tree-heights to the edge of a coniferous forest. In contrast, wind tunnel studies by Meroney (1970) demonstrated wind speed increasing above and within a model forest over the last 10h to the forest edge.

Few air flow measurements have been made in the lee of forest edges. It might be expected that turbulent air flow behind a forest edge would resemble that behind a thin windbreak, but this is not strictly the case (McNaughton, 1988). The enhanced turbulence above a forest leads to a much shorter distance at which the wake reaches the ground behind a forest edge, compared to a thin shelter belt, so that the sheltered zone behind a forest edge is much shorter. Raupach (commenting on McNaughton, 1988) used smoke tracers to observe an intermittent recirculating eddy behind his model canopy of between 2h and 3h downwind extent. Although intermittent recirculating eddies have been observed at the edge of forest clearings using smoke
tracers (Bergen, 1975), there are no accounts of rotors in the lee of simple forest edges.

In terms of the recovery of the air flow downwind of a forest edge, Gash (1986) observed a fairly rapid speed up in velocity over the heath for a distance of 20h, followed by a more gradual increase in velocity out to 70h. The minimum velocity was observed at a downwind distance of 5h. The turbulence variables (**U**, **σ_v** and **σ_w**) over the heath reached steady values at a distance of 20h downwind from the forest edge. These results suggest that the immediate effect of the forest edge is past by 20h, but that the wind continues to accelerate over a longer distance as the deeper boundary layer adjusts to the new surface roughness.

The only attempts to develop aerodynamic theory in the forest lee have been the simple continuity calculations of Bergen (1979) and the first order model of Li et al (1990), neither of which give any information of the turbulent flow field. Li et al (1990) modelled air flow entering a forest and predicted a significant high pressure centre at the front of the forest. For flow leaving the forest, there was a corresponding low pressure center near the trailing edge.

When air flows through forest borders, advective edge effects are observed over considerable distances. Some controversy surrounds the distance from the edge to where equilibrium is regained. It appears that a forest edge influences the air flow for distances of at least 20h, so that forests of much larger extent are required before the air flow can be simplified to one dimension. Therefore any predictions of flow through forests of relatively small downwind extent must address the problem of edge effects.

In summary, further research is needed in order to better understand the nature of turbulent air flow near forest edges and the role that canopy density plays on determining the air flow.

### 1.3 RESEARCH AIM

The basic aim of the thesis work was to use the three complementary techniques of field experiments, wind tunnel experiments and numerical simulation experiments to examine and predict the influence of tree/element density on the turbulent air flow through and above a forest of widely spaced trees.

The two fundamental questions this thesis work sets out to answer are: (a) what effect does a forest of widely spaced trees have on the air flow within and above the
forest canopy?, and (b) can these effects be modelled in order to predict air flow through a given forest canopy?

In order to achieve its aim, this thesis proposes a canopy flow model, works out its implication by computer analysis and compares the results with experimental data from a comprehensive wind tunnel study. Complementary field data are obtained from an extensive set of field measurements in a forest of widely spaced Sitka spruce trees, at different spacings. The thesis presentation is described in the following section.

1.4 THESIS LAYOUT

The thesis is organized into 6 chapters which deal with the main body of the work, and a number of Appendices containing additional data, performance tests of the instrumentation, and listings of computer programs used in the collection and analysis of velocity data, and in the prediction of canopy flow. A brief description of the content of each chapter is given below.

Chapter 1 is an introductory chapter. It gives a background to the project, introduces the basic concepts of air flow through plant canopies and discusses the aim and presentation of the thesis.

Chapter 2 presents the governing flow equations, proposes a mathematical model for canopy/airflow interactions, discusses the problem of turbulence closure and the use of an eddy-viscosity as a possible solution, and presents the various statistical techniques used to analyze velocity data from the field and wind tunnel experiments.

Chapter 3 presents experimental field data of mean velocity and turbulence statistics measured in 3 stands of 8 m tall Sitka spruce, in relation to tree spacing. Turbulence length scales and velocity spectra are presented, and analyses of the microstructure underlying the turbulent transport of momentum are discussed.

Chapter 4 presents wind tunnel data of mean velocity and turbulence statistics through and above a model forest canopy as a function of forest density and size. Various dynamic and aerodynamic properties of the model trees are examined. Turbulent events contributing to the transport of momentum within the canopy are identified and analyzed.

Chapter 5 presents numerical predictions of turbulent air flow through a forest of widely spaced elements, and compares these predictions with experimental wind tunnel data presented in Chapter 4. Several turbulence models based on the eddy viscosity
concept are tested. The majority of simulations are performed using a two-equation 
k-ε closure model for the turbulence energy.

Chapter 6 completes the thesis by summarising the findings, exploring the linkages 
between the three experiments to answer the question of whether we can use these 
techniques to study successfully turbulent air flow in vegetative canopies, and suggests 
some areas for further research.
CHAPTER 2.
THEORY AND COMPUTATIONAL METHODS.

This chapter is devoted to presenting a theoretical background to the prediction and measurement of canopy turbulence. The chapter is separated into three sections. In the first section a brief outline is given of the development of turbulence modelling with emphasis on flow models within and above plant canopies. The second section discusses the problem of turbulence closure and presents three turbulence models, based on an eddy-viscosity parameterization for the Reynolds stresses. A simple zero-equation (mixing length) model, a one-equation \((k-l)\) model, and a more complex two-equation \((k-c)\) model of turbulence are developed for canopy flow. The third section of this chapter deals with a statistical description of turbulent flow, presenting the various methods used in both the field and wind tunnel studies to analyze the flow measurements.

2.1 MODELLING CANOPY FLOW

2.1.1 Introduction

A plant canopy consists of a complex aggregation of numerous elements such as leaves, stems and branches. The vegetation interacts with the airflow in five principle ways: (i) momentum is extracted from the mean flow in the form of skin friction and form drag, (ii) kinetic energy of the mean flow (MKE) is converted into turbulence kinetic energy in the wakes formed behind the plants (WKE), (iii) larger scale shear-generated turbulence kinetic energy (SKE) is transformed into smaller scale turbulence kinetic energy in the element wakes, thereby short circuiting part of the normal energy cascade and accelerating the dissipation for large scale SKE in the canopy, (iv) counter-gradient momentum transport occurs by downsweep motions, and (v) the production of turbulence kinetic energy (TKE) may be enhanced by the convective transfer of sensible heat between plant parts and the airstream. The canopy therefore acts as a sink for momentum, and provides a source for the generation and dissipation of turbulence kinetic energy.

The result is a strongly 3-dimensional turbulent flow field which is mechanically and thermally influenced by the complex geometry of the canopy array. In order to provide a realistic description of canopy flow, a turbulence model must be able to simulate these four principle canopy/airflow interactions, or at least the first
three if the effects of buoyancy can be neglected. Theory describing the way in which the effects of a vegetative canopy can be modelled will now be described.

2.1.2 The governing equations

The set of equations that form the basis of turbulent flow theory are the equations for which describe motion of a viscous, Newtonian fluid in a rotating coordinate system. The origins of the equations are the conservation laws for mass and momentum. A detailed derivation of the equations can be found in Hinze (1959). For a neutrally stratified, incompressible flow the equations of motion for flow at a single point in space can be expressed in cartesian tensor notation as:

Mass conservation: continuity equation

\[ \frac{\partial U_i}{\partial x_i} = 0 \]  

(2.1)

Momentum conservation: Navier Stokes equations

\[ \frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} + \nu \frac{\partial^2 U_i}{\partial x_j \partial x_j} \]  

(2.2)

where \( U_i \) is the instantaneous velocity component in the direction \( x_i \), \( P \) is the instantaneous static pressure, \( \rho \) is the fluid density and \( \nu \) is the molecular (kinematic) viscosity. The summation convention has been adopted whereby terms containing repeated indices are summed over the three coordinate directions. For simplicity, the buoyancy effects have been ignored and the Coriolis-forces have also been neglected since they are usually negligible in the surface layer (Lumley and Panofsky, 1964).

These equations form a closed set and describe all the details of the turbulent motion. However, for turbulent flows of practical interest, these exact equations cannot be solved either analytically or numerically. The reason is that the turbulent motion contains elements or eddies which are very small compared with typical dimensions of the flow domain. To resolve the motion of these elements in a numerical scheme is beyond the capacity of present-day computers. Nevertheless, the details of the micro-scale turbulent motion need not be known and it is sufficient to solve equations for the time-averaged velocity and pressure fields and adopting a 'modelling' approach to account for the effects of microscale turbulence.
2.1.3 Time averaged continuity and momentum equations

A statistical approach must be taken (the Reynolds convention) whereby the instantaneous values of the velocity $U_i$ and the pressure $P$ are separated into mean and fluctuating values given by

$$U_i = \bar{U}_i + u_i , \quad P = \bar{P} + p$$

(2.3)

and the mean values are defined as

$$\bar{U}_i = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} U_i \, dt, \quad \bar{P} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} P \, dt$$

(2.4)

The averaging time interval $t_2 - t_1$ is taken to be long compared to the scale of the turbulent motion (typically 10 to 30 minutes for atmospheric turbulence). Substituting Eq. 2.3 into Eqs. 2.1 and 2.2 and subsequent averaging in the manner indicated by Eq. 2.4 yields the following equations describing the mean motion of a fluid of uniform density and viscosity.

**Continuity equation:**

$$\frac{\partial \bar{U}_i}{\partial x_i} = 0$$

(2.5)

**Momentum equation:**

$$\frac{\partial \bar{U}_i}{\partial t} + \bar{U}_j \frac{\partial \bar{U}_i}{\partial x_j} = - \frac{\partial u_i u_j}{\partial x_j} - \frac{1}{\rho} \frac{\partial \bar{P}}{\partial x_i} + \nu \frac{\partial^2 \bar{U}_i}{\partial x_j \partial x_j}$$

(2.6)

These are the time-averaged equations governing the mean-flow quantities $\bar{U}_i$ and $\bar{P}$ at a single point in space. The equations are exact since no assumptions have been used in deriving them, but they no longer form a closed set because the averaging process has introduced an unknown correlation between the fluctuating velocities $u_i$ and $u_j$. These terms are known as the 'Reynolds stresses', $\bar{u}_i \bar{u}_j$. When multiplied by the fluid density, $\rho$, these stresses represent the transport of momentum due to the fluctuating (i.e. turbulent) motion. The appearance of stress terms in the mean flow equations implies that whenever a solution to the mean flow is sought, the effects of turbulence must be considered. As a consequence, additional equations must be found, or assumptions made, for these stress terms in order to obtain a closed set of equations.
Physical variables such as velocity, pressure, density and other fluid properties exist only in the fluid space and not in the space occupied by the plant parts. Thus within a plant canopy, the governing equations are strictly valid only in the fluid space so that these time-averaged equations do not describe explicitly the canopy/airflow interactions. In order to include the effects of a plant canopy in the mean flow equations, a spatial average must be performed over the canopy domain in the manner indicated below.

2.1.4 The mean flow equation for canopy flow

The flow field in the plant canopy can be approximately described by taking a spatial average of the time-averaged conservation equations (Wilson and Shaw, 1977). When a horizontal average is performed over an area large enough to eliminate variations due to both interplant spacing and the largest scales of motion contributing to momentum transport, the conservation equations for mass and momentum in neutrally stratified, incompressible flow are given by

\[ \frac{\partial \bar{U}_i}{\partial x_i} = 0 \quad \text{(2.7)} \]

\[ \text{Momentum equation:} \]

\[ \frac{\partial \bar{U}_i}{\partial t} + \bar{U}_j \frac{\partial \bar{U}_i}{\partial x_j} = - \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} - \frac{1}{\rho} \frac{\partial \bar{P}}{\partial x_i} + \nu \frac{\partial^2 \bar{U}_i}{\partial x_j \partial x_j} \]

\[ \quad - \left[ \frac{1}{\rho} \frac{\partial \bar{P}}{\partial x_i} - \nu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} \right] \quad \text{(2.8)} \]

and the overbars now represent a horizontal average of the time-averaged flow variables. Extra terms which arise through this averaging procedure correspond to the form drag and skin friction at the air/solid interfaces (the terms in brackets).

A formal analysis of the spatial averaging process by Raupach and Shaw (1982) identified an additional term, known as a dispersive momentum flux, which arises from the spatial correlation of the time averaged wind field. However, dispersive fluxes are usually assumed to be negligible since detailed experiments have failed to find direct evidence of their size, even in situations where they should be
large (Raupach et al, 1986). In this case, Eq. 2.8 describes formally the interaction between a vegetative canopy and the mean flow.

For reasons of simplicity Wilson and Shaw (1977) assumed that pressure forces contributed to the major portion of the total drag of the vegetation and the average form drag was subsequently modelled using a drag coefficient expression,

\[ \frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} = \nu_2 C_d A \overline{U_i |U_i|} \] (2.9)

where \( A \) is the leaf area density (dimensions of \( m^2 \)) and \( C_d \) is the corresponding drag coefficient. The effects of viscous drag have been neglected. This parameterization has been used widely to model the effects of a plant canopy on the mean flow conditions and leads to a momentum equation expressed by

\[ \frac{\partial \overline{U_i}}{\partial t} + \overline{U_j} \frac{\partial \overline{U_i}}{\partial x_j} = -\frac{\partial \overline{u_j u_j}}{\partial x_i} - \frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} - \nu_2 C_d A |\overline{U_i |U_i|} \] (2.10)

Eq. 2.10 provides the theoretical framework for a model of mean flow in and above a plant canopy. However the Reynolds stresses represent additional unknowns in the equations set. Thus a solution to the mean flow equations is only possible if the turbulence correlations \( \overline{u_i u_j} \) can be determined in some way. In fact the determination of these correlations is the main problem in calculating turbulent flows. Two approaches can be adopted to close the set of equations. Either the stress terms can be approximated using a model which relates the unknown stresses to known mean values or an alternative approach can be taken by employing rate equations to solve for the individual stress terms. This second approach enables more complex turbulence phenomenon to be described with (hopefully) increasing realism.

2.1.5 The general stress equation

An exact transport equation for the stress terms, \( \overline{u_i u_j} \), can be derived by appropriate mathematical manipulation of the momentum equations (Busch, 1973). For neutrally stratified, incompressible flow, the single-point stress equation is written
\[
\frac{\partial u_i u_k}{\partial t} + \overline{U_j} \frac{\partial u_i u_k}{\partial x_j} = - \frac{u_i u_j}{\partial x_j} - \frac{u_j u_k}{\partial x_j} - \frac{\partial u_i u_k u_l}{\partial x_j} \\
- \frac{1}{\rho} \left[ u_k \frac{\partial p}{\partial x_i} + u_i \frac{\partial p}{\partial x_k} \right] \\
+ v \frac{\partial^2 u_i u_k}{\partial x_j \partial x_j} - 2v \frac{\partial u_i}{\partial x_j} \frac{\partial u_k}{\partial x_j}
\]

in which it is customary to identify terms representing time-rate-of-change, advection, production, turbulent transport, pressure transport, pressure strain, molecular transport and dissipation. However, like the momentum equations, the stress equations also contain turbulence correlations of the next-higher order, that is the triple velocity-correlation terms \( \overline{u_i u_j u_k} \). The equation set cannot be closed by resorting to equations which describe higher and higher moments. Instead, at some stage a 'turbulence model' must be introduced which approximates the correlations of a certain order in terms of lower order correlations and/or mean flow quantities.

Eq. 2.11 is only valid in the air space between plant elements and a spatial average must be performed within the canopy domain in order to introduce explicitly the effect of the canopy/airflow interactions in the stress equations.

2.1.6 The stress equation for canopy flow

A generalized stress budget equation for canopy flow was developed first by Wilson and Shaw (1977). The effects of the canopy appear in the stress equations once the proper spatial averaging is performed. The fluctuating pressure, \( p \), is not a continuous function across the air/solid interface, so that averaging and differentiation operations on terms involving \( p \) no longer commute. The correct expansion for the velocity-pressure fluctuation term of Eq. 2.11 is:

\[
\left[ \overline{u_k \frac{\partial p}{\partial x_i} + u_i \frac{\partial p}{\partial x_k}} \right] = \left[ \frac{\partial u_k p}{\partial x_i} + \frac{\partial u_i p}{\partial x_k} \right] - p \left( \frac{\partial u_k}{\partial x_i} + \frac{\partial u_i}{\partial x_k} \right) \\
- \left[ \overline{U_k \frac{\partial p}{\partial x_i} + U_i \frac{\partial p}{\partial x_k}} \right]
\]

The first term on the right-hand-side represents transport by the pressure correlation. This term is thought to be small and therefore omitted from the model. The second
term is known as the pressure strain term. This describes the way in which energy is redistributed amongst the components and the rate of the accompanying destruction of the tangential stresses. Both terms are quite conventional and therefore appear throughout the flow domain.

The effects of a plant canopy are described using the remaining term on the right hand side of Eq. 2.12 which involves the product of a mean wind component and a fluctuating pressure gradient or form drag. This term represents the work done by the flow against the form drag and provides a pathway describing the conversion of mean kinetic energy of the flow into turbulence kinetic energy in the wakes formed behind the plants.

2.1.7 The turbulence kinetic energy equation for canopy flow

Substituting the pressure term (Eq. 2.12) into the general stress equation (Eq. 2.11) and setting $i=k$ gives the conventional rate equation for turbulence kinetic energy in a plant canopy as:

$$
\frac{\partial k}{\partial t} + \overline{U_j} \frac{\partial k}{\partial x_j} = -u_i u_j \frac{\partial U_i}{\partial x_j} - \frac{\partial}{\partial x_j} \left[ u_j k + \frac{1}{\rho} u_j \rho \right] 
+ v \frac{\partial^2 u_i}{\partial x_j^2} + \frac{1}{\rho} \overline{U_i} \frac{\partial \rho}{\partial x_i}
$$

(2.13)

The right hand side contains four terms which represent (i) a shear production term which converts MKE to TKE, (ii) a transport term with turbulent and pressure terms, (iii) a viscous dissipation term and (iv) a 'wake production' term.

Formal analysis of the spatial averaging procedure by Raupach and Shaw (1982) identified the appearance of an additional dispersive turbulent energy flux, analogous to the dispersive momentum flux appearing in the momentum equation. Their analysis also gave rise to an alternate form for the wake production term, involving the product of local Reynolds stress and velocity-gradient perturbations. However, if all dispersive fluxes are negligible, then the two forms of the wake production term are equal (Raupach and Shaw, 1982), and Eq. 2.13 describes formally the turbulence kinetic energy budget within the canopy.
2.1.8 Dissipation of large-scale turbulence within a plant canopy

One term that is missing from the spatial averaging procedure is a mechanism to describe the additional effect of the canopy of breaking down large scale shear-generated turbulence (SKE) into smaller motions in the wakes of plants, that is into wake turbulence (WKE). This omission was recognised by both Wilson and Shaw (1977) and Raupach and Shaw (1982). Subsequent measurements by Shaw and Seginer (1985) and Raupach et al (1986) have shown the wake conversion of SKE to WKE as being an important sink for large scale turbulence.

Shaw and Seginer (1985) were the first to propose a framework for modelling canopy aerodynamics to include the way in which form drag acts on the large scale shear-turbulence. More recently, Wilson (1988) presented a 'second-order' turbulence closure model for canopy flow using a similar but simplified version of that outlined by Shaw and Seginer (1985). In both models, the turbulence kinetic energy was split into two wavebands and a pathway provided for the dissipation of low-frequency (large-scale) SKE into high-frequency (small-scale) WKE. It was suggested that such a model provides a more complete description of the canopy/airflow interaction by discriminating between turbulent motion of (two) differing scales.

Wilson (1985, 1988) developed a set of equations to describe the dissipation of SKE to WKE, by including a body force, $F$, in the instantaneous momentum equations, with components given by

$$ F_x = \nu_2 C_d A u^2, \quad F_y = \nu_2 C_d A u v, \quad F_z = \nu_2 C_d A u w $$

(2.14)

where $F_x$ refers to a body force in the x-direction, and so on for the other forces. By deriving the Reynolds averaged equations in the normal way, this approach generates extra terms in the stress equations given by

$$ \frac{\partial \overline{u^2}}{\partial t} + \ldots = -\nu_2 C_d A \left( 4 \overline{U u^2} + 2 \overline{u^3} \right) $$

(2.15a)

$$ \frac{\partial \overline{v^2}}{\partial t} + \ldots = -\nu_2 C_d A \left( 2 \overline{U v^2} + 2 \overline{u v^2} \right) $$

(2.15b)

$$ \frac{\partial \overline{w^2}}{\partial t} + \ldots = -\nu_2 C_d A \left( 2 \overline{U w^2} + 2 \overline{u w^2} \right) $$

(2.15c)

$$ \frac{\partial \overline{u w}}{\partial t} + \ldots = -\nu_2 C_d A \left( 3 \overline{U w} + \overline{U u^2} \right) $$

(2.15d)
By considering only the leading terms in brackets, the transfer of SKE to WKE was approximated (Wilson, 1988) as

$$\varepsilon_{fd} = -\frac{3}{2} C_d A \left( 2 \overline{u^2} + \overline{v^2} + \overline{w^2} \right)$$

(2.16)

These terms where then added to the individual stress equations to account for the energy transformation of SKE to WKE. In the present study we are limited to solving a budget equation for the turbulence kinetic energy, $k$, so that Eq. 2.16 has to be simplified. In anticipation of the final form of the turbulence model, the expression for $\varepsilon_{fd}$ is simplified by assuming that $\overline{u^2} = \overline{v^2} + \overline{w^2}$, and the dissipation of SKE to WKE is approximated as

$$\varepsilon_{fd} = -3 / 2 C_d A \overline{U} k$$

(2.17)

The final form for turbulence kinetic energy equation in a plant canopy is reached by adding this expression for $\varepsilon_{fd}$ to the $k$-budget equation (Eq. 2.13),

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = - u_j u_j \frac{\partial \overline{U}_i}{\partial x_j} - \frac{\partial}{\partial x_j} \left[ \overline{u_j k} + \frac{1}{\rho} \sigma_j \right] + v \frac{\partial^2 u_i}{\partial x_j^2}$$

$$+ C_d A \overline{U} \overline{U}^2 - 3 / 2 C_d A \overline{U} k$$

(2.18)

Here the wake production term has been replaced with the modelled form, by substituting for fluctuating pressure gradient using the definition of form drag (Eq. 2.9).

This form for the $k$-budget equation is unconventional. Nevertheless, essential source terms for the generation and dissipation of turbulence kinetic energy are incorporated into the equation to describe the three principle canopy/airflow interactions that occur inside a plant canopy. Combining the continuity equations for mass (Eq. 2.7) and momentum (Eq. 2.8) with the kinetic energy equation (Eq. 2.17), provides a theoretical framework necessary to predict distributions of the mean flow variables and turbulence kinetic energy in and above a plant canopy.

Such a model does not differentiate between airflow within the confines of a single plant and the airflow in the relatively open spaces between individual plants. For this reason Wilson and Shaw (1977) suggest that care should be taken in comparing calculated wind flows with experimentally measured values at a fixed point
in space. This cautionary note will be especially applicable to widely spaced tree canopies where local horizontal variability is likely to be large.

These equations can be used interpretively without the need of a closure hypothesis. However, in order to solve the equations there remains the problem of specifying the higher order moments occurring in the various budget equations. This closure problem represents the main challenge to turbulence modelling since the closure scheme employed in numerical simulations of any turbulent flow problem is decisive in controlling the success (or accuracy) of the simulation. This is well documented in the numerical study of the aerodynamics of shelterbelts by Wilson (1985). Several well known turbulence closure hypotheses are described in the following section.

2.2 TURBULENCE CLOSURE SCHEMES
2.2.1 Introduction

Time-averaging the equations of motion causes higher-order statistical correlations to appear in the flow equations. Because there is no direct way to know these terms, they must be approximated (modelled). A hierarchy of closure schemes exists by utilising algebraic or differential equations to describe higher order terms in what is collectively called a 'turbulence model' (Rodi, 1980). Such models are based on hypothesises about the turbulent process and often require empirical expressions in the form of constants and gradients of lower-order terms. A turbulence model therefore does not simulate the exact details of the turbulent motion but only the (observed) effects of turbulence on the flow behaviour. The choice of the closure scheme therefore determines the ultimate success of the numerical simulation of a turbulent flow.

Closure schemes are conveniently classified according to the order of the differential equations they utilise. An $nth$-order turbulence model solves flow equations of the $nth$-order, and closure is achieved by modelling the $(n+1)th$-order terms. So a first-order turbulence model is one in which the momentum equations are solved and closure is achieved by modelling the Reynolds stresses; a second-order turbulence model is one in which the full set of stress equations are utilized and closure is achieved by modelling third-order terms; and so on for higher order turbulence models. The $k-l$ and $k-c$ turbulence models lie somewhere between a first- and second-order model in terms of complexity. These models solve for the mean flow and the
turbulence kinetic energy, which is a subset of the stress equations. As a result, the 
k-l and k-e are referred to as being 'one-and-a-half-order' closure schemes.

Turbulence models are divided into two kinds - those that close the equation set using a turbulence or eddy viscosity (one-and-a-half-order and lower), and those that calculate Reynolds stresses directly from their own rate equations (2nd-order and higher). This study employs a computer simulation model based on eddy-viscosity closure methods. Therefore only variations of the this type of closure model will be discussed further. The concept of an eddy viscosity is presented below.

2.2.2 The eddy-viscosity concept

By analogy with the definition of molecular viscosity in a laminar flow, a turbulent or eddy viscosity, \( \nu_i \), is defined (Rodi, 1980)

\[
-u_i u_j = \nu_i \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) - \frac{\nu_a k}{8} k \delta_{ij}
\]

(2.19)

where \( \delta_{ij} \) is the kronecker delta (\( \delta_{ij} = 1 \) if \( i=j \), and 0 otherwise). In contrast to a molecular viscosity, \( \nu \) of Eq. 2.2, the eddy viscosity is not a fluid property. Rather \( \nu_i \) is a property of the flow and depends strongly on the local state of the turbulence. The formulation of Eq. 2.19 alone does not constitute a turbulence model, but it does provide a framework for constructing such a model. The main problem is now shifted to determining the distribution of \( \nu_i \).

The eddy viscosity is usually considered to be proportional to the product of a length scale (\( L_3 \)) and a velocity scale (\( V_3 \)) characteristic of the local turbulent flow. Eddy viscosity models therefore require additional information to describe these scales, and are commonly classified according to the number of additional equations they employ to solve for \( V_3 \) and \( L_3 \).

2.2.3 Zero-equation (mixing length) model of turbulence

The very simplest turbulence model is the constant eddy viscosity model which involves no more than setting \( \nu_i \) to a suitable value by specifying constant velocity and length scales. This provides a good starting point in order to ascertain convergence of the mean flow variables, but little else, and was therefore not considered appropriate for the present study.
The most popular mixing length model solves for the mean flow by employing a mixing-length hypothesis to parameterize the Reynolds stresses (Prandtl, 1925). In this case the length scale is specified by a mixing-length, \( l_m \), and the velocity scale is calculated from the product of \( l_m \) and the velocity gradient \( (dU/dz) \) which is calculated from local mean flow conditions. The modelled form of \( v_r \) is calculated using

\[ L_s = l_m, \quad V_s = l_m \left| \frac{\partial U}{\partial z} \right|, \quad v_r = l_m^2 \left| \frac{\partial U}{\partial z} \right| \]  

A mixing length model is applicable to simple boundary-layer type flows where \( l_m \) is easily prescribed empirically and the predominant mean velocity gradient does not change sign (Patankar, 1981).

This formulation for \( v_r \) is often referred to as 'K-theory' and has formed the basis for many of the early models of mean flow in and above plant canopies (Inoue, 1963; Cionco, 1965; Seginer, 1974; Kondo and Akashi, 1976). However, serious theoretical objections concerning the validity of using K-theory to describe flow within the canopy domain were raised by Corrsin (1974), Legg and Long (1975) and others, on the grounds that K-theory can only properly describe transport processes if the length scales of the motion are much smaller than the scales over which average gradients change appreciably. Experimental observations show that much of the turbulence transport to and within a canopy occurs during intermittent downsweeps of high-velocity fluid emanating from above the canopy (Raupach et al., 1986). These downsweep motions lead to counter-gradient momentum fluxes deep within plant canopies which cannot be predicted using simple K-theory (Denmead and Bradley, 1987). This inadequacy of K-theory has lead to the adoption of higher-order turbulence closure models to simulate canopy flow.

A notable exception however, is the work of Li et al (1985) who presented a mixing length turbulence model in which an additional (empirical) term was added to the streamwise momentum equation in order to model transport by downsweeps and ultimately enhance the prediction of a sub-canopy velocity maximum. Recently Li et al (1990) presented a two-dimensional simulation of flow through a forest edge using their modified mixing length closure scheme. Predictions from this simple model were in good agreement with field measurements of vertical wind profiles at a series of distances into the forest. As a consequence, the model of Li et al (1985) was
investigated in the present study for the purpose of predicting mean velocities inside a forest canopy. Relevant details from Li et al (1990) are summarised below.

2.2.4 Mixing length model of canopy flow

Formulation of the canopy flow model of Li et al (1990) involves prescribing a value for the length scale within and above the canopy, and parameterizing the downsweep transport term. The mixing length in the region outside the canopy is that suggested by Blackadar (1962)

\[ l_m = \frac{\kappa(z-d)}{1 + \frac{\kappa(z-d)}{\lambda}} \]  

(2.21)

where \( \kappa \) is the von Karman constant (\( \kappa = 0.4 \)), \( d \) is the zero plane displacement height, \( z \) is the height above the ground and the ratio \( \kappa/\lambda = 0.015 \) m\(^{-1} \) is assumed. The mixing length within the canopy is calculated by interpolation as

\[ l_m(z) = \frac{l_h z}{(1 + 0.4A)h} \]  

(2.22)

where \( A \) is the area density and \( l_h \) is the mixing length at the top of the canopy given by Eq. 2.21. The length scale within one tree height of the leading and trailing edges of the canopy is obtained by linear interpolation between \( l_m \) in the open and \( l(z) \) in the canopy. This defines the mixing length across the whole flow domain. Gradient diffusion (K-theory) is modelled using an eddy viscosity expressed as

\[ v_t = l^2 \sqrt{\left( \frac{\partial U_i}{\partial x_j} \right)^2 + \left( \frac{\partial U_j}{\partial x_i} \right)^2} \]  

(2.23)

An additional (empirical) term to describe momentum transport by downsweep motions in the plant canopy is used to parameterize the vertical momentum transport. This takes the form of a source term in the momentum equations parameterized by \( c(U_T - U) \) where \( U_T \) and \( U \) are the horizontal components of the wind speed at the top of the canopy and at a height \( z \), within the canopy, respectively. \( c \) is a transfer coefficient given the value \( [a/(1 + bA_i)](z/h) \), where \( h \) is the height of the canopy, \( A_i \) is the maximum surface area density, and \( a \) and \( b \) are constants (0.04 m s\(^{-1} \) and 0.8 m\(^2 \), respectively) as determined by Li et al (1985).
The closure scheme of Li et al (1990) is equivalent to modelling the Reynolds stress terms as

\[
\frac{\partial u_i u_j}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) + c(U_r - \bar{U}) \delta_{i1} \delta_{j3} \quad (2.24)
\]

Mean velocity is solved by substituting this expression for the stress terms directly into Eq. 2.8. The modelled form for the equation set becomes

**Mass conservation:**

\[
\frac{\partial \bar{U}_i}{\partial x_i} = 0 \quad (2.25)
\]

**Momentum equation:**

\[
\frac{\partial \bar{U}_i}{\partial t} + \bar{U}_j \frac{\partial \bar{U}_i}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial \bar{U}_j}{\partial x_i} \right) - \frac{1}{\rho} \frac{\partial \bar{P}}{\partial x_i} - \frac{\nu}{2} C_A S \frac{\partial | \bar{U}_i |}{\partial x_i} - c(U_r - \bar{U}) \delta_{i1} \delta_{j3} \quad (2.26)
\]

Form drag has been modelled using the magnitude of the wind speed, S. The boundary conditions and numerical scheme used to solve the resulting set of equations are presented in Chapter 5.

**2.2.5 One-equation (k-l) model of turbulence**

One way to avoid the use of a simple gradient-diffusion model is to close the set of flow equations at higher than first order. The simplest alternative is to solve for the turbulence kinetic energy budget using a one-and-a-half-order closure scheme. The k-l model employs an eddy-viscosity to approximate the Reynolds stresses, and utilizes one additional equation, the k-equation, to derive a velocity scale. K-theory assumptions still occur in the theory, however, since they are used to achieve closure in much the same way as for the K-l model described above.

In a k-l turbulence model, length scales, velocity scales and the eddy viscosity are formulated using the Prandtl-Kolmogorov expression:

\[
L_s = L_m, \quad V_s = k^{0.5}, \quad v_t = C_\mu k^{0.5} L_s \quad (2.27)
\]

where \( C_\mu \) is an empirical constant (\( C_\mu = 0.5478 \) in accordance with experimental data on certain flows). The velocity fluctuations are characterised by a single velocity scale.
\[ V_s = k^{0.5}, \] which is effectively an integrated measure of the intensity of the turbulent fluctuations in the three coordinate directions.

The velocity scale is obtained by employing Eq. 2.18 to solve for \( k \). Higher order terms appearing in the \( k \)-equation are the Reynolds stress term representing the production of \( k \), the triple-velocity correlation and the pressure correlation terms representing the diffusion of \( k \), and the viscous term representing the dissipation of \( k \), for which a closure hypothesis must be made.

The production term for \( k \) is formulated using an eddy-viscosity (Eq. 2.27) to describe the Reynolds stresses such that

\[ \frac{u_i u_j}{u_i u_j} \frac{\partial \bar{U}_i}{\partial x_j} = \nu \left( \frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial \bar{U}_j}{\partial x_i} \right) \frac{\partial \bar{U}_i}{\partial x_j} \] (2.28)

In analogy to the gradient-diffusion expression for the Reynolds stresses, the diffusion flux of \( k \) is assumed to be proportional to the gradient of \( k \) and is modelled as

\[ \frac{u_i k + \frac{1}{\rho} u_i p}{\frac{\partial k}{\partial x_i}} = -\frac{\nu}{\sigma_k} \frac{\partial k}{\partial x_i} \] (2.29)

where \( \sigma_k \) is an empirical diffusion coefficient known as the turbulent Prandtl number \( (\sigma_k=1.0) \). The modelled form for viscous dissipation term is

\[ \nu \left( \frac{\partial u_i}{\partial x_j} \right)^2 = C_D \frac{k^{1.5}}{L_s} \] (2.30)

where \( C_D \) is a turbulence coefficient assigned a value of 0.1643. The rate of dissipation of turbulence energy, \( \varepsilon \), is governed by large-scale motion even though the dissipation takes place at the smaller scales. Eq. 2.30 follows from dimensional arguments (Rodi, 1980), since the large scale motion is characterised by the scales \( k \) and \( L \). The modelled form of the \( k \)-equation is given by

\[ \frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \frac{\nu}{\sigma_k} \frac{\partial k}{\partial x_j} \right] + \nu \left( \frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial \bar{U}_j}{\partial x_i} \right) \frac{\partial \bar{U}_i}{\partial x_j} - C_D \frac{k^{1.5}}{L_s} \] (2.31)

This equation is not strictly applicable to low-Reynolds-number flows occurring near the boundaries of solid walls. Consequently, wall-functions are usually employed over these regions (see Chapter 5).
In the context of predicting canopy flows, a potential weakness of these models is that the length scale still has to be prescribed empirically. This is difficult for complex flows and the trend has been to use two-equation models and to determine the length scale from an additional transport equation (see section 2.2.7). Nevertheless, a $k-l$ model represents a relatively simple extension to the commonly used mixing-length models and it was therefore decided to investigate the use of this type of model in predicting canopy flows.

Recent papers by Gross (1987a, 1987b) have demonstrated the use of a $k-I$ closure model to simulate flow around single trees and the effects of deforestation on airflow in complex (forested) terrain, respectively. The predictions of flow around single trees were in reasonable agreement with wind tunnel data. A $k-l$ turbulence model was considered in this study as the simplest model to predict both mean velocity and turbulence kinetic energy inside the canopy. Details of such a model are presented below.

### 2.2.6 $k-l$ model of canopy flow

The proposed $k-l$ turbulence model for canopy flow is a simple modification to the mixing length model presented earlier in section 2.2.4. The momentum equations are treated in the conventional manner by modelling the form drag using the product of a drag coefficient, a plant-area density and a velocity-squared. In this respect the model is similar to that presented by Gross (1987a, 1987b) except for the definition of the mixing length which has been taken from Li et al (1990). However, since the source terms in the $k$-equation have been treated in an unconventional manner, the model predictions from the present study are expected to be quite different. The $k-l$ model is summarised by the following conservation equations:

**Mass conservation:**

\[
\frac{\partial \bar{U}_i}{\partial x_i} = 0 \tag{2.32}
\]
Momentum equation:

\[
\frac{\partial \bar{U}_i}{\partial t} + \bar{U}_j \frac{\partial \bar{U}_i}{\partial x_j} = - \frac{\partial}{\partial x_j} \left( \nu_t \left( \frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial \bar{U}_j}{\partial x_i} \right) \right) - \frac{1}{\rho} \frac{\partial \bar{F}}{\partial x_i}
\] (2.33)

\[-\nu_t C_d A \overline{S} |\bar{U}_i|\]

Turbulence kinetic energy equation:

\[
\frac{\partial k}{\partial t} + \bar{U}_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \nu_t \left( \frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial \bar{U}_j}{\partial x_i} \right) \right] + \nu_t \left( \frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial \bar{U}_j}{\partial x_i} \right) \frac{\partial \bar{U}_i}{\partial x_j} - C_D \frac{k^{1.5}}{L_s} \] (2.34)

\[+ C_d A \overline{U}^2 |\overline{U}| - 3/2 C_d A \overline{U} k\]

where \( \nu_t \) is given by Eq. 2.27, and the length scale \( L_s \) is that prescribed by Li et al (1985). A discussion of the boundary conditions and implementation of these equations is presented in Chapter 5.

2.2.7 Two-equation (k-\( \varepsilon \)) model

Two-equation models offer a potential advantage over the simpler one-equations models by eliminating the need to specify the turbulence length scale as a function of position throughout the flow domain. Instead the length scale is derived by solving a second differential equation for which fairly extreme approximations are usually made. The k-\( \varepsilon \) turbulence model is the most widely used of the two-equation models, and involves solving conservation equations for momentum and turbulence kinetic energy (as in the k-l model) and an additional budget equation for the dissipation of turbulence kinetic energy, \( \varepsilon \). The form of the k-\( \varepsilon \) model is presented below.

In a k-\( \varepsilon \) turbulence model, length scales, velocity scales and the eddy viscosity are modelled as:

\[
L_s = C_D \frac{k^{1.5}}{\varepsilon}, \quad V_s = C_\mu k^{0.5}, \quad \nu_t = C_\mu C_D \frac{k^2}{\varepsilon}
\] (2.35)

The values for \( C_\mu \) and \( C_D \) are exactly those used in the simpler k-l model (the product \( C_\mu C_D = 0.09 \)). Although previous investigations have suggested that \( C_\mu C_D \) should be a function of flow field quantities (Launder, 1982), modification to these 'constants'
will not be considered here. The length scale, $L$, is derived explicitly from the ratio of $k$ to $\varepsilon$.

The dissipation rate is the product of the (molecular) kinematic viscosity and the fluctuating vorticity $(\partial u/\partial x_j)^2$. An exact transport equation for the fluctuating vorticity can be derived from the Navier-Stokes equations, and hence for the dissipation rate $\varepsilon$ (Launder and Spalding, 1974). However, the exact equation contains complex correlations whose behaviour is poorly understood and for which fairly extreme assumptions must be made in order to reach a solution. Hence only the modelled form of $\varepsilon$ will be given. At high Reynolds number, the transport equation for $\varepsilon$ is usually expressed (Hanjalic, 1970):

$$\frac{\partial \varepsilon}{\partial t} + \frac{\overline{U}_j}{\overline{U}_i} \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \nu \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1\varepsilon} \frac{\varepsilon}{k} \nu_t \left( \frac{\partial \overline{U}_i}{\partial x_j} + \frac{\partial \overline{U}_j}{\partial x_i} \right) \frac{\partial \overline{U}_i}{\partial x_j} - C_{2\varepsilon} \frac{\varepsilon^2}{k}$$

2.36

Here $\sigma_\varepsilon$ is turbulent Prandtl number for the diffusion of $\varepsilon$ (assumed equal to 1.3) and $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are empirical 'constants' whose values are optimised to match the observed rates of decay of grid-generated turbulence (Launder and Spalding, 1974).

The modelled form of the $k$-equation is exactly that for the one-equation model, namely

$$\frac{\partial k}{\partial t} + \frac{\overline{U}_j}{\overline{U}_i} \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \nu \frac{\partial k}{\partial x_j} \right] + \nu_t \left( \frac{\partial \overline{U}_i}{\partial x_j} + \frac{\partial \overline{U}_j}{\partial x_i} \right) \frac{\partial \overline{U}_i}{\partial x_j} - \varepsilon$$

(2.37)

although the eddy viscosity is now defined by Eq. 2.35 and the dissipation rate is solved by its own rate equation, Eq. 2.36.

The standard $k-\varepsilon$ turbulence model involves specification of six constants which have been evaluated using experimental data on certain boundary layer flows. However, these constants have been found to have limited universality. For example, the same constants are not applicable over regions in the flow where the local Reynolds number is low, such as near walls where viscous effects become dominant. In these regions the so-called 'wall-function' approach is adopted (see Chapter 5). A standard $k-\varepsilon$ also gives highly diffusive results for bench-mark flow problems such as the turbulent flow over a backward facing step, where the reattachment point is underpredicted by as much as 30% (Kline et al., 1981).

The apparent inconsistency of the $k-\varepsilon$ model is often attributed to the dissipation rate equation which is highly empirical in nature. The model performance
can be improved by modifying the dissipation rate equation (Chen and Kim, 1987). Such modifications proved unsuccessful in the present study, possibly because they are considered to be problem dependent. Instead, the standard form of the k-ε model has been employed throughout this study, using values for the coefficients as recommended by Launder and Spalding (1972) (see list of symbols, xxii).

Yin et al (1985) compared the performance of a k-ε model in one-dimension with that of a Reynolds stress model to predict velocity profiles in corn and spruce. The predictions of the two models were similar and in agreement with experimental observations. Wilson (1985) demonstrated the use of a k-ε turbulence model in two-dimensions to simulate air flow through a porous shelter belt and obtained good agreement of the velocity deficit behind the fence and 'reasonable agreement' in the pattern of turbulent kinetic energy behind the fence. The performance of the k-ε model was found to be only marginally worse than that of a 2nd-order Reynolds-stress closure scheme.

A k-ε turbulence model in two-dimensions was investigated in the present study. However, since the sink/source terms for turbulence energy were treated in an unconventional manner the corresponding k- and ε-equations differ from those used by both Wilson (1985) and by Yin et al (1985) (in any case the models by Wilson and Yin et al were dissimilar in the way they treated the ε-equation). The set of equations I am proposing for a k-ε model of canopy flow are presented below.

### 2.2.8 k-ε model of canopy flow

Additional terms describing the sources and sinks of turbulence energy which result from the canopy/airflow interaction are added to the k-equation (Eq. 2.18). The inclusion of these extra source/sink terms for k implies that, in order to be consistent, additional terms must be added to the ε-equation. The way these extra terms are derived follows the approach taken by Richards (1989), although the final form of the ε-equation differs because of the unconventional form adopted for the k-equation. Additional source/sink terms for the ε-equation are derived by considering the modelled form of the tangential momentum stress,

\[
-\overline{u'w'} = C_u C_p \frac{k^2}{\epsilon} \left( \frac{\partial \overline{U}}{\partial z} + \frac{\partial \overline{W}}{\partial x} \right) \tag{2.38}
\]
Eq. 2.38 can be rearranged to make ε the subject and, by taking the partial differential with respect to time, one obtains an equation of the form

$$\frac{\partial \varepsilon}{\partial t} = \frac{2\varepsilon}{k} \frac{\partial k}{\partial t} - \frac{\varepsilon}{u_w} \frac{\partial u_w}{\partial t} + \ldots$$

(2.39)

Hence extra terms in the ε-equation arise naturally from the modelled form of the k-equation (Eq. 2.18) and stress equation (Eq. 2.15d). Combining the additional canopy terms with Eq. 2.39 leads to extra terms in the ε-equation of the form

$$\frac{\partial \varepsilon}{\partial t} + \ldots = \ldots C_4 e \frac{\varepsilon}{k} C_d A |\overline{U}|^2 - \frac{\varepsilon}{k} 3/2 C_d A |\overline{U}| k$$

(2.40)

These two terms describe the additional effect of the canopy on modifying ε. Initially, a multiplying coefficient $C_3 e$ was included in the second term, but it was subsequently found unnecessary and was therefore dropped. This derivation is a convenient manipulation of the ε-equation, and is therefore considered a 'gross' approximation.

As the ε-equation is already in a highly parameterized form this approximation is considered an suitable starting point. In practice, the source term for ε is optimised using an empirical coefficient ($C_d e$) which effectively controls the size of the wake production term (see Chapter 5). The full set of equations proposed for a k-ε model of canopy flow are presented below.

**Mass conservation:**

$$\frac{\partial \overline{U}_l}{\partial x_l} = 0$$

(2.41)

**Momentum equation:**

$$\frac{\partial \overline{U}_l}{\partial t} + \overline{U}_j \frac{\partial \overline{U}_l}{\partial x_j} = -\frac{\partial}{\partial x_j} \nu \left( \frac{\partial \overline{U}_l}{\partial x_j} + \frac{\partial \overline{U}_j}{\partial x_i} \right) - \frac{1}{\rho} \frac{\partial \rho}{\partial x_l}$$

$$- \nu \frac{C_d A S}{\overline{U}_l}$$

(2.42)

**Turbulence kinetic energy equation:**

$$\frac{\partial k}{\partial t} + \overline{U}_j \frac{\partial k}{\partial x_j} = \frac{\nu}{\sigma_k} \frac{\partial k}{\partial x_j} \left[ \frac{\nu}{\sigma_k} \frac{\partial k}{\partial x_j} \right] + \nu \left( \frac{\partial \overline{U}_l}{\partial x_j} + \frac{\partial \overline{U}_j}{\partial x_i} \right) \frac{\partial \overline{U}_l}{\partial x_j} - \varepsilon$$

$$+ C_d A |\overline{U}|^2 - 3/2 C_d A |\overline{U}| k$$

(2.43)
Dissipation rate equation:

\[
\frac{\partial e}{\partial t} + \overline{U_j} \frac{\partial e}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \nu e \frac{\partial e}{\partial x_j} \right] + C_{1e} \frac{e}{k} \nu \left( \frac{\partial \overline{U_i}}{\partial x_j} + \frac{\partial \overline{U_j}}{\partial x_i} \right) \frac{\partial \overline{U_i}}{\partial x_j} - C_{2e} \frac{e^2}{k}
\]

\[
+ C_{4e} \frac{e}{k} C_d A \overline{U} |\overline{U}| - \frac{e}{k} 3/2 C_d A \overline{U} k
\]

where \( \nu \) is given by Eq. 2.35. Implementation and testing of this model is presented later, in Chapter 5. The following section deals with the statistical methods employed in this study to analyze the experimental data.

2.3. STATISTICAL DESCRIPTION OF TURBULENT FLOW

2.3.1 Introduction

Turbulence behaviour is a three dimensional phenomenon that is random in both time and space. The randomness makes a deterministic description of turbulent flow difficult. Instead we are forced to retreat to the use of statistics where we are limited to average or expected measures of turbulence. A statistical approach is implicit in the Reynolds averaged equations presented above, where the turbulent fluctuations are separated from the mean flow. Experimental observations of the various averaged quantities (mean velocity, velocity variance, velocity covariance and the higher order moments appearing in the flow equations) are needed to improve our understanding of within-canopy wind flow.

However, averaging turbulence quantities tends to mask important information concerning the relative size and frequency of fluctuations in the wind. Additional information regarding typical length and time scales of the turbulence are needed to improve our understanding of turbulence structure. For example, coherent turbulence events can be identified and analyzed using conditional sampling and quadrant analysis techniques (Lu and Willmarth, 1973), and turbulence velocity spectra can be used to examine the relative contribution of short- and long-term fluctuations of the total variance in the velocity fluctuations.

This section describes some statistical methods commonly used to analyze turbulent flows. The mean components make sense only under a stationary or quasi-stationary condition. Therefore, the following discussion of the statistical properties of turbulence is limited to stationary flow, that is when the mean velocity is not a
function of the time. To satisfy this constraint, a time interval of between 5 to 30 minutes is usually adopted for the average.

2.3.2 The mean flow

In order to examine the basic features of the mean flow we introduce the Reynolds convention

\[ U_i = \bar{U}_i + u_i \quad \bar{u}_i = 0 \quad (2.45) \]

which is equivalent to partitioning the flow into a mean flow, \( \bar{U}_i \), and the fluctuating part, \( u_i \), the mean of which is identically zero. In meteorological terms the velocity components are usually shown as \( U, V, W \) (for \( i=1,2,3 \)). In normal convention, the \( U \) and \( V \) components describe mean velocity in the horizontal plane along the \( x \) and \( y \) coordinate axis respectively, and the \( W \) component lies in the vertical plane along the \( z \) coordinate axis. A one dimensional coordinate rotation is sometimes adopted to reduce \( V \), the mean cross-stream velocity component, to zero. In this case the \( x \)-axis is aligned with the direction of the mean flow.

Mean velocity is the simplest and most fundamental property of canopy flow. Profiles of mean velocity are usually formed from many observations in order to eliminate peculiarities associated with individual profiles. In this case a universal velocity profile is established by normalizing the velocity data using either the velocity at the top of the canopy, \( U_T \), or by the friction velocity, \( U_* \). Typically, the ratio of \( U/U_* \) at \( z=h \) lies somewhere between 2.5 to 5.0, depending on factors such as canopy density and the atmospheric stability. Mean wind profiles through a plant canopy are strongly sheared near the top of the canopy, with both \( U \) and \( dU/dz \) decreasing with depth into the canopy at a rate depending on the canopy density (Raupach, 1988). Lower down in the canopy the wind profile is often 'S' shaped or nearly constant with height. This phenomenon has been observed in various extensive forests, such as a Japanese larch (Allen, 1968), a pine (Landsberg and James, 1971), oak (Baldocchi and Meyers, 1988a) and spruce (Amiro and Davis, 1988) and other tree canopies such as orange (Kalma and Stanhill, 1972) and almond (Baldocchi and Hutchison, 1987).

2.3.3 Probability density distributions

The probability density distribution formally describes how fluctuating velocities, \( u_i \), are distributed about the mean, \( \bar{U}_i \). The probability that at any instant in
time a random variable, \( u(t) \), will assume a value within some defined range \( \Delta u_i \) is given by:

\[
p(u_i) = \lim_{\Delta u_i \to 0} \frac{\text{Prob}(u_i < u(t) < u_i + \Delta u_i)}{\Delta u_i}
\]  

(2.46)

Well above the surface layer, atmospheric turbulence is assumed to be a 'normal' or Gaussian process with a probability density function defined by:

\[
p(u_i) = \frac{1}{\sigma_i \sqrt{2\pi}} \exp\left(\frac{-u_i^2}{2\sigma_i^2}\right)
\]  

(2.47)

where \( u_i \) stands for \( u, v \) or \( w \). Atmospheric turbulence contains 'events' of a significantly non-Gaussian nature, particularly in the lower 30 m (ESDU, 1985), when larger gusts and longer lulls occur more frequently than indicated by the Gaussian distribution.

The turbulence velocity in and just above a plant canopy is non-Gaussian (Maitani, 1978). In general within-canopy velocity distributions are asymmetric (strongly skewed) and more peaked than those measured above the canopy (Shaw et al, 1979; Baldocchi and Meyers, 1988a). Higher-order moments associated with the velocity fluctuations reveal just how 'non-Gaussian' the flow is.

2.3.4 Velocity variance

The variance is a statistical measure of the spread of data about a mean value and is calculated using

\[
\sigma_i^2 = \frac{1}{n} \sum_{i=0}^{n} u_i^2 = \frac{u_i^2}{n}
\]  

(2.48)

where \( u_i \) is the instantaneous velocity fluctuation and \( n \) is the number of observations. This is a measure of the turbulence strength. The turbulence kinetic energy per unit mass, \( k \), is equal to the sum of the variances of the three wind components,

\[
k = \frac{1}{2} \sum_{i=1}^{3} \sigma_i^2 = \left(\frac{\sigma_u^2 + \sigma_v^2 + \sigma_w^2}{2}\right)
\]  

(2.49)

and is a measure of the energy associated with the three fluctuating wind velocities.
The standard deviation of the velocity fluctuations, equal to the square root of the variance, has the same dimensions as wind speed and is regarded as velocity scale for the turbulence.

Profiles of velocity variance are usually normalised either by \( U_T \) or the corresponding friction velocity, \( U_* \). Well above a plant canopy, the ratios \( \sigma_u/U_* \) and \( \sigma_w/U_* \) approach typical surface-layer values of 2.5 and 1.5, respectively. These ratios decrease towards the surface having values at \( z=h \) of about 2.0 and 1.1, respectively, and decreasing progressively with depth into the canopy (see Fig. 1.2).

A non-dimensional measure for intensity of the turbulent velocity fluctuations is given by

\[
I_t = \frac{\sigma_t}{\overline{U}}
\]

where \( U \) is the local mean velocity component in the streamwise direction. Cionco (1972) summarised early measurements of longitudinal turbulence intensity from observations in widely differing canopies. It was concluded that in forest canopies \( I_u \) reaches a maximum through the canopy layer, with \( I_u \) around 0.6 in temperate forests and between 0.7 to 1.2 in tropical forests. \( I_u \) decreases rapidly both downward into the trunk space and upward into the boundary layer above. The effect of increasing atmospheric stability is to suppress turbulence intensity, whereas the effect of increasing canopy density is to increase turbulence intensity. The lateral and vertical turbulence intensities, given by \( I_v \) and \( I_w \), are usually proportional to the longitudinal component, and ranked as \( I_w < I_v < I_u \) (Shaw et al., 1974).

### 2.3.5 Coefficient of skewness

An important property of canopy turbulence emerges from the third velocity moments. These moments describe the transport of turbulence energy (Maitani, 1978) and are often presented in a normalised form, using the coefficient the skewness defined as

\[
S_i = \frac{u_i^3}{\sigma_i^3}
\]

When velocity fluctuations are distributed symmetrically about the mean, skewness values equal zero. However, if there are more large positive excursions from the mean than negative excursions, the skewness value is positive, and vice versa. In a homogeneous plant canopy the signs of the skewness are predictable (Shaw and
Seginer, 1987; Raupach, 1988). The streamwise velocity is usually positively skewed ($S_u = 1.0$) because the faster moving air above the canopy occasionally 'sweeps' into the canopy while there is no equivalent ground-level source. On the other hand, the vertical velocity is usually negatively skewed ($S_w = -1.0$) because the strongest turbulent events are usually downward moving gusts, and there are normally very few large updrafts.

2.3.6 Coefficient of Kurtosis

Another important property of canopy turbulence is indicated by the relative size of the fourth order terms which are usually presented in a normalized form by the kurtosis factor, defined as

$$K_i = \frac{\mu_i^4}{\sigma_i^4} \quad (2.52)$$

Kurtosis is a measure of the peakedness or flatness of a probability density distribution and equals 3.0 for a normal or Gaussian distribution.

Horizontal and vertical kurtoses approach the Gaussian value only well above the canopy (Maitani, 1979; Raupach et al, 1986). Within-canopy kurtoses are usually much greater than 3.0. The kurtosis of the horizontal velocity components is usually between 6 to 7 at the densest part of the canopy. The vertical kurtosis has larger values, reaching values as high as 8 or 9 near the ground (Baldocchi and Meyers, 1988a). A large kurtosis value indicates the existence of extreme events at the tail ends of the distribution with probabilities exceeding Gaussian, and therefore implies turbulent events which are extreme and intermittent.

2.3.7 Correlation functions

Statistical correlation methods can be used to examine the way in which fluctuations of the three velocity components are related in time. Correlation methods can also be used to reveal the process by which momentum is transported to and within a plant canopy, and assist in identifying and describing turbulent structures.

The process of momentum transfer can be understood by considering a small parcel of air in a turbulent shear flow. When the parcel is displaced upwards it encounters a relatively faster moving airstream and tends to decrease the mean velocity and momentum at the higher level. Conversely, when a parcel of air is displaced downwards it encounters a relatively slower moving airstream and tends to
increase the mean velocity and momentum at the level. Hence, on average, updrafts ($w > 0$) are associated with decreases in velocity ($u < 0$) and downdrafts ($w < 0$) are associated with increases in velocity ($u > 0$), so that $u$ and $w$ have a negative correlation ($uw < 0$) and there is a continuous transfer of momentum from the mean flow to the turbulence through the shear layer.

2.3.8 Velocity covariances

Covariance values are a measure of the degree of common relationship between two variables. Velocity covariances for the three wind components are related to the flux of momentum, and are calculated from:

$$\bar{u_i}u_j = \frac{1}{n} \sum_{k=1}^{n} u_i u_j$$  \hspace{1cm} (2.53)

In meteorological terms, the component $\bar{uw}$ is defined as the tangential momentum stress and represents the time-averaged rate of downward diffusion of horizontal momentum (see above). The other covariance terms ($i \neq j$) are negligible when $U$ is aligned with the mean wind direction.

In an extensive, horizontally homogeneous plant canopy the vertical gradient in the momentum stress ($d\bar{uw}/dz$) is balanced by the form drag and skin friction of the canopy elements (Wilson and Shaw, 1977). Since momentum is generally absorbed most strongly in the upper part of the canopy, the momentum stress decreases rapidly with depth into the canopy. Momentum stress is nearly constant with height in the inertial sublayer above the plant canopy. Typically profiles of momentum stress are normalised by $U^2$, so that the ratio of $\bar{uw}/U^2$ at $z=h$ is 1.0 (see Fig. 1.2).

An alternative normalization of $\bar{uw}$ is defined by the linear correlation coefficient:

$$r_{ij} = \frac{u_i u_j}{\sigma_i \sigma_j}$$  \hspace{1cm} (2.54)

This ranges from -1 to 1 by definition. Two variables that are perfectly correlated (i.e. vary together) have an $r$ value of 1, two variables that are negatively correlated yield a value of -1, and two variables for which there is no net variation together yield $r$ equal to 0.
In the surface layer well above a plant canopy the correlation coefficient may be -0.3. As the surface is approached the r value becomes increasingly more negative, reaching a maximum value of about -0.45 at \( z = h \) and then decreases with depth into the canopy (Raupach, 1988).

2.3.9 The joint-probability density distribution

This property can be used to describe how the magnitudes of two fluctuating velocity components, for example \( u(t) \) and \( w(t) \), are jointly distributed in the uw plane. The joint probability that at any instant in time two random variables \( u(t) \) and \( u_j(t) \), will assume values within some defined range \( \Delta u_i \) and \( \Delta u_j \) is given by:

\[
P(U_j, U_j) = \lim_{\Delta u_i, \Delta u_j \to 0} \frac{\text{Prob}(u_i < u_i(t) < u_i + \Delta u_i, u_j < u_j(t) < u_j + \Delta u_j)}{\Delta u_i \Delta u_j}
\]

(2.55)

Typically, contours of equal joint probability for longitudinal and vertical velocity fluctuations are approximately elliptical with the major axis at a negative rotation angle from the x-axis (Shaw et al., 1989). Separation of the velocity fluctuations into a joint probability distribution forms the basis of the conditional sampling and quadrant analyses described below.

2.3.10 Conditional sampling and quadrant analysis

Conditional sampling of the longitudinal momentum stress provides a means of examining the underlying processes contributing to momentum transfer. The 'quadrant-hole analysis' technique of Willmarth and Lu (1974) identifies events in the turbulent motion which dominate momentum transfer and enables information about the turbulence structure to be deduced from single point measurements.

Conditional sampling involves determining the contribution of the instantaneous product of \( u(t) \) and \( w(t) \) to the computation of the mean momentum stress, \( \bar{uw} \). The \( u \) and \( w \) velocity fluctuations are sorted into four categories (quadrants) in the \( uw \) plane, according to the signs of the two fluctuating velocities. The four quadrants are defined and named as follows:
Quadrant 1: \( u > 0, \ w > 0; \) outward interaction,
Quadrant 2: \( u < 0, \ w > 0; \) burst or ejection,
Quadrant 3: \( u < 0, \ w < 0; \) inward interaction,
Quadrant 4: \( u > 0, \ w < 0; \) sweep or gust.

Events occurring in quadrants 2 and 4 contribute to the downward transfer of momentum and the instantaneous product \( u(t)w(t) \) is negative, whereas events defined by quadrants 1 and 3 contribute to the upward transfer of momentum and the instantaneous product \( u(t)w(t) \) is positive. This terminology follows the convention adopted by Willmarth and Lu (1974) and others. A fifth region is defined by the parameter \( H \), the hole size, which is a hyperbolic exclusion zone in the \( uw \) plane given by

\[
H = \frac{|uw|}{|\bar{uw}|}
\]  

(2.56)

These five regions are defined in Fig. 2.1. This scheme allows for the examination of different sized events occurring in each quadrant, which contribute to \( \bar{uw} \).

![Fig. 2.1. Definition of the five regions in the \( uw \) plane used in the quadrant analysis of longitudinal momentum stress.](image)

The relative importance of turbulent events of different magnitudes is obtained by considering \( u(t) \) and \( w(t) \) at a single point and defining the normalised conditional stress, \( S_{i,H} \) as

\[
S_{i,H} = \frac{1}{\sigma_u \sigma_w T} \int_0^T u(t)w(t)I_{i,H}(u,w) \, dt
\]  

(2.57)
where \( I_{ij,H} \) is an indicator function which equals 1 if \( u(t) \) and \( w(t) \) lie in the \( ith \) quadrant and \( |uw| \geq H\sigma_u\sigma_w \). Otherwise \( I_{ij,H} \) equals 0. So \( S_{i,H} \) is the stress contribution arising from events occurring in quadrant \( i \) that lie outside the region defined by \( H \). The time fraction during which the stress contribution \( S_{i,H} \) is being made is

\[
T_{i,H} = \frac{1}{T} \int_0^T I_{i,H}(u,w) \, dt
\]

(2.58)

When \( H \) equals 0, so that there is no exclusion zone, we have

\[
\sum_{i=1}^4 S_{i,H} = r_{uw^*}, \quad \sum_{i=1}^4 T_{i,H} = 1
\]

(2.59)

where \( r_{uw} \) is the correlation coefficient defined by Eq. 2.54. The normalization by \( \sigma_u\sigma_w \) was chosen in order to compare regions of different \( r_{uw} \), following Raupach et al. (1986).

The quadrant-hole analysis has established that momentum transfer close to and within plant canopies occurs mainly during gusts or sweep events. Such events are intense and intermittent and become progressively more dominant as height decreases within the canopy (Shaw and Tavangar, 1983; Raupach et al., 1986). The intermittency of momentum transfer is well demonstrated in the time traces of velocity fluctuations and momentum stress at different depths in a wheat canopy by Finnigan (1979), and in a deciduous forest canopy by Shaw et al (1989).

The vertical distribution of stress and time fractions, at hole size zero, has been observed in a deciduous forest by Baldocchi and Meyers (1988a). Within the forest canopy, magnitudes of the stress fractions were typically between 1 to 3 and the corresponding time fractions were between 20% to 30% in each quadrant. It was concluded that the momentum stress is comprised of a relatively small sum of large contributions from each of the quadrants. By analyzing the stress and time fractions at different hole sizes Baldocchi and Meyers (1988a) found that momentum transfer occurred during extreme events which accounted for a disproportionate amount of total momentum transfer. At midcanopy, 65% of the momentum transfer was accounted for in less than 10% of the time.

The same technique has been applied to heat transfer, and reveals that gusts dominate the turbulent transfer of sensible heat under near-neutral conditions above a spruce canopy (Grant et al, 1986). However, during unstable conditions updrafts
become more efficient for vertical transfer of momentum and sensible heat (Grant et al, 1986; Maitani and Ohtaki, 1987).

2.3.11 Autocorrelation function

Autocorrelations performed on single point time series are commonly used to measure length scales associated with the turbulence. This approach assumes the validity of Taylor’s hypothesis: the statistical properties of the turbulence remain frozen, so that turbulent eddies are convected on a free stream. The calculation of turbulence length scales proceeds as follows. Firstly, an auto-correlation is performed on the $u$-component and $w$-component velocity fluctuations. The correlation functions, $R_u(\tau)$ and $R_w(\tau)$ are then plotted against a time lag, $\tau$, and the area between the curve and the $\tau$ axis is estimated. This yields the integral time scale of the longitudinal and vertical gusts. The Eulerian turbulent length scales $L_{Eu}$ and $L_{Ew}$ are calculated as the product of this time scale and a velocity scale:

$$L_{Ew} = \frac{U}{\sigma_w^2} \int_0^{\tau_1} w(t)w(t+\tau) \, d\tau$$

$$L_{Eu} = \frac{U}{\sigma_u^2} \int_0^{\tau_1} u(t)u(t+\tau) \, d\tau$$

where $\tau_1$ is the time lag for the first zero crossing of $R(\tau)$.

These length scales, especially $L_{Ew}$ have been suggested as the turbulence-derived scales relevant to scalar dispersion within the canopy (Wilson et al, 1981). In general, turbulence length scales decrease with depth into the canopy and increase with height above the canopy. Near the top of the canopy $L_{Eu}$ is typically of the order of $h$ and $L_{Ew}$ is of the order of $1/3h$, so that turbulence length scales are comparable to the height of the canopy (Raupach, 1988a). Thus turbulent eddies remain coherent over streamwise and vertical distances of the order of $h$, providing evidence that simple gradient diffusion models are not well founded within the canopy (Denmead and Bradley, 1987).
2.3.12 Spectral density function

Atmospheric turbulence is comprised of a spectrum of eddies ranging in size from hundreds of meters to millimeters. The auto-correlation function provides a means of calculating a characteristic time (or length) scale for the turbulence, as shown above. Spectral analysis of the velocity fluctuations, on the other hand, provides a means of examining the contribution of different frequencies (or wave lengths) to the observed velocity variances, which are components of the turbulence kinetic energy. The spectral density, \( S_j(\omega) \) and the autocorrelation function \( R_j(\tau) \) are Fourier transform pairs defined as:

\[
S_j(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} R_j(\tau) e^{-i\omega\tau} d\tau
\]

\[
R_j(\tau) = \frac{1}{2\pi} \int_{-\infty}^{\infty} S_j(\omega) e^{-i\omega\tau} d\omega
\]

where \( S_j \) is the spectral density, \( j \) denotes a wind velocity component \( (j = 1,2,3 \text{ for velocity components } u,v,w, \text{ respectively}) \) and \( \omega \) is the wave period \( (\omega=2\pi n, \text{ where } n \text{ is the natural frequency}) \).

There are many ways of presenting turbulence spectra (Stull, 1988). Most commonly they appear as a log-log plot of \( n.S/j^2 \) versus \( n/U \). In this case, the turbulence spectra are generally hump shaped with a prominent or broad peak located at wavenumbers corresponding to the dominant scales of the turbulent eddies.

Velocity spectra in the surface layer are composed of three subranges (Panofsky and Dutton, 1984). To the left of the spectral peak is the energy containing subranges, to the right of the peak lies the inertial and dissipation subranges. Typically peak spectral densities occur at wave numbers ranging between 0.005 to 0.02 m\(^{-1}\) which are characteristic of eddies with length scales of between 200 m to 50 m. In the inertial subrange the normalized spectral density exhibits a slope of \(-2/3\).

Allen (1968) reported multiple peaks for within canopy turbulence from individual periods, and suggested these peaks were associated with eddies comparable is size to the tree spacing. Baldocchi and Hutchison (1987) suggest the occurrence of multiple peaks is more likely to be an artifact of random noise associated with the computation of the spectral estimates. Block averaging of the turbulence velocity is
usually carried out using spectra from many periods, to reduce the random noise and standard errors of individual runs.

Within a plant canopy, there is a general shift in the spectral peak towards higher frequencies, that is larger wave numbers corresponding to smaller turbulence length scales. Baldocchi and Meyers (1988b) show a peak in the region $n/U$ of the order of 0.1 to 0.2 m$^{-1}$, corresponding to wavelengths of the order 5 m to 10 m, deep within a deciduous forest canopy. In addition, the spectral density in the inertial subrange decreases at a much higher rate than $-2/3$, with slopes of between -0.78 and -1.3. This faster roll off in the inertial subrange is seen as evidence of the short-circuiting of the energy cascade as discussed by Shaw and Seginer (1985) (see section 2.1.8). Spectral slopes of $-2/3$, at wave numbers in the inertial subrange, have been demonstrated within corn (Shaw et al., 1974) and artificial canopies (Raupach et al., 1986). Differences in area density and canopy height are thought to account for the differences in spectral slopes in different plant canopies.

The above statistical methods have been employed in the present study to analyze velocity fluctuation data from extensive field and wind tunnel measurements which are described in the next two chapters. Implementation of the various turbulence models proposed in this chapter are described in Chapter 5, where the predictions are compared with corresponding experimental data from the field and wind tunnel studies.
CHAPTER 3.
FIELD STUDY OF AIR FLOW THROUGH AND ABOVE A FOREST OF WIDELY SPACED CONIFER TREES.

3.1 INTRODUCTION

The interaction between a plant canopy and the local microclimate depends amongst other factors on the structure and density of the canopy elements and the thermal stability of the atmosphere (Shaw et al., 1988). The main physical and geometrical properties of the plant canopy are the size, shape and elasticity of plants parts, and the spatial arrangement and planting density of the individual plants. The thermal stability usually changes from near-neutral or slightly unstable conditions during the daytime to stable conditions during nighttime periods. The plant/atmosphere interactions result in a strongly three-dimensional turbulent flow that is mechanically and thermally influenced by the complex geometry of the canopy array.

Relationships between air flow and the structure and density of a forest may be sought by direct observations using full-scale field measurements (Allen, 1968; Oliver, 1975; Shaw et al., 1988; Baldocchi and Meyers; 1988a), by physical modelling, for example using wind tunnel models (Kawatani and Meroney, 1970; Seginer et al., 1976; Raupach et al., 1986), or by computational modelling (Wilson and Shaw, 1977; Wilson, 1988; Meyers and Paw U, 1987). The conventional approach is often to consider the plant canopy as being extensive and horizontally homogeneous whereby, a one dimensional vertical profile of velocity statistics can be adopted to describe the turbulent air flow.

In reality, a forest canopy is never homogeneous. It is a complex structure consisting of numerous elements such as stems, branches and leaves. Unless the forest canopy is extremely dense with continuous overlapping tree crowns, there will be local variations in the foliage density which allow more wind to penetrate the canopy. This results in a turbulent flow that is spatially variable in the horizontal plane. Therefore a one dimensional description of the flow properties is only an approximation to a process that is more complex.

Preferred pathways exist for within-row and between-row wind flow regimes in vineyard crops (Weiss and Allen, 1976) and agricultural row crops (Baldocchi et al., 1983). The degree of spatial variability in turbulence statistics in extensive tree canopies has only recently been reported, and depends very much on the openness of
the tree canopy (Baldocchi and Hutchison, 1987; Amiro and Davis, 1988). For example, in a dense black-spruce forest canopy (7450 stems per ha) Amiro and Davis (1988) reported the within-canopy spatial variation of horizontal 'cup' wind speed to be 5% and the spatial variation in $\sigma_w$ to be less than 10%. In a relatively sparse almond orchard canopy (156 stems per ha) Baldocchi and Hutchison (1987b) reported subcanopy mean velocities to be slightly greater for between-row flow than for within-row flow, the other turbulence statistics being in broad agreement at two locations in the subcanopy. More information on the spatial variation of wind flow and turbulence is needed to extend our knowledge of flow in different forest canopies.

An area which has received relatively little research effort in the past concerns the characteristics of turbulent air flow in sparse or widely spaced forest canopies. We are interested in this type of forest as part of a larger scale agroforestry program initiated by the Macaulay Land Use Research Institute (MLURI), the Forestry Commission and Edinburgh University. The aim was to study the effect of trees at wide spacing on the microclimate and productivity of agroforestry systems. Agroforestry has a possible role in alleviating adverse effects of wind by providing shelter to animals and pasture. The provision of a sheltered environment represents an important management aspect in livestock production. This requires a knowledge of the influence of tree structure and density on air flow.

A field study was established to measure winds in and above three stands Sitka spruce (*Picea sitchensis* (Bong.) Carr.), planted at stocking densities of 156, 278 and 625 stems ha$^{-1}$. The purpose of this chapter is to present and examine the influence of tree spacing on the vertical variation of turbulence statistics, and the intermittency of turbulence events occurring inside a coniferous forest at wide spacing. Data are reported from extensive measurements in and above the forest canopy using arrays of three-component propeller anemometers. Details of turbulence length scales and turbulence velocity spectra, the later obtained using sonic anemometry, are reported.

### 3.2 THE FIELD SITE AT CLOICHI

The field site is located in Cloich Farm Forest (compartment 3108, Nat Grid Ref NT 20-46), 32 km south of Edinburgh. The average site elevation is 380 m. The predominant wind direction is from the westerly quarter. From a micrometeorological viewpoint the site is non-ideal since it is neither flat nor level, and surrounding topography is complex and far from homogeneous (Fig. 3.1). The experimental site
generally slopes gently to the east with a slope of between 5° and 10°, although the surrounding area is hilly and undulating. Several hills within 3 km to the west of the site have elevations greater than 450 m. A relatively flat area lies within 3 km to the east of the site at an elevation of about 300 m.

Nevertheless the site provides an ideal opportunity for a comparative study of the influence of tree density on turbulent air flow since there are three plots of even-aged trees at different spacings in sufficiently close proximity to allow simultaneous measurements of turbulent air flow to be made under similar atmospheric conditions.

### 3.2.1 Experimental plots

In 1970 the site was stocked with Sitka spruce trees (*Picea sitchensis* (Bong.) Carr.) planted on top of 2 m wide ridges at an average density of about 3000 stems per ha. The ridges were 600 mm deep and aligned in the E-W direction for drainage. In early 1986, a 2.5 ha area within the site was established as an agroforestry experiment by the MLURI, the Forestry Commission and the Edinburgh University. Three plots of widely spaced trees were created by selectively thinning part of the forest plantation to create stands at densities of 625, 278, and 156 stems per ha. Each plot was approximately rectangular in shape and 0.8 ha in size. The location and orientation of the plots is illustrated in Fig. 3.2. The remaining trees were in a square grid pattern at spacings of approximately 4 m, 6 m, and 8 m. Hereafter the 4 m, 6 m, 8 m plots will be referred to as the 'narrow', 'medium' and 'wide' plots respectively.
An adjacent unplanted area will be referred to as 'open'.

The experimental site was surrounded by unthinned plantations of Sitka spruce and Larch of the same age in all directions except to the north of the wide plot, which was separated from neighbouring forest by an open area 80 m wide running from northwest to southeast of the site, and to the west of the medium plot where there was a 20 m wide forest track running from north to south of the site. In addition the medium and wide plots shared a common N-S boundary. None of the plots were bounded by extensive open areas. Wind speeds in each plots were therefore likely to be affected in some way by the mutual sheltering of neighbouring forest. A few trees were missing in the wide and medium plots as a result of wind throw. As the missing trees were near the boundary of the plots and not directly upwind of the measurement towers their loss was not expected to have a noticeable effect on the wind measurements.

3.2.2 The tree canopy

The trees in each plot had the lowest four whorls of branches removed in 1986 to give a pruned bole length of 1.6 m, thereby creating an open trunk space. Tree heights of all trees were measured in early 1989 by the Forestry Commission and are indicated by their height distribution in Fig. 3.3a. At the beginning of the experimental study (May, 1989) mean tree heights in the wide, medium and narrow plots were 7.6 m, 7.5 m and 8.0 m, respectively.
The area density term, $A \text{ (m}^2\text{)}$, is a measure of the tree canopy density. This parameter is defined as the silhouette area of the canopy elements normal to the wind per unit canopy volume, where this volume is taken as the volume of the space apportioned to each tree. This parameter was not measured directly at the site. Instead, a vertical profile of $A$ was estimated from the optical porosity of individual trees in the following manner.

When the plantation was thinned, a total twelve trees were removed from the site and photographed. A vertical scale (2 m) was included in the foreground of each photograph so that basic measurements could be taken from the photographs. In addition various canopy measurements, including tree height, were made by MLURI, at the time of harvest. With such measurements it was possible to scale the photos to match the tree heights (and therefore the silhouette areas) during the experimental period.

A silhouette picture of each tree was produced from the photographs by tracing the canopy outline and shading-in the interior area (Fig. 3.3c). These pictures were then sectioned horizontally at 15 evenly-spaced height intervals from the base of the trunk to the top of the tree, and the area of each section measured using a Delta-T leaf area meter. The areas were then scaled-up to tree height to produce a vertical profile of silhouette area for the 'average' tree crown, assuming a similar tree shape. An
Fig. 3.3c. Typical silhouette pictures used in determining the projected frontal area of the tree crown from photographs of Sitka spruce trees.

approximate estimate of $A$ was calculated for each plot using the mean value of the crown silhouette area weighted by the respective tree-height distributions.

The estimated area densities are shown in Fig. 3.3b. These give only a rough estimate for the area density in each plot, since these estimates are based on projected frontal area of the tree crown silhouette and not the projected area of the canopy elements. Even so, these estimates are important in showing that values of $A$ are low in comparison to closely spaced forests, which are typically of the order of 1-3 m$^{-1}$.

3.3 INSTRUMENTATION

Air flow in a plant canopy is highly turbulent and three dimensional. Therefore an accurate measure of the statistical properties of the flow requires the use of special anemometry that is capable of resolving all three components of the instantaneous wind vector, and is able to respond to the principal gusts, or turbulence, in the wind. In this study two types of anemometer were used, and they are described below.

3.3.1 The Gill UVW propeller anemometer

The Gill UVW anemometer (R. M. Young Co., Michigan, U.S.A.) is a fixed array of three propeller anemometers mounted at right angles to one another. The axis of rotation of the propellers is usually arranged so that two axes are in the horizontal
plane, to sense the $U$ and $W$ components of the instantaneous velocity vector, and the third axis is in the vertical plane, to sense the $W$ component. The propellers are 22 cm diameter by 30 cm pitch (Model 08274) and have 4 blades made from light-weight polystyrene. The propeller response is designed to follow a 'cosine law', sensing only that component of the wind parallel to the propeller shaft. Each propeller drives a small d.c. tachometer generator to provide an analogue voltage directly proportional to its rotation speed and hence proportional to the wind component parallel to the propeller shaft (500 mV per 8.8 m s$^{-1}$).

The propeller anemometer is a mechanical device and therefore responds only approximately to the instantaneous wind vector. The manufacturers calibration data shows a slight deviation from the 'cosine law', and an iterative procedure is recommended to correct for this non-cosine response (Horst, 1972). The anemometer response can be improved if the vertical anemometer is tilted by $45^\circ$ towards mean wind direction (Pond, 1979). This overcomes some non-linearities associated with the $W$ sensor, such as the 'dead zone' when the propeller reverses direction, and improves significantly measurements of $\sigma_w$ and $uw$ (Pond, 1979; Bowen and Teunissen, 1986). The $U$, $V$ and $W$ components can be recovered later using a coordinate rotation.

Turbulence statistics measured with a 'tilted' Gill differ by no more than 7% when compared with data from a sonic anemometer over level terrain (Bowen and Teunissen, 1986). Similar comparisons within a forest canopy were not available, so an intercomparison of the turbulence statistics measured using a tilted Gill and the sonic anemometer was carried out (Appendix B1). The comparisons showed good agreement to within at least 7% when both anemometers were placed in the forest canopy. This confirmed the Gill UVW anemometer as a suitable instrument for the present study to measure flow within the forest canopy. Consequently, all Gill anemometers were tilted by an angle of $45^\circ$ towards the predominant wind direction.

### 3.3.2 The Kaijo-Denki sonic anemometer

A sonic anemometer is generally considered to be the ideal instrument to measure atmospheric turbulence because it requires no calibration and because it has no moving parts. This anemometer works on the doppler-shift principle, utilizing the difference in transit time of two simultaneous pulses of ultra-sound sent in opposite directions along the same path, to measure that component of the wind vector parallel to the acoustic path. The influence of temperature and humidity fluctuations, which
affect the speed of sound, are negligible on the velocity measurement (Kaimal, 1979). So the sonic anemometer is free from non-linearities, time lags and other deficiencies of the propeller anemometer.

A three component sonic anemometer (WA200, Kaijo-Denki Co., Tokyo, Japan) with a 20 cm path length and 10 Hz response time, was used on a limited number of occasions in this study. The anemometer has three non orthogonal pairs of transmitter receiver probes and incorporates a vector synthesising unit to produce an analogue output (0.1 V per m s⁻¹) proportional to the three orthogonal velocity components. The sonic anemometer and vector synthesizer were powered by a 110 V a.c. generator.

3.3.3 Deployment of Instruments

A 10 m high instrument tower was erected in each plot at a distance of approximately 120 m downwind from the western edge of the plots. The tower was positioned at the centre of a group of four trees. A second 10 m high tower was erected in the medium and wide plots. This tower was located beside the first tower, at the point midway between 2 trees and on a line approximately downwind (to the east) of a tree. In other words, the second tower was positioned approximately in the wake formed behind a tree. This tower arrangement was chosen in order to examine spatial variation in the between-row (gap) and within-row (row) measurements within the canopy.

Six propeller anemometers were used in this study, and for the majority of measurements all six anemometers were mounted in a vertical array on a single tower in one of the plots (Plate 1). The anemometers were supported on 1 m long booms which extended from the tower, in the windward direction. Each anemometer was tilted by an angle of 45° towards the predominant wind direction. Since this was usually from the west, the anemometers were orientated with the W arm tilted towards the west, and the U arm pointing towards the north. A special bracket was designed to enable the anemometer to be levelled quickly and to a reasonable accuracy (est. ±1°) using a spirit bubble level.

Two sonic anemometers were used on a limited number of occasions. These were supported on similar booms that extended 1 m from the tower, in the windward direction. The anemometer axis was levelled to within ±1° of horizontal using a spirit bubble level.
Plate 1. Tower arrangement and deployment of Gill anemometers in the medium plot at Cloich. The average tree height and spacing is 7.5 m and 6 m, respectively.

3.3.4 Data logging facilities

Velocity signals were sampled using a Campbell CR10 data logger (Campbell Scientific Ltd, Loughborough, England). A full description of the CR10 logger is found in Campbell (1988). These loggers are specially designed to monitor environmental variables and are capable of measuring, processing and storing data.
from a wide range of equipment. Because of its low current drain (0.5 mA in a quiescent state, 13 mA while processing and 35 mA during an analogue measurement) the CR10 was powered by a 12 V, 24 A hr rechargeable battery.

The analogue to digital conversions using a CR10 logger are made using a 13 bit successive approximation technique. This gives a resolution one bit in 3500 of the full scale range for a single-ended measurement. The input measurement range was software selectable using 5 voltage ranges from ±2.5 mV up to ±2.5 V. In the present study, the logger was operated on the ±2.5 V range giving a resolution of better than 0.01 m s⁻¹ for the velocity measurements.

A standard CR10 logger has 12 single-ended analogue inputs. A maximum of 4 anemometers could therefore be monitored at any one time, since each anemometer generated three velocity signals and therefore required 3 channels of the logger. However, because of the restricted speed and storage capacity of the CR10 (see below), in practice only 2 anemometers were connected to each logger.

For most of measurements, the CR10 was housed in a water proof enclosure box at the site, and left to operate in an automatic mode of collecting and processing wind speed records every 20 minutes. On a limited number of occasions when time series data were captured, the CR10 was operated in a standby mode and data was transferred via an RS232 modem directly to a portable PC (Amstrad PPC640 micro-computer).

3.3.5 Sampling strategy

A sample rate of 1 Hz was chosen for the 'online' processing of velocity records from the Gill anemometers. This sample rate was a compromise between three factors, namely (a) the storage and processing capability of the data logging equipment, (b) the response characteristics of the Gill anemometer and (c) the minimum time interval required to get reliable estimates of the turbulence statistics. Each of these factors is discussed below.

(a) The main limitation of the logging system for an online analysis of the wind data, was the restricted storage capacity and relatively slow computational speed of the CR10s. With expanded memory, the CR10 loggers had 64K of RAM but could only hold a maximum of 6862 data values in temporary storage, the remainder of the memory being allocated to output storage and program and system memory. It was essential to store the whole time series in order to process the velocity records. This
requirement meant that a maximum of 6x1144 data values could be stored at any one time. The actual length of the time series was less than 1144, because additional memory was required for the data collection and analysis.

Consequently, a time series of 6x1100 values was collected. An additional 100 storage values were used to process the velocity records, so that 98% of available memory was used during periods of data collection and processing.

The computational speed of the CR10s posed a second limitation on the logging. On average, only about 2 mathematical operations could be performed every 1 ms, but trigonometric functions took up to 10 ms to compute. Therefore it took at least 3 s to perform a simple mathematical operation on the full time series, and upwards of 30 s if trigonometric functions were required. Therefore, any complicated mathematical procedures like a 'cosine' correction to the velocity components, could have taken a very long time to compute (e.g. about 13 minutes).

In practice, it took about 0.1 s to measure 6 velocity records. This left a reasonable time between measurements in which to carry out some pre-processing of the data. The procedure to 'cosine' correct 6 velocities took about 0.7 s to execute. This was done between samples, giving a maximum through-put rate of about 1.2 Hz for 'corrected' velocities from 2 Gill anemometers. The maximum sample rate for online analysis was set to 1 Hz in order to guarantee no samples would be lost from the time series.

(b) The optimum sampling frequency is related to the spatial and temporal resolution of the sensors (Wyngaard, 1981). The Gill UVW propeller anemometer has a response time of the order of 2 s due to the inertia of the propellers, depending on such factors as velocity and wind angle. In addition, a Gill anemometer has an associated 'distance constant' of about 0.7 m due to the separation of the individual propellers. This means the anemometer is unable to resolve completely any gusts passing the sensor in less than 2 s or any gusts which have an 'eddy size' of less than 0.7 m. Information at frequencies above about 0.5 Hz is progressively filtered from the u-v-w signals. A sample rate of 1 Hz is in keeping with the Nyquist requirements needed to resolve the anemometer signals.

(c) The time scale required to observe the full spectrum of microscale turbulence can be determined from a spectral analysis wind speed fluctuations. Three distinct peaks are found in the spectrum of wind speed near the ground (Van der Hoven, 1957). These peaks show which size eddies contribute the most to the turbulence kinetic
energy. The peaks correspond to time scales of about 100 h, showing the passage of fronts and weather systems, 24 h showing the diurnal variation in wind speed, and between 10 s to 10 min corresponding to microscale turbulence motion.

A 'spectral gap' exists over time scales of between 30 minutes to several hours, centred near the one hour time period. Fluctuations over intervals longer than about 1 h are associated with changes in the mean flow, whereas wind speed fluctuations over intervals of less than an hour are associated with the microscale turbulence. An averaging time of between 10 min to 1 h duration is usually adopted to observe the full spectrum of microscale turbulence.

After consideration of the points above, the CR10 logger was programmed to collect wind speed records at a rate of 1 Hz during a time interval of 18.33 mm. Cosine corrections were applied to the 'raw' data during the time between sampling. At the end of an observation period, turbulence statistics associated with the flow were computed and the results were stored in the output memory for collection at a later date. As the data processing took about 90 s to execute, each run was programmed to occur automatically at 20 min intervals, starting on the hour. This meant the CR10 logger was in an active state of data collection and processing for about 99% of the time. A listing of the CR10 program is in Appendix C1.

The data logging and online analysis operated reliably for the duration of the field experiment and resulted in almost all of the data being recovered over a 3 month period. One weeks data was lost however, when the author accidentally stepped on one of the battery terminals - such is life.

3.4 MEASUREMENT PROCEDURE

The measurement procedure fell into two categories - online analyses and time series analyses. For the online analyses, wind speeds were measured using a vertical array of six Gill anemometers by processing the velocity data in near real-time using three CR10 data loggers. The anemometers were positioned at 6 height intervals over the range of approximately 0.25h to 1.25h. Velocity statistics of up to fourth order were calculated from the velocity fluctuation data collected at a rate of 1 Hz over a period of 18.33 min. During post-processing, observations were restricted to times when the mean wind direction was between SW and NW and, therefore, blowing approximately parallel to the tree rows.
Time series data were collected using both types of anemometer. Velocity data were measured using a vertical array of six Gill anemometers at heights of between approximately 0.25\(h\) to 1.25\(h\), mounted on a single tower in the gap position. Velocity fluctuations were measured at a rate of 5.5 Hz for 25 min periods, and stored directly to floppy disc for later analysis. In all, 15 data runs were collected in each plot between the hours of 1000 and 1600 GMT. These data were used to compute vertical profiles of turbulence length scales and as inputs for the quadrant analyses.

On a limited number of occasions, time series velocity data were collected using the sonic anemometers. In this case the sonics were mounted at two heights in the canopy, corresponding to 0.25\(h\) and 0.65\(h\). The velocity data were captured at a rate of 8 Hz over 25 min periods. These data were used to determine turbulence velocity spectra, where the slower-response propeller anemometers were inadequate.

3.4.1 Data capture, online processing and retrieval

Wind speed records were collected either as a time series of instantaneous velocity values, to be processed at a later date, or as a statistical summary. The statistical methods described in Chapter 2, were common to both sets of data. Part of the data processing was a one-dimensional coordinate rotation to the data, making \(u\) the streamwise velocity and \(v\) the lateral component (the mean of which is zero). Instantaneous velocity components were computed as:

\[
\begin{align*}
    u &= u_i \cos \theta + v_i \sin \theta, \\
    v &= v_i \cos \theta + u_i \sin \theta
\end{align*}
\]  

(3.1)

where

\[
\begin{align*}
    \cos \theta &= \bar{u_i}/(\bar{u_i}^2 + \bar{v_i}^2), \\
    \sin \theta &= \bar{v_i}/(\bar{u_i}^2 + \bar{v_i}^2)
\end{align*}
\]  

(3.2)

The subscript \(i\) denotes the initial value and the overbar represents time averaging. The vertical velocity was not rotated to zero since non-zero values inside the canopy are possible in the wakes of elements (Raupach et al., 1980), and non-zero values of \(W\) can occur above the canopy resulting from streamline deformation due to sloping terrain.

Turbulence statistics for the online analyses were stored in a sequential ring buffer in the final memory of the CR10 logger. The maximum time interval that the CR10 logger could be left to operate unattended was just over 7 days. After that time the logger memory became full causing any additional values to overwrite the
previous records. Data were retrieved from the CR10 before the end of 7 days, using an RS232 link to an Amstrad PPC640 portable computer. The communications program TERM (Campbell Scientific Ltd, England) was used to download the CR10 memory onto a 3.5" floppy disk (formatted to 720 kBytes). These data were then transferred, via the communications package KERMIT, to the ERCVAX minicomputer for plotting and archival.

Time series data were saved directly to 3.5" floppy disks using an Amstrad PPC640 portable computer and a communications program called FASTTERM (Campbell Scientific, England). This program has a combined measurement and data transfer capability of just over 100 samples per second. Since the time series data were captured at rates of 5.33 Hz (Gill anemometers) and 8 Hz (Sonic anemometers) the CR10 was not fast enough to perform any preprocessing of the data. Instead, only instantaneous velocity data were stored.

3.5 RESULTS AND DISCUSSION

The main measurement period was from mid May to mid August (summer) 1989, although the equipment was extensively tested at the forest site during the previous summer in order to become familiar with the instrumentation and to establish suitable measurement procedures. The experiment ran for 3 months because of the time involved in setting up and moving the instrumentation (single handedly) and also because of the need to have a suitable number of observations with the winds from the right direction.

The results to be presented are averages from many observations over different periods. For example, results from the time series data have been averaged using observations from fifteen 25-minute periods during daytime conditions. Results from the online analyses are averages from many more observations over 18.33-minute periods during the day and night (about 600 observations in each plot, but only about 300 had a suitable wind direction). Error bars on all figures show one standard deviation about the mean of the turbulence statistics. Where appropriate, the data have been suitably normalized in order to combine statistics over a wide range of wind speeds and atmospheric conditions.
3.5.1 Wind reductions in the trunk space

Wind shelter as a function of tree spacing was assessed by comparing mean wind speed in the forest trunk space to those winds measured at the same time in the open site. Data for the comparison were obtained in the following way. Below canopy windspeeds were measured using the lowest Gill anemometer (2 m), by processing the wind data in the standard way (section 3.4). Mean wind direction and wind speed were also recorded above the canopy.

A reference windspeed in the open site was measured using a 3-cup anemometer (Type A101M, Vector Instruments, Rhyll, Wales) mounted at a height of 2 m. This anemometer was operated as part of a standard meteorological station, and was maintained by MLURI. Mean windspeeds were calculated at 1-hour intervals using wind-run for the previous hour.

In order to compare windspeeds in the forest to those in the open site, the two data sets were synchronised by averaging the forest data over three successive observations. In addition, a correction was applied to the forest data in order to make them compatible with the open site measurements, since cup anemometers sense the total scalar windspeed \( U_s \) and not individual velocity components. The following formula was used (Meyers and Paw U, 1987)

\[
U_s = U \left(1 + \frac{\sigma_v^2 + \sigma_w^2}{2U^2}\right)
\]  

The results summarised in Table 3.1 were compiled from about three hundred 1-hour observations using a standard least squares regression (MINITAB). Mean windspeed in the forest trunk space was significantly lower than comparable windspeeds measured in the open site. When expressed as a fraction of windspeed in the open, that is by forcing the regression equation through zero, trunk space winds were 46% (wide), 29% (medium) and 16% (narrow), respectively. So large reductions in windspeed occur in the forest trunk space, at these relatively wide tree spacings. The magnitude of wind reduction increases almost linearly with decreasing tree spacing, at a rate of about 7% per m of tree spacing. This simple relation could be used to predict wind shelter near the ground as a function of tree spacing, but would only be valid for 8 m tall Sitka spruce with an open trunk space. In general, a more sophisticated model is required to predict windspeed as a function of canopy density (see Chapter 5).
A significant scatter is observed in the comparisons, which may result from stalling of the anemometers or inadequacies of the forest site. Although the comparison of forest and open wind speeds was restricted to times when the mean wind direction above the forest was from the westerly quarter (i.e. between SW and NW), it is possible that the open site was sometimes sheltered by neighbouring forest (see Fig. 3.2). This would tend to increase the scatter in the observations.

3.5.2 Relative above-canopy wind speeds

Mean wind speeds were measured simultaneously at a height of 2 m above the tree tops in each plot and at a height of 2 m above the ground surface in the open site. A comparison between the above canopy wind speed with that measured in the open site is summarised in Table 3.2. The forest data were interpolated to give mean velocity at 2 m above the tree tops, although this adjustment was only a few percent.
was 71% (wide), 68% (medium) and 61% (narrow), respectively. So the wind speed at a height of 2 m above the forest canopy was reduced in magnitude relative to wind speed at a height of 2 m above the ground in the open site.

These data suggest that a larger reduction in above-canopy wind speeds occurs above a forest of greater canopy density. This is in accord with similar wind tunnel observations conducted during this thesis work, under controlled conditions (Table 4.1). These results are also in general agreement with Gash (1986) who took simultaneous measurements of mean velocity at a height of 3.5 m above a 10 m tall Scots pine forest and a 0.25 m tall heather heath, and found the ratio $U_{\text{forest}} / U_{\text{heath}}$ was 83% when air flow was from the forest to the heath, and 64% when air flow was from the heath to the forest.

3.5.3 Vertical profiles: Preliminaries

The profiles of turbulence statistics have been constructed using data from many half-hourly observations over a three week period in each plot. The vertical profile data have been normalized in order to eliminate peculiarities of individual profiles, and in order to compare wind profiles in different plots measured at different times. $h$ and $U_*$ are the important length and velocity scales for canopy turbulence, and are therefore suitable normalizers for measurement heights and velocity statistics, respectively (Raupach, 1988a). Two velocity scales have been chosen for the present work, namely $U_*$ which is a turbulence velocity scale, and $U_T$ (the mean velocity at tree top height) which is a mean velocity scale. Both $U_*$ and $U_T$ were measured at tree top height. The effect of thermal stability on turbulence profiles was examined by partitioning the data set into daytime events (0800 to 1800 GMT) and night time events (2000 to 0600 GMT), and any data collected outside these times were subsequently ignored.

From the large number of observations taken in each plot, approximately 300 periods were chosen as being acceptable. The observations selected satisfied the following two criteria; (a) the mean wind speed above the canopy (at a height of approximately $1.25h$) exceeded 2 m s$^{-1}$, and (b) the mean wind direction was between SW and NW, giving an acceptance angle of $\pm 45^\circ$ of west. The first criterion of a threshold in wind speed was chosen to minimise the effect of anemometer stalling on the flow measurements at lower levels in the canopy. The second criterion was chosen
to maximise the limited fetch at the site, and to attempt to obtain consistent approach conditions for flow into each plot.

3.5.4 Normalized profiles of mean velocity

Vertical profiles of $U/U_T$ measured in the wide, medium and narrow plots are shown in Fig. 3.4. On the basis of these figures $U_T$ was a good normalizer for $U$ since the profiles at a single location were reduced to a universal curve. The coefficient of variation (standard deviation divided by the mean) was between 10% and 25% for individual velocity profiles within the canopy. A smaller variation in $U/U_T$ of between 2% to 5% was observed just above the canopy. This would seem to suggest that the reference wind speed, $U_T$ had only a secondary role in governing velocity profiles.

These profile data were from long time averages (20 minutes) and for periods of only modest winds ($U < 6$ m s$^{-1}$). Other studies show relatively less wind in the lower parts of the canopy during strong wind conditions. Oliver (1975) demonstrated an almost halving of relative windspeed in the trunk space region of a Scots pine forest for a four times increase in mean velocity above the canopy. While it is possible the same may have been true in these plots, no attempt was made to determine the influence of above canopy velocity on windspeed profiles within the canopy.

A significant variation in the horizontal plane was observed in the within-canopy windspeed profiles in TM and TW. Mean velocity within the canopy was higher in the gap position than in the corresponding row position. At mid-canopy ($0.5h$) the ratio of mean velocity in the gap to that measured in the row was 2.1 (wide) and 1.9 (medium). In the trunk space ($0.25h$) the same ratio was 1.2 (wide) and 1.5 (medium). So there were preferred pathways for flow, with maximum wind speeds in the gap, or channel between tree rows. The local variation in mean wind speed in the trunk space was between 20% to 50%.

Only small differences of the order of 5% were observed between day and night wind profiles when the velocities were normalized by $U_T$. Relative velocity within the canopy tended to reduce at night in the wide and medium plots, but nocturnal changes in wind profiles in the narrow plot were negligible. These nocturnal differences in windspeed profiles were small in comparison to differences resulting from local variation of mean velocity in the horizontal plane.

A much larger nocturnal change in windspeed profiles was observed when the velocity data were normalized by $U_\ast$ (Fig. 3.5). Large day/night differences were
Fig. 3.4. Spatial variation in vertical profiles of mean velocity normalized by the tree top velocity, $U_T$. Error bars are one standard deviation about the mean ($n > 100$).

Fig. 3.5. Spatial variation in vertical profiles of mean velocity normalized by the friction velocity at tree top height, $U_*$. Error bars are one standard deviation ($n > 100$).

found in the medium and wide plots. An increase in $U/U_*$ was observed above the canopy and a corresponding decrease in $U/U_*$ was observed within the canopy. Corresponding normalized windspeed profiles in the narrow plot were relatively unchanged between day and night observations. Since $U_*$ is a turbulence scale, this
observation implies that, for a given mean velocity, turbulence above the canopy is reduced at nighttime relative to daytime conditions.

A nocturnal suppression in turbulence is expected because the atmospheric boundary layer tends to be more stable at night, with the only mechanism for generating turbulence being through the wind shear that results from the surface drag. In contrast, the atmosphere during the day tends to be near-neutral or unstable and buoyancy acts to increase turbulence, which in turn increases $U_*$ for the same mean wind speed and decreases the ratio of $U/U_*$.  

A spatially-averaged windspeed profile was calculated by taking the arithmetic mean of measurements in the row and gap positions. Figs. 3.6a and 3.6b show the wind profiles for daytime and nighttime periods, respectively, and the corresponding spatially-averaged profiles of shear stress through the canopy. The distribution of mean velocity through the canopy was similar to distributions observed in other canopies, as presented in Fig. 1.1 (from Raupach, 1988a). The normalised profiles exhibited the largest decrease in velocity in the upper part of the canopy from about $1.0h$ to $0.5h$, and had a nearly constant velocity in the trunk space. Corresponding shear stress profiles decreased in magnitude with depth into the canopy as a result of momentum absorption by the canopy elements.  

Velocity gradients near the top of the canopy tended to decrease with increasing tree density, as can be seen by comparing wind profiles in Figs. 3.6a for the wide and narrow plots. The effect of decreasing tree density by a factor of 4 was a significant ($P=0.01$) increase in mean velocity within the canopy. A local maximum or nearly constant velocity was observed in the canopy trunk space. The presence of a subcanopy jet was probably due to advection through the forest edges caused by the relative openness of the trunk space and the limited fetch of the plots, but also may have been caused by slope and terrain induced effects.  

Significant ($P=0.05$) nocturnal changes of around 10% in $U/U_*$ were observed at tree top height in the wide and medium plots, but this ratio did not change significantly in the narrow plot. Values of $U/U_*$ at $z=h$ were 3.0 (wide), 3.0 (medium) and 2.6 (narrow) during the day and equalled 3.3 (wide), 3.3 (medium) and 2.7 (narrow) during the night.  

Baldocchi and Meyers (1988a) reported a much larger nocturnal shift in $U/U_*$ in a deciduous forest where the ratio of $U/U_*$ at $z=h$ increased from a daytime value of around 3.0 to a value of 12.0 during the night. However, unlike the present study
which was carried out during summer, the data from Baldocchi and Meyers (1988) were obtained in autumn and were associated with a strong temperature inversion at night. A bulk momentum transfer coefficient (equal to the aerodynamic drag coefficient of the forest surface) is defined by $C_M = (U_s/U)^2$. In a closed-stand,
coniferous forests it is usually assumed that this coefficient is approximately 0.1 (Jarvis et al., 1976). In the present study, measurements at $z=h$ give rise to a value of $C_M$ equal to 0.11 (wide), 0.11 (medium) and 0.15 (narrow) during the day and equal to 0.09 (wide), 0.09 (medium) and 0.14 (narrow) during the night. These results are in broad agreement with the commonly accepted value of 0.1, but suggest the drag coefficient is a function of tree density and is, therefore, not a simple constant for widely spaced tree canopies.

In a previous experiment at Cloich, Teklehaimanot (1990) examined the influence of tree spacing on the evaporation of water from a wetted tree canopy. Measurements of the aerodynamic resistance, $r_a = C_E U(h)$ (s m$^{-1}$), were made and these gave rise to mass transfer coefficients ($C_E$) equal to 0.04 (wide), 0.06 (medium) and 0.08 (narrow). The present study confirmed a reduction in the transfer coefficients as tree density is decreased. However, measured momentum transfer coefficients were larger than corresponding measured mass transfer coefficients (Teklehaimanot, 1990).

Decreasing tree density by a factor of four has a greater influence on drag coefficient than do nocturnal changes. This is counter to the observations of Shaw et al. (1988) above a deciduous forest where a relatively little change in drag coefficient was observed in near-neutral conditions for an almost 15 fold decrease in leaf area, whereas the calculated drag coefficient during stable conditions decreased by a factor of three or more. In the present study, we were unable to stratify observations by atmospheric stability so that differences between the present results, carried out during the summer, and those of Shaw et al. (1988) carried out during the fall, may be due to the absence of strong nocturnal inversions necessary for the formation of strongly-stable conditions.

3.5.5 Normalized profiles of turbulence velocity

Turbulence velocity is an important characteristic of the turbulent flow and is normally computed as $\sigma_i$ where $i$ stands for the $u$, $v$ and $w$ components, respectively. In order to combine measurements over a range of wind speeds and atmospheric conditions the data have been suitably normalized by both $U_T$ and $U_*$. Normalization of turbulence velocities by a turbulence scale, $U_*$, was chosen in order to compare results from the present study with those from a variety of different canopies, as presented in Fig. 1.1 (from Raupach, 1988a). Normalization of turbulence velocities by a mean velocity scale, $U_T$, was carried out in order to highlight nocturnal changes
Fig. 3.7. Spatial variation in vertical profiles of longitudinal turbulence velocity normalized by tree top velocity, $U_T$. Error bars are one standard deviation ($n > 100$).

Vertical profiles of $\sigma_u/U_T$ are well defined functions of height as shown in Fig. 3.7. Largest values of $\sigma_u/U_T$ are observed above the tree tops. A progressive decrease in $\sigma_u/U_T$ occurs with increasing depth into the canopy. In the canopy trunk space, the profiles are near uniform or show a small local maximum. The coefficient of variation in individual profiles is about 15% at levels above the canopy and increases to about 30% in the canopy trunk space. So individual profiles of $\sigma_u/U_T$ appear to be more scattered than corresponding profiles of $U/U_T$, although this is probably due to changing wind direction.

Generally, turbulence velocities at a given height within the canopy are larger in the gap position than in the row position. At mid-canopy ($0.5h$) the ratio of $\sigma_u/U_T$ in the gap to that measured in the row is about 1.5 (wide) and 1.9 (medium). In the trunk space ($0.25h$), the ratio is about 1.3 (wide) and 1.2 (medium). Above the canopy, the values in the gap and row positions are similar. The pattern of spatial variability in turbulence velocity is therefore similar to the pattern in mean velocity, reflecting the fact that there are preferred pathways for flow through widely spaced tree canopies.
Fig. 3.8. Spatial variation in vertical profiles of longitudinal turbulence velocity normalized by friction velocity, $U_*$. Error bars are one standard deviation ($n > 100$).

Normalization by $U_T$ is successful in reducing profiles of turbulence velocity to a universal curve and in highlighting significant ($P=0.05$) nocturnal differences in the forest turbulence in the wide and medium plots. Daytime values of $\sigma_u/U_T$ at tree top height are 0.45 (wide), 0.46 (medium) and 0.58 (narrow). Corresponding nighttime values of $\sigma_u/U_T$ at tree top height are 0.40 (wide), 0.38 (medium) and 0.56 (narrow). So for a given mean wind speed, turbulence velocity above the canopy is reduced by up to 15% at night, as the nocturnal boundary layer becomes more stable. Similar nocturnal changes are observed in the lateral and vertical turbulence velocity components (see Appendix A1).

Vertical profiles of $\sigma_u/U_*$ in the wide, medium and narrow plots are shown in Fig. 3.8. Whilst there are some obvious similarities between these data and the profiles of $\sigma_u/U_T$, there are also some important differences. For instance, when normalized by $U_*$ values of $\sigma_u$ above the canopy showed little nocturnal change. At tree top height, $\sigma_u/U_*$ was 1.64 (wide), 1.64 (medium) and 1.60 (narrow) during the daytime and equal to 1.62 (wide), 1.60 (medium) and 1.60 (narrow) during the night. This result suggests that $\sigma_u$ and $U_*$ above the canopy were suppressed by similar amounts at night since the ratio $\sigma_u/U_*$ remained unchanged. In contrast, values of $\sigma_u/U_*$ within the canopy were reduced by up to 25%. In the trunk space, $\sigma_u/U_*$ was 0.68 (wide),
0.50 (medium), and 0.30 (narrow) during the daytime and reduced to 0.50 (wide), 0.36 (medium) and 0.25 (narrow) during the night. So turbulence in the canopy was reduced at night compared to daytime conditions.

A spatially-averaged turbulence velocity profile was calculated by taking the arithmetic mean of measurements in the row and gap positions. Figs. 3.9a and 3.9b
show these profiles for daytime and nighttime periods, respectively. A four times
decrease in tree density lead to a significant increase in normalized turbulence velocity
within the canopy, but had surprisingly little influence above the canopy. In general
the turbulence velocities were ranked as: $\sigma_u > \sigma_v > \sigma_w$ through the depth of the
canopy.

Shaw et al (1988) reported increasing levels of turbulence within a deciduous
forest canopy following leaf fall, and attributed this to an opening up of the forest
canopy and a greater coupling with the atmospheric layers above. The distribution of
turbulence velocity through the canopy lies within the envelope of observations
compiled by Raupach (1988a) who reported values of $\sigma_u/U_*$ of between 1.6 and 2.3
at canopy top, reducing to between 0.4 and 1.0 lower down in the canopy, and
reported values of $\sigma_w/U_*$ between 1.0 to 1.2 at canopy top, reducing to between 0.1
to 0.5 lower down in the canopy, for a wide range of artificial, crop and forest
canopies.

3.5.6 Profiles of Turbulence Intensity

The influence of tree density on turbulence intensity, $I_i=\sigma_i/U$, is shown in Figs.
3.10a and 3.10b for daytime and nighttime periods, respectively. All three components
of turbulence intensity were higher in the canopy than above, and showed a steady,
progressive increase with increasing depth into the canopy, except in the trunk space
where a reduction in turbulence intensity was observed. The maximum turbulence
intensity occurred where $U$ was smallest, that is where the foliage was densest. Both
$\sigma_i$ and $U$ decreased with depth into the canopy, but values of turbulence intensity
suggest that $U$ decreased faster than $\sigma_i$ within the canopy. This is because the canopy
acts as a source for turbulence energy, but a sink for momentum.

Turbulence intensities were observed to vary spatially in the horizontal plane
(Appendix A1). The highest levels of turbulence intensity occurred in the rows,
coinciding with the wakes formed behind trees and where $U$ was reduced most. Above
the canopy, turbulence intensities were ranked as $I_u \geq I_v \geq I_w$. Within the canopy, $I_v$
is as large, or larger, than $I_u$. $I_i$ generally increased with increasing tree density at all
levels within the canopy, so that within-canopy turbulence intensity was ranked as
narrow $\geq$ medium $\geq$ wide.

The influence of a change to nocturnal conditions on turbulence intensities was
large (between 10% to 25% reduction), as illustrated by comparing Figs. 3.10a and
Fig. 3.10a. Spatially-averaged vertical distribution of turbulence intensity as a function of tree density during daytime periods ($n > 100$).

Fig. 3.10b. Spatially-averaged vertical distribution of turbulence intensity as a function of tree density during nighttime periods ($n > 100$).

3.10b. The largest nocturnal reduction occurred in the cross-stream component, $I_v$. The mean daytime value of $I_v$ at mid-canopy was 0.67, 0.86, 1.70, compared with a nighttime value of 0.57, 0.60, 1.49 in the wide, medium and narrow plots, respectively. Turbulence intensity above the canopy reduced from a daytime value of $I_v$ around 0.44 (wide), 0.42 (medium) and 0.49 (narrow) to a nighttime value of $I_v$ around 0.36...
Baldocchi and Meyers (1988) observed much larger changes in the turbulence intensity, upwards of 50%, between day and night runs within a deciduous forest canopy during late autumn.

### 3.5.7 Profiles of Tangential momentum stress

Within canopy measurements of tangential momentum stress are shown in Fig. 3.11. Normalized tangential momentum stress, $\overline{\tau_{w}}/U^2$, was relatively constant above the canopy, but was attenuated with depth into the canopy due to momentum absorption by the canopy elements. Small, positive values of $\overline{\tau_{w}}$ were observed periodically in the canopy trunk space. These probably resulted from advective edge effects due to the small size of the plots, or they may have been due to instrumental errors where we are trying to resolve very small numbers.

The local spatial variation in momentum stress is significant within the canopy. Generally, values of $\overline{\tau_{w}}$ were larger in the gap position than in the row position, which suggests momentum was absorbed more efficiently in the rows than in the gaps between trees. At mid-canopy levels ($0.65h$) the ratio of normalised momentum stress in the gap to that measured in the row was about 3.24 (wide) and 1.49 (medium).

A spatially-averaged shear stress profile calculated by taking the arithmetic mean of measurements in the row and gap positions is shown in Figs. 3.6a and 3.6b for daytime and nighttime periods, respectively. The effect of a decrease in tree density on the momentum stress within the canopy was such that values of $\overline{\tau_{w}}$ were narrow $\leq$ medium $\leq$ wide. So momentum penetrated deeper into the canopy as tree density was decreased. In contrast, the forest canopy absorbed more momentum and at progressively higher levels in the canopy, as tree density was increased.

At night time, when turbulence generation was suppressed, normalised momentum stress within the canopy was reduced below the day time values. So the momentum did not penetrate as deeply into the canopy at night. Within canopy wind speeds were also reduced at nighttime, relative to daytime conditions which confirms that less momentum penetrated the forest at night.

The absorption of momentum was strongest in the upper half of the canopy, where about 72% (wide), 86% (medium) and 92% (narrow) of the momentum was absorbed during the daytime. With the onset of stable conditions at the night, less momentum penetrated the forest canopy and the corresponding absorption of momentum in the upper half of the canopy was increased to 86% (wide), 92%
Fig. 3.11. Spatial variation in the vertical distribution of tangential momentum stress, normalized $U_z^2$ at tree top height. Error bars are one standard deviation ($n > 100$).

The level of mean momentum absorption is an estimate of the zero plane displacement (Thom, 1975). Based on this definition, the $d$-values were interpolated to be about $0.74h$ (wide), $0.80h$ (medium) and $0.85h$ (narrow) during the daytime, increasing to values of $0.89h$ (wide), $0.89h$ (medium) and $0.87h$ (narrow) at night. These values lie between the $d$-value of $0.7h$ for a widely spaced almond orchard (Baldocchi and Hutchison, 1987) and the $d$-value of $0.9h$ for a fully leafed deciduous forest (Baldocchi and Meyers, 1988a).

Shaw et al. (1988) examined the influence of canopy density and thermal stability on tangential momentum stress within a deciduous forest canopy. In near neutral conditions, they report $d$-values for a fully-leafed canopy to be $0.86h$, reducing to $0.72h$ with partial leaf fall and to $0.64h$ with almost no leaves present. A sharp reduction was observed in momentum penetration into the forest canopy, with increasing nocturnal stability. The influence of increasing thermal stability produced a similar effect on $d$ as that resulting from an almost total loss of leaves by the deciduous trees.

In the present study a reduction in $d$ was observed with increasing tree density and with the onset of nocturnal stability, although the relative reduction in momentum...
penetration at night was not large as that observed by Shaw et al (1988), presumably because the present study was carried out during summer when strongly stable conditions were less likely to have occurred.

3.5.8 Higher-order moments

Presentation of the basic wind statistics in the forest plots is rounded off with an evaluation of the higher order moments of skewness and kurtosis, which were computed during the on-line analysis phase of this study using time series data from the Gill anemometers. Skewness factors for the longitudinal, transverse and vertical velocity components in and above the forest canopy are presented in Fig.3.12.

![Skewness plots](image)

Fig. 3.12. Vertical distribution of skewness as a function of tree density. Data are spatially-averaged and include both day and night observations.
In general skewness values increased with depth into the canopy, from a value near zero above the canopy to maximum value within the canopy of the order of +1 for the horizontal component and of the order of -1 for the vertical component. The skewness factor for the transverse velocity component, $V$, assumed a value near zero throughout the depth of the canopy. These measurements quantify the corresponding shifts in location of the peak in the probability distributions presented in section 3.5.10.

The magnitude of the skewness factor is in general agreement with the results from other investigations, compiled by Raupach (1988a). In terms of the effect of tree density on skewness values, the sign of the skewness factor remains the same in all three forest stands, but the magnitude increases with increasing tree density.

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Fig. 3.13. Vertical distribution of kurtosis as a function of tree density. Data are spatially-averaged and include both day and night observations.
Values of the kurtosis factor for the longitudinal, transverse and vertical velocity components in and above the forest canopy are presented in Fig. 3.13. Above the canopy, kurtosis values for the streamwise and vertical velocity components are close 3.0, the values for the normal or Gaussian distribution. This agrees with measurements over open terrain by Raupach et al (1986). Kurtosis values for the transverse velocity component above the canopy are closer to 4.0. In general, the kurtosis values increase with depth into the canopy, with the vertical components having larger values than the corresponding horizontal component. Kurtosis values show a trend towards larger values with increasing tree density. These values confirm the peaked nature of the probability density distributions presented in section 3.5.10.

Observations of the higher order moments, as presented in Figs. 3.12 and 3.13, suggest that turbulence events become more intermittent with depth into the canopy, and with increasing canopy density. A quantitative measure of the intermittency of turbulent transport processes is gained from the quadrant analysis technique (3.5.11).

3.5.9 Probability density distribution

The probability density distributions (PDD) of vertical ($w$) and horizontal ($u$) wind speed fluctuations were computed using time series velocity data from the Gill anemometers. The velocity fluctuations were normalized by their respective standard deviations and then sorted into 23 class intervals in the range ± $5\sigma$. The wind direction was predominantly from the west in all cases.

The velocity distributions for the $u$ and $w$ velocity fluctuations in the wide, medium and narrow plots are shown in Figs. 3.14 a-c, respectively. The 'normal' or Gaussian distribution is shown by the solid line in each figure.

The general shape of the PDD's provides a qualitative measure of the distribution of winds. Peaks in the PDD's for the $u$ fluctuations are shifted to the left and peaks for the $w$ fluctuations are shifted to the right, with respect to a Gaussian distribution. The $u$ distribution is said to be positively skewed and the $w$ distribution is said to be negatively skewed. This means that relatively more large values of $u$ and relatively more downdrafts in $w$ occur in the canopy than would be predicted from a Gaussian distribution. The frequency distributions of wind velocity are non-Gaussian at levels within and just above the tree canopies. The peak of the PDD is shifted by increasing amount as depth increases into the canopy and as canopy density increases. This is agreement with the measured skewness factors reported section 3.5.9.
Fig. 3.14a. Probability density distribution of \( u \) and \( w \) velocity fluctuations in the wide plot at different heights \( z/h \). The solid line is a Gaussian distribution.

The peak height of the PDD tends to increase with depth into the canopy and to increase with increasing tree density. This means there are relatively more velocity fluctuations at the extreme ends, i.e. the tails of the distribution, than would be predicted from a Gaussian distribution. The results are in accord with the measured changes in the kurtosis factor (section 3.5.9).

All velocity distributions observed in the widely spaced spruce plantation are monomodal, positively skewed for \( u \) and negatively skewed for \( w \), and considerably more peaked than a Gaussian distribution. These observations are in general agreement with probability density distributions reported in deciduous forest (Baldocchi and Meyers, 1988a), and almond orchard (Baldocchi and Hutchison, 1987) and corn fields (Shaw et al, 1979).
The relative importance of extreme events such as large horizontal wind gusts can be examined via the frequency of occurrence above a chosen threshold, as done by Baldocchi and Hutchison (1987). Wind gusts in the trunk space ($0.25h$) exceeding two times the standard deviation of the mean ($|\mu/\sigma_u| \geq 2$) occurred about 4.6%, 5.1% and 5.0% of the time in the wide, medium and narrow plots, respectively. The same comparison above the canopy ($1.25h$) yielded values of 3.7%, 3.7% and 3.9%, respectively. So relatively more large longitudinal velocity fluctuations occur in the trunk space than occur above the canopy, and these tend to be of faster moving gusts rather than lulls in the wind speed.

The relative importance of extreme vertical wind gusts can be examined in the same manner. Vertical velocities in the trunk space exceeding two times the
Fig. 3.14c. Probability density distribution of $u$ and $w$ velocity fluctuations in the narrow plot at different heights $z/h$. The solid line is a Gaussian distribution.

normalised standard deviation of the mean ($|w/\sigma_w| \geq 2$) occurred about 4.8%, 5.4% and 5.4% of the time in the wide, medium and narrow plots, respectively. The same comparison above the canopy yielded values of 4.3%, 4.5% and 5.1%. So relatively more large vertical fluctuations occur in the trunk space than occur above the canopy, and these tend to be downdrafts.

The fractional occurrence of extreme velocity gusts reported here is similar to those reported in an almond orchard (Baldocchi and Hutchison, 1987) and a deciduous forest (Baldocchi and Meyers, 1988a). The duration of these gusts may have implications for the well being of plants and animals in an agroforestry plantation. For example, extreme wind gusts are likely to aggravate the problem of wind throw of the trees particularly at wide spacing. Wind throw was a problem at the present site
because of the shallow rooting of the trees and the poor soil type, although problem may have been worsened by the fact the trees had not originated at these wide spacings. A significant number of the trees had been blown over in the wide and medium plots, and these had to be pulled up and tethered to maintain the field site and prevent the trees falling over again.

3.5.10 Quadrant analysis

Data for the quadrant analysis comprised $u$ and $w$ time series collected at a rate of 5.5 Hz, using the vertical arrays of propeller anemometers. The results to be presented are the average from fifteen 25-minute periods collected between 1000 and 1600 GMT. Because of data logging limitations no measurements of atmospheric stability were possible. However measurements were on days when the weather was generally overcast and windy, so atmospheric stability was assumed to be near neutral.

![Graph](image)

**Fig. 3.15a.** Time and stress fractions associated with tangential momentum stress as function of hole size, $H$, at different heights, $z/h$, in the wide plot.

The contribution of turbulence events exceeding a given magnitude (hole size) to the total stress and time fractions is presented in Figs. 3.15a-c, for the wide,
medium and narrow plots respectively. The stress fraction is defined as the ratio of the tangential momentum stress resulting from events exceeding a given magnitude (the hole size) to the total tangential momentum stress and is defined by Eq. 2.56. The corresponding time fraction is the ratio of the number of events exceeding a given hole size, to the total number of turbulent events and is defined by Eq. 2.57.

Events exceeding twice the mean tangential momentum stress (normalized by $\sigma_U \sigma_W$) occurred less than about 8% of the time at all levels in the canopy. Such events accounted for a disproportionate amount of the total tangential momentum stress. For example, above the canopy events exceeding $H = 2$ occur 8.7%, 7.4% and 7.5% of the time and these events account for 46%, 46% and 45% of the total tangential momentum stress in the wide, medium and narrow plots, respectively. At mid-canopy levels, events exceeding 2 times the mean normalized tangential momentum stress occur 8.5%, 8.0% and 6.7% of the time and these events account for 58%, 58% and 79% of the total stress in the wide, medium and narrow plots, respectively.
Fig. 3.15c. Time and stress fractions associated with tangential momentum stress as function of hole size, $H$, at different heights, $z/h$, in the narrow plot.

In general the time fraction for events exceeding a particular magnitude remains relatively constant with depth into the canopy, but the corresponding stress fraction shows a significant increase. So the momentum transfer process becomes more intermittent and the events become more extreme with depth into the canopy.

Similar observations of the extreme, intermittent nature of momentum transfer within plant canopies have been made in corn (Shaw et al., 1983), an almond orchard (Baldocchi and Hutchison, 1987), a deciduous forest (Baldocchi and Meyers, 1988a) and a model canopy (Raupach et al., 1986). The magnitude of the time and stress fractions in the these reports varies due to differences canopy structure, and also because of differences in anemometry used and normalizations adopted. The present results examine the influence of leaf area on momentum transport processes and show that turbulence events become more extreme and intermittent with increasing tree density.

In a second analysis, the vertical profile of the relative contributions of events occurring in each quadrant is presented in order to examine which events dominate
momentum transfer at different heights within the canopy. The vertical variation of stress and time fractions for each quadrant at hole size zero, which includes all events, is shown in Figs. 3.16a-c. The main mechanism for momentum transfer is via downward moving sweeps which predominate at all levels in and just above the
canopy. Upward moving burst events are the second most important type of events, with relatively little momentum transfer occurring by way of interaction events, at least in the upper canopy. Sweep events are more intense and intermittent than burst events because they transfer more momentum in relatively less time. For example near midcanopy \((0.65h)\) the ratio of \(S_d/S_2\) is 1.92 (wide), 1.82 (medium) and 3.86 (narrow) and the corresponding ratio of \(T_d/T_2\) is 0.73 (wide), 0.65 (medium) and 0.51 (narrow), respectively.

Fig. 3.16c. Vertical profiles of the magnitude of stress and time fractions associated with the momentum stress in each quadrant at hole size zero, in the narrow plot.

The ratios of \(S_d/S_2\) of the present study are higher than those observed in a deciduous forest (Baldocchi and Meyers, 1988a) where factors ranged between 1.1 and 2.3. Another difference between this study and that of Baldocchi and Meyers (1988a) is in the corresponding time fractions where they report \(T_i\)'s in a narrow range of between 20% and 30%. In the present study \(T_2\) is as high as 42% near midcanopy.

In the trunk space, the momentum stress is small and sometimes positive values of \(uw\) occur. Thus interaction events (positive contributions to total momentum stress) are of increasing importance, occupying larger time fractions with depth into the canopy. This is similar to the observations of Baldocchi and Hutchison (1987) who report positive momentum stress in the trunk space of an almond orchard and attribute this observation to either a sloshing of air near the floor of the orchard canopy, or the
existence of a recirculating eddy in the wake behind a tree. It is possible the same phenomenon is occurring in the wide spaced spruce canopies of the present study.

It is worth commenting on the size of the stress fractions since this indicates the magnitude of given events. Raupach (1986) report values of the four stress fractions of a similar magnitude to those observed here, typically being less than 0.5 in their sparse model canopy. In contrast, Baldocchi and Hutchison (1987) and Baldocchi and Meyers (1988) report much larger stress fractions in an almond orchard and a deciduous forest respectively, with the four stress fraction being of the order of 1 to 3. It is difficult to compare these two observations with the present work since a different normalization scheme was used; I chose to follow Raupach et al (1986) in order to compare regions of different $\overline{uv}$. The present data here suggest, however, that turbulent events occurring in the widely spaced forest canopies are less extreme and intermittent than those occurring in closed forest stands.

3.5.11 Turbulence velocity spectra

Power spectra for the $u$, $v$ and $w$ velocity components at two heights within canopy are shown in Figs. 3.17a-c, for the wide, medium and narrow plots, respectively. The spectral densities have been multiplied by the natural frequency ($f$) and normalized by the respective variance, $\sigma^2$. The normalized spectral densities are plotted against wavenumber (m$^{-1}$) obtained by dividing frequency by the local mean wind speed, $U$. The spectra presented here are the ensemble average from fifteen 25-minute periods sampled at a rate of 8 Hz using the sonic anemometers. They have been block-averaged to provide smoothed estimates over approximately 40 frequency bands.

The spectra are all hump-shaped and exhibit a prominent or broad peak. The general shape of the normalized within-canopy velocity spectra is similar to spectral measurements within a deciduous forest (Baldocchi and Meyers, 1988b) and an almond orchard (Baldocchi and Hutchison, 1987b). Allen (1968) measured $u$-spectra in Japanese Larch and reported secondary peaks occurring at higher frequencies which he attributes to local eddies created by individual trees at wavelength equal to the spacing between trees. Recently Amiro and Davis (1988) observed secondary peaks in $w$-spectra at frequencies about an order of magnitude greater than the primary peak and attributed these to the generation of wake turbulence caused by form drag on the canopy elements. No distinctive secondary peaks were observed at higher frequencies.
in the turbulence spectra presented here. Instead, all spectra exhibited a single broad peak which generally became more pronounced with depth into the canopy.

At $z=0.75h$, peaks in the $u$-spectra occurred at wavenumbers of 0.018, 0.022 and 0.029 m$^{-1}$ in the wide, medium and narrow plots, respectively. Assuming Taylor's hypothesis that the typical wavelength of an eddy is equal to wavenumber$^1$, that is $L=Uf$, peaks in the $u$-spectra correspond to eddies which had horizontal length scales of the order of 55, 44 and 35 m in the upper canopy of the wide, medium and narrow plots, respectively. At $z=0.25h$, peaks in the $u$-spectra occurred at wavenumbers of 0.056, 0.090 and 0.115 m$^{-1}$ and corresponded to horizontal length scales of 17.8, 11.1 and 8.7 m in the wide, medium and narrow plots respectively. So a shift in the peak frequency towards larger wavenumbers, corresponding to smaller horizontal length scales, occurred with increasing tree density and with increasing depth into the canopy. Peak wavenumbers and corresponding length scales obtained from the $u$-, $v$- and $w$-spectra are tabulated in Table 3.3.
Peak wavenumbers of individual velocity spectra in the upper canopy ranked as: \( w > v > u \) whereas in the canopy trunk space they tended to rank \( w > u = v \). The \( w \)-spectra peak at higher wavenumbers than horizontal velocity spectra because vertical velocity fluctuations predominantly scale with height above the ground, whereas horizontal velocity fluctuations tend to be influenced by the height of the planetary boundary layer and the scale of the upwind topographic features (Panofsky, 1973).

Spectral peaks occurred at higher wavenumbers in the trunk space (0.25\( h \)) than in the upper canopy (0.75\( h \)). This is in agreement with wind tunnel measurements of Raupach et al (1986), who report a shift towards higher peak frequency in the \( u \)-spectrum with depth into the canopy, but runs counter to many other observations (Allen, 1968; Baldocchi and Hutchison, 1987b; Baldocchi and Meyers; 1988b) where peak frequencies in the \( u \)-spectrum shift towards lower frequencies in the trunk space. The increased relative contributions from small scale, wake-generated eddies will be
Fig. 3.17c. Normalized velocity spectra at midcanopy (0.75h) and in the trunk space (0.25h) of the narrow plot.

The greatest in the region of maximum density of plant parts. Therefore the observed shift in peak frequency with depth into the canopy most likely reflects differences in foliage distribution. For example, Baldocchi and Meyers (1988b) observed a shift towards lower wavenumbers in the trunk space of a deciduous forest where most of the leaf area was concentrated in the top 20% of the canopy. In contrast the present study showed a shift towards higher wavenumbers in the trunk space of Sitka spruce where the maximum foliage was lower down in the canopy.

At wavenumbers greater than the spectral peak, the Kolmogorov hypotheses predict the spectral densities of $u$, $v$ and $w$ to decrease with a slope of $-2/3$ into the inertial subrange (Kaimal et al, 1972). Anderson et al (1986) and Baldocchi and Meyers (1988b) present velocity spectra above deciduous forest canopies that exhibit a $-2/3$ slope in the inertial subrange. Within-canopy velocity spectra of Shaw et al (1974) and Raupach et al (1986) show a $-2/3$ spectral slope in the inertial subrange, consistent with Kolmogorov’s scaling. In the present study spectral slopes of the $u$-
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<td>0.75h</td>
<td>0.029</td>
<td>34.5</td>
<td>-0.72</td>
</tr>
<tr>
<td>TN - v</td>
<td></td>
<td>0.046</td>
<td>21.7</td>
<td>-0.61</td>
</tr>
<tr>
<td>TN - w</td>
<td></td>
<td>0.114</td>
<td>8.8</td>
<td>-0.52</td>
</tr>
<tr>
<td>TW - u</td>
<td>0.25h</td>
<td>0.056</td>
<td>17.8</td>
<td>-0.68</td>
</tr>
<tr>
<td>TW - v</td>
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<tr>
<td>TW - w</td>
<td></td>
<td>0.112</td>
<td>8.9</td>
<td>-0.47</td>
</tr>
<tr>
<td>TM - u</td>
<td>0.25h</td>
<td>0.090</td>
<td>11.1</td>
<td>-0.81</td>
</tr>
<tr>
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<td></td>
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</tr>
<tr>
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<tr>
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</tr>
<tr>
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</tr>
<tr>
<td>TN - w</td>
<td></td>
<td>0.288</td>
<td>3.5</td>
<td>-0.63</td>
</tr>
</tbody>
</table>

Table 3.3. Peak wavenumbers, corresponding turbulence length scales and spectral slopes derived from velocity spectra observed in the mid canopy and sub canopy trunk space.

spectra, at wavenumbers between about 0.05 m\(^{-1}\) and 1 m\(^{-1}\), equalled -0.66, -0.69 and -0.72 in the wide, medium and narrow plots, respectively. So the \(u\)-spectra exhibited some inertial subrange with the required -2/3 slope in the upper canopy.

In contrast, however, the slopes of the \(u\)-spectra in the trunk space equalled -0.68, -0.81 and -0.89 in the wide, medium and narrow plots, respectively. Thus the \(u\)-spectra in the trunk space of the medium and narrow plots decreased at a rate faster than that predicted by Kolmogorov hypotheses. Baldocchi and Meyers (1988b) observed spectral slopes of between -0.79 to -1.21 in a deciduous forest canopy, the largest slopes being found in the canopy crown where foliage was most dense. Similarly, Baldocchi and Hutchison (1987b) report spectral slopes of the order of -1.0 inside an almond orchard canopy.
Spectral slopes more negative than -2/3 are seen as evidence of a bypass in the normal eddy cascade of energy probably due to the plant parts breaking down the eddies, as suggested by Shaw and Seginer (1985). Baldocchi and Hutchison (1987b) suggest that differences in canopy density effect the 'short-circuiting' or not of the eddy cascade. The present results seem to confirm this hypothesis. In general the spectral slopes tended to increase with depth into the canopy and increased with increasing tree density (Table 3.3).

At wavenumbers beyond the peak in the $v$ and $w$ spectra, spectral slopes are between -1/2 and -2/3. The reason for the spectral slopes being less than -2/3 may be attributable to some high frequency aliasing in the signals which were not filtered.

3.5.112 Turbulence length scales

The vertical distribution of turbulence length scales $L_E$ and $L_E$, calculated from Eqs. 2.59 and 2.60, is shown in Fig. 3.18. Turbulence length scales were largest above the canopy and reduced with depth into the canopy. At tree top height, $L_E$ was 3.6$h$ (wide), 2.9$h$ (medium) and 1.6$h$ (narrow) and $L_E$ was 0.68$h$ (wide), 0.48$h$ (medium) and 0.28$h$ (narrow). In the trunk space (0.25$h$) $L_E$ equalled 1.4$h$ (wide), 0.39$h$ (medium) and 0.30$h$ (narrow) and $L_E$ was 0.34$h$ (wide), 0.13$h$ (medium) and 0.08$h$ (narrow). So $L_E$ was greater than $L_E$ and both were reduced with increasing depth into the canopy and with increasing tree density.

The vertical distribution of turbulence length scales was similar to measurements in other tree canopies, although the magnitude of the length scales is somewhat greater, particularly in the wide plot. For example, Allen (1968) measured $L_E$ in a Japanese larch plantation (1100 stems ha$^{-1}$) and reported a mean value of 0.6$h$ at tree top height, decreasing to a value of 0.25 $h$ in the trunk space. Following leaf fall, Allen observed a slight tendency for values to be higher with no needles present. Results from the present study in a more widely spaced canopy confirm Allen's observations of an increase in turbulence length scale with reducing leaf area density.

Comparable measurements of vertical length scales in a dense black spruce forest (7450 stems ha$^{-1}$) were made by Amiro and Davis (1988) who reported $L_E$ (their $L_S$) to be of the order of 0.3$h$ at canopy top, decreasing to 0.1$h$ in the trunk space. These values are similar to measurements from the present study in the narrow plot. However values of $L_E$ in the wide plot are a factor of 2-3 larger. The reason why larger length scales are observed in more widely spaced tree canopies is because
Fig. 3.18. Vertical profiles of Eulerian length scales for horizontal \( (L_u) \) and vertical \( (L_w) \) scales as a function of tree density.

when leaf area is reduced less form drag occurs and this results in less production of smaller scale wake turbulence.

Comparing \( L_{Eu} \) and \( L_{Ew} \) with the length scales derived from the spectral peaks, it is apparent that the Eulerian length scales are about a factor of between 2-5 smaller than the spectral derived estimates. Baldocchi and Meyers (1988b) made a similar comparison of length scales in a deciduous forest and found a factor of ten difference in the two estimates, although it should be pointed out that they used a different definition for length scales than in the present study.

3.6 SUMMARY AND CONCLUSIONS

A detailed experimental study was undertaken to examine the influence of tree density on the turbulence characteristics in a forest of widely-spaced conifer trees. Extensive measurements of turbulence statistics were made using arrays of propeller anemometers in and above Sitka spruce \( (Picea sitchensis) \), at stocking densities of 156, 278 and 625 stems per hectare. The experiments covered a four fold change in tree density and included both daytime and nighttime conditions. Turbulence length scales and velocity spectra were measured in the canopy and the technique of quadrant analysis was used to examine relative contribution from various turbulence events to
the momentum transfer process. The most significant findings of the present study are summarised as follows:

(i) Velocity fluctuations are non-gaussian and become progressively more so with increasing depth into the tree canopy and with increasing tree density. The velocity distributions are highly skewed and kurtotic and show the presence of more extreme events occurring within the canopy than occur above the canopy.

(ii) Turbulent air flow in widely spaced tree canopies is strongly three dimensional. Horizontal spatial variation in mean wind speed is of the order of 100% at levels within the canopy. Corresponding spatial variation in turbulence velocity is also of the order of 100%, with smallest values observed in the wakes behind individual trees. Therefore measurements at more than one location are required to produce profiles of turbulence statistics representative of turbulent flow in widely spaced tree canopies.

(iii) Decreasing tree density by a factor of four leads to a substantial increase in mean windspeed within the canopy. When expressed as a fraction of mean wind speed in the open, mean velocity at the same height in the forest trunk space is 46% (wide), 29% (medium) and 16% (narrow), respectively. Nevertheless, significant reductions in mean velocity in the trunk space can be achieved in a forest of widely spaced conifer trees. The reduction in trunk space velocities decreases with increasing tree density at a rate of approximately 7% per m spacing between the trees.

(iv) Significant day-to-night differences of the order of 10% to 25% are observed in the turbulence statistics. These changes reflect the influence of the thermal stability of the nocturnal boundary layer, which acts to suppress turbulence at night.

(v) Highest levels of turbulence intensity occur within the forest canopy at levels of greatest canopy density. Turbulence intensity decreases with decreasing tree density. The influence of a four times decrease in tree density on the turbulence intensity is much greater than day-to-night differences.

(vi) The tangential momentum stress is approximately constant with height above the forest canopy and decreases with depth into the canopy as momentum is absorbed by the tree canopy. Measurements of momentum stress inside the canopy illustrate the expected change in momentum penetration with increasing tree density, giving rise to daytime $d$-values of $0.74h$ (wide), $0.80h$ (medium) and $0.87h$ (narrow), respectively. Thermal stability strongly influences momentum stresses by reducing the magnitude of $\overline{uw}$ within the canopy at night, and giving rise to nighttime $d$-values of $0.89h$ (wide), $0.89h$ (medium) and $0.88h$ (narrow), respectively.
Examination of the tangential momentum stress using quadrant analysis shows the predominant events occurring within the canopy crown are sweeps and bursts, with relatively little contribution from inward and outward interactions. In the trunk space the contribution from interaction events increases. Turbulent events become more extreme and intermittent with depth into the canopy. The intermittency increases with increasing tree density. Turbulence events within a forest of widely spaced trees are less extreme than those occurring in closed stands.

Velocity spectra within the canopy are all monomodal and display prominent peaks at wavenumbers which increase with depth into the canopy and which increase with increasing tree density. Spectral slopes for $u$-spectra in the upper canopy are near $-2/3$, indicating the existence of an inertial subrange. There is a tendency for spectral slopes of the $u$-spectra to increase with depth into the canopy and to increase with increasing tree density. Slopes of $u$-spectra in the trunk space approach $-0.9$ in the medium and narrow plots suggesting a bypass of the normal eddy cascade process is occurring.

Eulerian length scales are a function of height in the canopy and a function of tree density. Horizontal length scales are greater than vertical length scales and both are reduced with depth into the tree canopy and with increasing tree density. Horizontal length scales are comparable to the height of the canopy.

The objective of this thesis is to develop and test a higher-order model of canopy flow that can be used to predict turbulent flow through and above a forest of widely spaced trees. Part of the testing involves obtaining experimental data to validate the model. The field data described in this chapter provide important experimental documentation of the turbulent properties of air flow as a function of tree spacing, and demonstrate the important influence of thermal stability on these flow properties. However, being of a one dimensional nature, the present field data do not describe all the details of the flow in which we are interested. In particular they do not address important features like the flow transition through the edge of the forest domain. It was decided to examine this aspect of the flow in more detail using a wind tunnel simulation, which is discussed in the following chapter.
CHAPTER 4.
WIND TUNNEL STUDY OF TURBULENT AIR FLOW IN A MODEL CANOPY OF WIDELY SPACED ELEMENTS

4.1 INTRODUCTION

An alternative approach to field measurements is to perform experiments in a wind tunnel using small-scale models. In order to be realistic, these wind tunnel models should produce normalized profiles of the flow variables that display characteristics similar to field observations. Thus, knowledge accumulated from full-scale measurements provides a useful check on the validity of the model-scale data. It is well recognised that the important scaling parameters for canopy flow are the height of the model, \( h \), which determines the dominant length scale, and the friction velocity, \( U_0 \), which is the dominant velocity scale (Raupach, 1988a).

Since physical models only approximate real trees, usually by matching geometric proportions, they do not simulate all the features of a full-scale canopy. Therefore some discrepancy between model and full-scale observations is to be expected. Frequently, important features such as the dynamic response of the plant elements and the buoyant contribution to turbulence generation, are omitted. Finally it must be remembered that there are serious measurement difficulties within a model canopy due to the response of anemometers which are never really free from errors.

The aim of this chapter is to present and examine the influence of canopy density on turbulent air flow through and above a model forest of widely spaced elements. Data are reported from extensive measurements taken in model forests at different canopy densities and forest sizes, using a 3-hot-wire probe to measure two-velocity components of the turbulent flow.

4.2 THE WIND TUNNEL FACILITY

This study was carried out in a low-speed, open-jet wind tunnel in the Civil Engineering Department, Edinburgh University. Fig. 4.1 shows the layout and dimensions of the tunnel. The jet opening was 1.07 m high by 1.53 m wide and the working section was 2.0 m long by 1.53 m wide. An additional section 5.0 m long was added to the outlet of the original tunnel to accommodate the model forest. The tunnel floor was roughened using Lego board which also provided anchorage points for the model trees. All measurements reported here were obtained using a free-stream
velocity of 6 m s$^{-1}$ near the roof of the tunnel.

The Civil Engineering wind tunnel is somewhat unusual in that the jet flows through a short 'enclosed' section and then onto an 'open' table. The working section length is therefore limited and it is not possible to simulate completely an equilibrium boundary layer over the height of the tunnel. However, if the requirements of other scaling laws are relaxed (see Cermak, 1971), it is possible to model a suitable mean velocity profile which is both uniform and stable over the test section.

Various methods exist to generate the requisite flow conditions in 'short' tunnels, usually by placing specially designed obstacles in the flow, at a position upwind of the working section. These 'accelerated' velocity profiles invariably result in turbulence intensities which are lower than the corresponding full-scale profiles. Since the air flow within a forest canopy is highly turbulent, any inadequacies due to the mismatch in the turbulent properties in the approach flow were thought to be of a secondary importance.

A power-law velocity profile was generated by placing a grid of variable-spaced circular rods at the upwind end of the tunnel working section. The grid was made of 12 mm diameter wooden rods spaced so that they generated a 1/6th power-law mean velocity profile (Cowdrey, 1968). The power index for flow over rural terrain lies in the range of 0.143 - 0.167 (Counihan, 1975). So a 1/6th power-law
profile was considered suitable for the purpose of modelling mean flow conditions upwind of the model forest. Counihan (1975) reports typical turbulence intensities in rural areas in the range 10% to 20% for heights of between 2 m and 30 m above ground level. The grid-generated longitudinal turbulence intensities, $\sigma_v/U$, were between 5% to 25%. So the corresponding turbulence intensities were smaller, by a factor of between 1 to 2, than would otherwise be found in a rural boundary layer.

Details of the construction of the turbulence grid and its performance in the original tunnel are presented in Morgan and Wilson (1974). However, the profile data contained in that report were not applicable to the present study, since an additional section had been added to the length of the tunnel and the floor had been roughened with Lego. Therefore, essential properties of the flow were remeasured in order to characterize the wind flow in the empty tunnel. Results of these measurements are reported in Appendix A3. Flow in the empty was considered to be approximately steady for downwind distances of between 2 m to 5 m from the turbulence grid.

4.3 INSTRUMENTATION

4.3.1. Anemometry

The wind tunnel instrumentation consisted of a hot-wire anemometer system (Disa type P01 and P51 hot-wires) and associated electronics (Disa type M01 standard bridge circuit) for measuring fluctuating velocities, and a pitot tube and micromanometer (Farnell Equipment Co., U.S.A.) for measuring mean velocities.

One improvement that was necessary for the present study was to upgrade the hot-wire anemometry in order to get high quality turbulence measurements within the model canopies where turbulence intensities up to 100% were anticipated. Horizontal and vertical components of the velocity vector were measured with a 3-hot-wire probe using the digital technique described by Kawall et al (1983). Details of the construction, calibration and operation of the 3-wire probe are in Appendix B2.

A performance test of the 3-hot-wire probe was carried out prior to taking measurements in the model forests. Results of these tests are reported in Appendix B3. The 3-wire-probe was found to be linear over the range 1 to 6 m s$^{-1}$, and to have an acceptance angle of at least ±45° to the vertical velocities. This represents an improved response to a conventional X-wire probe which has an acceptance angle of only about ±22° (Perry, 1982).
4.3.2 Analogue to digital conversion

Voltage signals from the 3-wire probe were measured using a 16 channel, 12-bit A/D card (PC30 multi-function board, Amplicon Liveline Ltd., Brighton, U.K.) connected to an IBM compatible micro-computer (DCS 286, Datalink Computer Sales Ltd., Edinburgh, U.K.). Three input channels of the A/D card were used to measure voltages from the 3-wire probe and a fourth input channel was used to measure voltage signals from the micromanometer. All unused channels were tied to ground to avoid cross-talk.

4.3.3 Signal conditioning

In order to exploit the full voltage range of the A/D (±5 V, with a resolution of 2.5 mV), voltage signals from the hot-wire and the micromanometer were amplified using specially designed active filters (A. Phillips, MLURI). This signal conditioning was necessary because voltages from the hot-wire circuits were typically between 2.5 V to 4.2 V, and voltages from the micromanometer were typically less than 10 mV for velocities of less than 6 m s⁻¹. The effective resolution of the voltage measurements was increased in the following manner.

An offset voltage of 3.5 V was added electronically to the hot-wire output and the new signal was then amplified by a factor of approximately 4 using a Butterworth filter (96 db/decade at 500Hz). The original signal was therefore amplified to lie in the range -4.0 V to 2.8 V. This is somewhat less than the full range of the A/D, in order to provide a sufficient tolerance to avoid any clipping of the signal.

The micromanometer output was amplified by a factor of 300 (linear amplifier) to produce a voltage signal in the range 0-3 V. The micromanometer had a 10 s time constant so that no filtering was required.

The gains and offsets of each amplifier were determined by passing a known voltage through the circuits, using a precision DC voltage reference (Time Electronics Ltd., Type 2003S, 0.02%), and measuring the output using the A/D. A digital sample of the original signal was recovered in software using the measured values for each amplifier.

The measurement resolution for a single hot-wire operated at a constant temperature of 250 °C was approximately 0.002 m s⁻¹ for a flow of 2 m s⁻¹, which was typical of mean velocities in the model canopies. The corresponding measurement
resolution for the pitot tube was approximately 0.01 m s\(^{-1}\) for a flow velocity of 2 m s\(^{-1}\).

4.3.4 Sampling strategy

Typical conversion times for the A/D were 35 \(\mu\)s, and the maximum total sampling rate was 6000 Hz using software written in Turbo Pascal. In practice, however, the sample rate for the 3-wire probe signals was set at 410 Hz per channel and all analyses were performed on a time series of 8192 points, collected in a 20 s period. This sampling scheme was chosen in order to collect the maximum number of velocity records. The sample rate was determined from similarity arguments, where a sample rate of 410 Hz at model scale \((h = 0.2\ m)\) corresponds to a sample rate of around 10 Hz at full scale \((h = 8\ m)\).

4.3.5 Data processing

A suite of computer programs were developed to calibrate each wire of the 3-wire probe, and to calculate the first and second order statistics associated with the \(u\) and \(w\) velocity fluctuations. Listings of these computer programs, written in Turbo Pascal, appear in Appendix. C2.

4.4 MODELLING THE FOREST CANOPY

Complete modelling of the complex geometry and structural characteristics of a live tree is not practical. However, comparison of velocity and turbulence characteristics in model canopies indicates that simulation of dimensionless drag and wake characteristics of the individual canopy elements is sufficient in order to study general flow phenomena (Meroney, 1968; Raupach et al, 1986). The model tree was chosen on an intuitive basis as possessing the right shape and porosity for a conifer tree. An attempt was also made to model the dynamic properties of a tree.

4.4.1 Geometrical properties of the model tree

The model trees were conical-shaped bottle brushes, kindly loaned to the author by Dr B. Gardiner from the Forestry Commission’s Northern Research Station, Edinburgh. The model trees had been used in a previous study of wind damage in coniferous forests by Papesch (1984). The average dimensions of a model tree are shown in Fig. 4.2. A total of 2500 model trees were available for this study. The
heights were normally distributed, with an average height of 200 mm, extremes of 150 mm and 250 mm, and a standard deviation of ±20 mm ($0.1h$).

![Diagram of model tree dimensions]

**Fig. 4.2.** Typical dimensions of the model trees.

The crown shape was based on full-scale measurements of the crowns of Sitka spruce and *Pinus radiata* growing in a typical forest, using a 1:75 scale (Papesch, 1984). The height to the crown base was made close to full-scale pruning heights of $1/3h$, and was therefore not designed to match the trees at the Cloich site.

The model stem was made from a double-twist of 1 mm wire (combined thickness approx. 2 mm), fixed to a 25 mm long base support of 3 mm OD brass tubing. A 6 mm high collar of 6 mm OD brass tube was fixed to the base of the stem in order to mount the trees onto the Lego baseboard. The crown was made from a nylon bottle brush consisting of 0.1 mm diameter filaments. The optical porosity of the canopy was estimated to be approximately 30% by scanning several silhouette photographs using a Delta-T leaf area meter.

### 4.4.2 Dynamic properties of the model tree

Papesch (1984) attempted to match the natural frequency of the model trees to that of full scale trees using similarity arguments based on the dimensionless number, $n.h/U_T$, where $n$ is the resonant frequency of the tree, $h$ is the height of the tree and $U_T$ is the corresponding velocity at tree top height. In his study of wind damage in coniferous forests, the critical tree-heights and tree-top velocities were
taken to be 15 m and 20 m s\(^{-1}\), respectively, and a natural frequency of 0.4 Hz was assumed (Mayhead, 1973). For an upstream reference velocity of 6 m s\(^{-1}\), similarity arguments led to a natural resonant frequency for the model trees of 9 Hz.

The mean natural frequency for the model trees was measured at 8.9 Hz, although the frequencies ranged between 5.3 Hz to 18.2 Hz for individual models in the height range 150 mm to 250 mm (Papesch, 1984). The model trees therefore represent full-scale tree stiffness but, because this stiffness is constant with height, they do not match the true dynamical response of full-scale trees which are stiffer near the stem base (B. Gardiner, pers. comm.).

The dynamic pressure of the wind exerts a force on the frontal area of the tree as the consequence of form drag. As a consequence, air flow is slowed down in the neighbourhood of a tree, and a turbulent wake is generated in the lee. It is therefore important to model correctly the form drag and wake characteristics of real trees. These two aerodynamic properties were examined for the model tree to see just how well they matched the observed properties for real trees. The results are reported below.

4.4.3 Drag coefficient of the model tree

Form drag is defined as the force per unit cross sectional area normal to the flow. The single element drag coefficient, \( C_d \), relates the actual drag to the maximum potential drag that could be exerted by the flow, and is defined using

\[
F_x = \frac{1}{2} \rho C_d A_s U^2
\]  

(4.1)

where \( F_x \) is the drag force on the tree in the direction of the flow, \( U \) is the flow velocity, \( A_s \) is the silhouette area normal to the flow, and \( \rho \) is the air density.

Measurements of \( C_d \) were made in a wind tunnel at the Physics Department, Edinburgh University. A model tree was placed in a laminar flow (\( \text{I}_v=0.1\% \)) for velocities in the range 2 m s\(^{-1}\) to 15 m s\(^{-1}\). \( F_x \) was measured using a multi-component force balance table, and \( U \) was measured using a pitot tube placed upwind of the model. Details of the force balance system and the Physics wind tunnel are described in Drabble (1989).

The force balance was set to a maximum range of 10 N giving a sensitivity of 1 \( \mu \)N, or a voltage of 1 \( \mu \)V. Voltages from the balance were measured using a
Campbell CR21X data logger (Campbell Scientific (U.K.) Ltd., Loughborough, U.K.), at the 0.02 mV resolution. Because the silhouette area of the model was only about $2.6 \times 10^3 \text{ m}^2$, the corresponding drag forces were small (about 6 mN at a velocity of 2 m s$^{-1}$), and comparable to the observed drift in the force balance (about 8 mN per minute).

A procedure was developed to remove the drift in the balance. This procedure was based on a time series of $F_x$ derived using mean values integrated at 15 s intervals, for a period of about 15 minutes. Commencing from zero flow, the tunnel was accelerated up to a steady velocity, $U$ was held constant about 5 minutes, thereafter the tunnel speed was reduced to zero. A linear regression using 'zero flow' data at the beginning and end of the time series, was used to remove the drift in the balance, and the drag force was then obtained during the 'steady flow' when $F_x$ reached a constant value. This procedure was least accurate at low velocities when the forces became relatively small.

![Fig. 4.3. Drag coefficient ($C_d$) of a model tree for a range of velocities ($U$).](image)

$C_d$ of the model tree over the velocity range 2 m s$^{-1}$ to 15 m s$^{-1}$ is shown in Fig. 4.3. The drag coefficient was only weakly dependent on Reynolds number ($\approx 10^5$) over this velocity range, with an average value of 0.96. The drag coefficient of Sitka spruce trees lies in the range 0.8 to 0.4 for wind speeds from 9 m s$^{-1}$ to 25 m s$^{-1}$ (Mayhead, 1973) and values of $C_d$ of up to 1.2 have been reported for Colorado
spruce trees (Raynor, 1962). So the drag coefficient of the model tree appears acceptable.

![Fig. 4.4. Velocity defect in the wake of a model tree. $x$ and $y$ are the streamwise and cross-stream distances, normalized by tree diameter, $d$. Free stream velocity is 4 m s$^{-1}$.](image)

![Fig. 4.5. Turbulence velocity, $\sigma_U$, in the wake of a model tree. $x$ and $y$ are the streamwise and cross-stream distances, normalized by tree diameter. Free stream turbulence is 0.2 m$^2$s$^{-1}$.](image)

4.4.4 Wake characteristics of the model tree

The wake characteristics of a model tree were examined in the Civil Engineering wind tunnel using a single hot-wire probe to measure $U$ and $\sigma_U$ in the wake of the tree. Figs. 4.4 and 4.5 show the wake characteristics measured in the
horizontal plane at midcanopy level behind a model tree.

These results are in qualitative agreement with measurements behind small specimens of Colorado spruce by Hsi and Nath (1968, as reported by Meroney, 1968) who observed a linear wake growth behind the trees and a near Gaussian velocity defect within 3-4 crown diameters. The wake characteristics of the model tree therefore appear acceptable.

The results from the dynamic and aerodynamic tests suggest that the model is a reasonable representation of a full-scale conifer tree.

4.4.5 Construction of the model forest

A model forest was constructed by mounting a large number of model trees (between 200 to 1600) onto Lego baseboard in a square-grid pattern to form a canopy of $10h$ and $20h$ in the downwind dimension. The model spanned the width of the tunnel in the cross stream direction. For most of the measurements, the elements were orientated with the diagonal of the square-grid parallel to the mean flow direction (Fig. 4.6), but for one study where the tree rows were parallel to the mean flow (Plate 2).

Plate 2. End view of wind tunnel and model R3. The model size is $10h$.

A four-fold change in element density was achieved by fixing model trees at spacings of approximately $1/3h$, $1/2h$ and $2/3h$ between element centres. These
spacings were convenient because they coincided with the stud spacing on the lego baseboard, and they were practical because they matched approximately a scaled area density of the Cloich agroforestry site (see below).

The vertical distribution in area density (defined as the element silhouette area per unit canopy volume) is given in Appendix. C3 (see Group 11 of the Q1 file). At an element spacing of $1/3h$, the maximum value of $A$ was estimated to be $7.3 \text{ m}^4$. Scaling the model elements to a height of 8 m (1:40) gives a corresponding maximum value of $A$ equal to about 0.18. This is similar to the maximum value of about 0.15 in the narrow plot at Cloich, estimated in the same manner.

Therefore it should be possible to generate suitably normalized velocity profiles in the model canopy that are similar to those measured at Cloich. Differences between model and full-scale observations are expected however, because the real trees are less regular in shape and spacing and the forest trunk space is less open than in the model canopies.

4.5 MEASUREMENT PROCEDURE

The flow field through a model forest was mapped by traversing a 3-wire probe in vertical and horizontal increments at points within and above the model forest. The probe position was adjusted manually in a vertical plane near the centre line of the wind tunnel. All measurements were taken at a distance of between 2 to 5 m downwind from the turbulence grid, and over the height interval of between 0.01 to 0.5 m above the tunnel floor.

Because the model was larger than the working section of the tunnel, it had to be moved in stages along the tunnel floor in order to take measurements near the leading and trailing edges of the model. For most of the measurements, the front of the forest was positioned at least 2 m downwind from the turbulence grid. The exception was for measurements near the back end of the 20$h$ model and in the lee of the 10$h$ model. In this case the forest was positioned at a distance of only 1 m downwind from the turbulence grid.

Measurements were taken 13 streamwise locations over the horizontal range $x$ equals $-5h$ to $19h$, using horizontal increments of $2h$. At each $x$-location, a vertical profile of first and second-order turbulence statistics was formed from measurements at 17 non-uniform height intervals over the vertical range $z$ equals $0.05h$ to $2.5h$. The measurement heights were as follows. The lowest measurement was at a height of
0.05h, 12 measurements were taken between 0.125h to 1.5h at intervals of 0.125h, and 4 measurements were taken between 1.75h to 2.5h at intervals of 0.25h.

Three vertical profiles were measured at each x-location within a model canopy, below a height of 1.5h. This was done in order to examine the spatial variation in the within-canopy flow statistics, and in order to estimate a horizontal spatial-average for the flow statistics. The location of the measurement points relative to the model trees is shown in Fig. 4.6.

Fig. 4.6. Arrangement of model trees relative to mean flow, and locations for 3-wire probe traverses; A= row position, B= gap position, C= intermediate position.

4.6 RESULTS AND DISCUSSION

In presenting the results all heights and distances have been normalised to the height of the model forest, h. So all heights are plotted as z/h, and all streamwise distances are plotted as x/h where x is positive for distances downwind of the leading edge of the forest and vice versa. Each streamwise location is referred to as XH where X=x/h. For example, 5H refers to a location that is a distance of 5 tree heights downwind from the leading edge of the forest. The three forest densities at element spacings of 1/3h, 1/2h and 2/3h, are referred to as R4, R3 and R2, respectively. So forest R4 has more elements per unit floor area, i.e. is more dense than R3 which in turn is more dense than R2. All measurements refer to the model with 20H as the downstream limit, unless stated otherwise.
4.6.1 Mean velocity

Single vertical profiles of mean velocity, $U$, at locations 5H and 15H are shown in Figs. 4.7 a-c for models R2, R3 and R4, respectively. Spatially-averaged profiles of $U$ computed by taking the arithmetic mean of the within-canopy measurements are shown in Fig. 4.7d. A vertical profile of $U$ upwind of the forest at -5H is provided for reference (the pecked line in each figure). These data demonstrate three important features of the mean flow, namely that the mean velocity is spatially variable at a given height within and just above the forest canopy, that the vertical profiles of $U$ change with increasing downwind distance, and that reductions in $U$ relative to upwind conditions increase with increasing element density.

The general features of the spatially-averaged mean velocity profiles (Fig. 4.7d) are as follows. Mean velocity within and above the forest canopy is reduced in magnitude relative to the value observed upwind of the forest edge, and this reduction increases with increasing canopy density and increases with increasing streamwise distance into the forest. For example near the front of the forest (5H) mean velocity in the trunk space ($0.25h$) relative to the approach flow at the same height is reduced by a factor of 0.81, 0.64 and 0.53, and near the back of the forest (15H) the corresponding reduction in trunk space velocity is 0.41, 0.24, 0.14 in models R2, R3 and R4, respectively.

![Fig. 4.7a. Velocity profiles in and above model R2 at distances of 5H and 15H downwind from the leading edge. The pecked line shows the upwind profile.](image)
Near the back of the forest (15H), vertical profiles of mean velocity within the canopy resemble the normalized velocity profiles in the field study (Fig. 3.5a). Values of $U/U_T$ in the trunk space ($0.25h$) are 0.59, 0.40 and 0.30 in models R2, R3 and R4.
Fig. 4.7d. Spatially-averaged profiles of mean velocity, $U$, at downwind distances of $5H$ and $15H$, as a function of forest density.

respectively compared to values of $U/U_T$ of between 0.15 to 0.5 in the trunk space of the 4 m to 8 m spaced plots, respectively. These trunk space values of $U/U_T$ at 0.25$h$ are also in good agreement with the envelope of observations compiled by Raupach (1988) who reported values of $U/U_T$ of between 0.1 to 0.5 lower down in the canopy, for a wide range of model and real canopies.

The ratio of $U_{forest}/U_{open}$, where $U_{open}$ is the upwind velocity at a height of 0.25$h$, are given in Table 4.1 for heights of 0.25$h$ and 1.25$h$ within and above the model canopy. These ratios are in good agreement with the field data (see sections 3.5.2 and 3.5.3) where trunk space wind speeds were found to be between 14% to 46% of open velocity in the 4 m to 8 m spaced plots, respectively.

Values of normalized mean velocity $U/U_*$ at canopy top are 4.83, 3.91 and 3.00, and corresponding values in the trunk space ($0.25h$) are 2.86, 1.53, and 0.92 for models R2, R3 and R4, respectively. Trends in these values are in good accord with field study where values of $U/U_*$ at tree top height were between 3.3 to 2.6 and reduced with depth into the canopy to values of between 1.2 to 0.3 in the trunk space (see Fig. 6.2). Differences in $U/U_*$ at canopy top height in the field and wind tunnel experiments are likely to be the result of differences in canopy density and upwind wind conditions between the two situations.
Model | $U_{open}$ (m s$^{-1}$) | $U_{tunnel}/U_{open}$ at 0.25h | $U_{tunnel}/U_{open}$ at 1.25h
---|---|---|---
R2 | 3.92 | 0.416 | 1.033
R3 | 3.96 | 0.237 | 0.874
R4 | 3.93 | 0.138 | 0.736

Table 4.1. Relative velocity at 15H in the trunk space (0.25h) and at the same height above the model canopy (1.25h) as a fraction of approach velocity, for the three canopy densities.

Momentum transfer coefficients for the model canopies, defined as $(U_{tunnel}/U)^2$ at canopy top height, are 0.042, 0.065 and 0.11 in models R2, R3 and R4, respectively, compared to values of between 0.11 to 0.15 found in the field study. The wind tunnel observations demonstrate that momentum transfer in a forest of widely spaced trees decreases with decreasing canopy density.

At these densities, momentum transfer coefficients are equal to or lower than the commonly accepted value of 0.1 for closed stand coniferous forests (Jarvis et al., 1976). Teklehaimanot (1990) has determined corresponding transfer coefficients for water vapour in the forest plots at Cloich to be between 0.04 to 0.08 for tree spacings between 8 m to 4 m. The wind tunnel data are therefore in good qualitative agreement with the evaporation studies at Cloich.

Sizeable mean updrafts ($W = 0.2$ m s$^{-1}$ to $0.5$ m s$^{-1}$, compared to $U = 4$ m s$^{-1}$) are observed near the leading edge of the forest where the flow is forced to rise above the canopy. A local downdraft ($W = -0.1$ m s$^{-1}$ to $-0.3$ m s$^{-1}$) is associated with a below-canopy wind jet, and this gives rise to the observed trunk space maximum in $U$ near the leading edge of the forest (5H). A jetting of air in the trunk space is still evident in the $U$ profiles at 15H suggesting that advective edge effects influence the flow over downwind distances of at least 15H.

The local horizontal variation in the vertical profiles of $U$ is large near the leading edge of the forest (5H) and remains significant at 15H in these widely spaced canopies. Largest mean velocities are observed in the relatively open gap position between tree rows, smallest velocities are observed within tree rows in the wakes formed behind the elements, and intermediate values of $U$ are observed at the point midway between the gap and the row positions (Figs. 4.7a-c). These features of the spatial variation in $U$ are in accord with the field data presented in Fig. 3.5a.
The largest spatial differences in $U$ occur at midcanopy levels $(0.5h)$. For example, near the leading edge of the forest $(5H)$ the ratio of $U$ in the gap relative to $U$ in the row ($U_{gap}/U_{row}$) is 4.1, 6.1 and 9.4, whereas near the back of the forest $(15H)$ the corresponding ratio remains large and is equal to 2.47, 1.93 and 2.23 for models R2, R3 and R4, respectively. Spatial variation in $U$ is also observed in the trunk space $(0.25h)$. Near the front of the forest $(5H)$ the ratio $U_{gap}/U_{row}$ is 1.14, 1.19, and 1.38, and this ratio reduces to values of 1.08, 1.08, and 1.09 near the back of the forest $(15H)$ in models R2, R3 and R4, respectively. So the local mean velocity in the trunk space varies spatially by between 10-40% depending on canopy density and distance from the leading edge of the forest, although this tends to decrease with increasing downwind distance.

The existence of preferred pathways for flow through widely spaced canopies implies that some spatial averaging is needed to determine the mean flow characteristics for a given downwind distance into the forest. The averaging scheme adopted here is a simple arithmetic mean of the within-canopy point values measured at each location.

The streamwise development of the mean velocity field can be examined by plotting the profile of $U$ at a given height in and above the canopy against downwind distance. Fig. 4.8a shows horizontal profiles of spatially-averaged mean velocity $U$ over the range $-5H$ to $19H$. $U$ attenuates most rapidly within the canopy where the blockage to flow is greatest, and this reduction in $U$ increases with increasing canopy density. Within canopy minimum values of $U$ are reached downwind at approximately $11H$, $7H$ and $5H$ in forests R2, R3 and R4, respectively. Thereafter a gradual acceleration in $U$ is observed towards the back end of the forest.

Mean velocity above the canopy $(1.25h)$ is reduced relative to the upwind value as the air flow interacts with the large roughness elements of the forest. Streamwise changes in $U$ increase with increasing canopy density. At a height of $1.25h$, minimum values of $U$ are reached downwind at approximately $13H$, $11H$ and $7H$ in the forests R2, R3 and R4, respectively. Thereafter $U$ above the forest maintains a steady value or tends to show a slight acceleration towards the back of the forest.

A small reduction in $U$ is observed near the ground $(0.25h)$, at locations a few tree heights upwind of the forest. The wind accelerates downwards into the trunk space at the leading edge, causing a small local increase in $U$ over the first one or two
Fig. 4.8a. Streamwise profiles of mean velocity in and above a 20h forest at heights of 0.25h, 0.75h and 1.25h, as a function of canopy density.

Tree heights into the forest. Thereafter $U$ continues to decrease with increasing downwind distance. The largest reductions in $U$ are observed in the densest forest, R4. We can expect the shelter provided by a forest of wide-spaced trees to be developing for a considerable distance downwind from a forest edge.

The rate of recovery in $U$ in the lee of a forest was examined using velocity measurements in the lee of a 10h model forest. Horizontal profiles of $U$ in the smaller sized forest are shown in Fig. 4.8b. Reductions in $U$ at the leading edge are similar in the 10h and 20h forests. However a significant acceleration in $U$ is observed towards the back and in the lee of the 10h forest where an approximately exponential rate of velocity recovery is observed. Mean velocities near the ground (0.25h) recover to the same value at a leeward distance of 9h behind models R2, R3 and R4, and this
Fig. 4.8b. Streamwise profiles of mean velocity in and above a 10h forest at heights of 0.25h, 0.75h and 1.25h, as a function of canopy density.

is about 55% of the upwind velocity. So a sheltered zone of at least 9h exists in the lee of a sparse canopy.

Contour plots of the mean velocity fields in and above the 10h and 20h sized models at densities of R2, R3 and R4 are shown in Appendix A2. The velocity data are presented in this manner in order to make it easier to compare gross features of the experimental data with the flow predictions from the K-\(k\)-\(c\) canopy flow model.

4.6.2 Turbulence velocity: \(\sigma_u\)

Vertical profiles of turbulence velocity, \(\sigma_{uv}\), at locations of 5H and 15H downwind from the leading edge of the forest are shown in Figs. 4.9 a-c for models R2, R3 and R4, respectively. Fig. 4.9d shows the spatially-averaged profile of \(\sigma_u\) at
locations of 5H and 15H in each model. A vertical profile of $\sigma_u$ upwind of the forest at -5H is provided for reference (the pecked line in each figure). These data demonstrate some important features of the turbulent flow, such as the rapid increase in turbulence velocity which occurs as the air flows through the leading edge of the forest, the large within-canopy spatial variability of turbulence velocity near the front of the forest, and the rapid growth of a turbulent boundary layer above the canopy that increases in height with increasing downwind distance and with increasing element density.

The general features of the spatially-averaged longitudinal turbulence velocity profiles are as follows (Fig. 4.9d). $\sigma_u$ within and above the forest canopy increases in magnitude relative to the value observed upwind of the forest. The increase in $\sigma_u$ relative to the value at -5H is greatest near the top of the canopy. This indicates the initial growth of an inner boundary layer over the rough surface of the forest. $\sigma_u$ at above the forest generally increases with increasing canopy density and increases with increasing distance downwind from the forest edge. This trend is reversed within the canopy where, at a given height, $\sigma_u$ tends to decrease with increasing canopy density and tends to decrease, in the trunk space, with increasing downwind distance.

Near the leading edge of the forest (5H), a local maximum in $\sigma_u$ is observed in the trunk space. This maximum is associated with the jetting of wind flow into the trunk space. At midcanopy levels (0.6h) a local minimum is observed in the vertical profile of $\sigma_u$ near the leading edge of the forest (5H). This minimum is associated with the rapid attenuation of $U$ by the forest wall at the leading edge (Fig. 4.7 a-d).

Towards the back of the forest (15H), profiles of the vertical distribution in $\sigma_u$ are similar in shape to those observed in the field study (Fig. 3.8a). At 15H, $\sigma_u$ is approximately constant from the top of the canopy to a height of about 1.2h, 1.5h and 1.75h in the forests of R2, R3 and R4, respectively. $\sigma_u$ decreases with increasing height above this level. The growth rate of the inner boundary layer over the forest becomes more rapid with increasing canopy density. $\sigma_u$ decreases with depth into the canopy so that values of $\sigma_u$ in the trunk space are reduced in magnitude compared to corresponding values measured upwind of the forest. The attenuation in $\sigma_u$ within the canopy increases with increasing canopy density.

Values of normalized longitudinal turbulence velocity $\sigma_u/U_*$ at canopy top are 1.69, 1.79 and 1.73, and corresponding values in the trunk space (0.25h) are 0.76, 0.70, and 0.51 for models R2, R3 and R4, respectively. These values are in good
Fig. 4.9a. Vertical distribution of longitudinal turbulence velocity, $\sigma_u$, for model R2 at downwind distances of 5h and 15h. The pecked line shows the upwind profile.

Fig. 4.9b. Vertical distribution of longitudinal turbulence velocity, $\sigma_u$, for model R3 at downwind distances of 5h and 15h. The pecked line shows the upwind profile.

agreement with data from the field study where values of $\sigma_u/U_*$ near the canopy top were about 1.62, and reduced with depth into the canopy to values of between 0.3-0.7 in the trunk space. The model data are also in good agreement with the envelope of observations compiled by Raupach (1988a) who reported values of $\sigma_u/U_*$ of between
Fig. 4.9c. Vertical distribution of longitudinal turbulence velocity, $\sigma_u$, for model R4 at downwind distances of 5h and 15h. The pecked line shows the upwind profile.

Fig. 4.9d. Spatially-averaged profiles of longitudinal turbulence velocity, $\sigma_u$, at downwind distances of 5h and 15h, as a function of forest density.

1.6 and 2.3 at canopy top, reducing to values of between 0.4 to 1.0 lower down in the canopy for a wide range of model and real canopies.

Significant spatial variation in $\sigma_u$ is observed near the leading edge of the forest (5H). The largest values of $\sigma_u$ are measured at the point midway between the
gap and the row positions, and are presumably due to vortices being shed from the sides of the elements. Smallest values of $\sigma_U$ are observed in the row position corresponding to the wakes formed behind elements and intermediate values of $\sigma_U$ are observed in the relatively open space found in the gap position between trees. Values of $\sigma_U$ above the canopy, and values in the trunk space, are relatively homogeneous. Towards the back of the forest (15H), the spatial variation in $\sigma_U$ reduces to between 10% to 50%. So $\sigma_U$ at 15H is more homogeneous, in a spatial sense, than are the corresponding vertical profiles of $U$.

Horizontal profiles of turbulence velocity $\sigma_U$ over the x range -5H to 19H are shown in Fig. 4.10a. As the air flows over the forest turbulence is generated rapidly near the top of the canopy, where mean velocity and wind shear are greatest. As a result, values of $\sigma_U$ near the leading edge exhibit an almost step change in magnitude above the forest surface (1.25h). Beyond a distance of 5H, a more gradual increase in $\sigma_U$ is observed with increasing downwind distance. Turbulence velocities increase at similar rates above the 3 models, equal to an increase in $\sigma_U$ of about 0.1 m s$^{-1}$ per m downwind. However, above the forest (1.25h) values of $\sigma_U$ tend to increase with increasing forest density. These trends are reversed for flow within the canopy where, in general, values of $\sigma_U$ are reduced with increasing canopy density.

A local maximum in $\sigma_U$ occurs within the canopy (0.75h), near the leading edge of the forest. This maximum continues for a distance of between 1H to 3H, giving way to a local minimum in $\sigma_U$ at around 5H. However, beyond a distance of about 5H values of $\sigma_U$ increase gradually with increasing distance downwind. The rate of increase in $\sigma_U$ at midcanopy is comparable to the observed rates of increase in $\sigma_U$ above the canopy, being of the order of 0.1 m s$^{-1}$ per m downwind.

Values of $\sigma_U$ in the trunk space generally decrease or are approximately constant with increasing downwind distance, in accord with the observed decrease in mean velocity, $U$ (Fig. 4.8a). A small increase in $\sigma_U$ occurs towards the back of the forest, in the region where $U$ is also accelerating. $\sigma_U$ in the trunk space generally decreases with increasing canopy density, except near the front of the forest where this trend is reversed over the first few tree heights. Near the back of the forest (15H), values of $\sigma_U$ in the trunk space (0.25h) are equal to or smaller than corresponding upwind values.

Turbulence velocities were measured in the lee of a small 10h forest, in order to study turbulence downwind of a forest edge. Horizontal profiles of $\sigma_U$ through the
Fig. 4.10a. Streamwise profiles of longitudinal turbulence velocity, $\sigma_u$, in and above a 20h forest at heights of 0.25h, 0.75h and 1.25h, as a function of canopy density.

smaller 10h model are shown in Fig. 4.10b. The streamwise development of $\sigma_U$ through the leading edge of the 10h model is similar to the pattern observed through the leading edge of the 20h forest. An almost step change in $\sigma_U$ occurs near the front of the forest which is rapidly dissipated with increasing downwind distance, reaching a local minimum at about 5h. This turbulence is thought to be generated mainly by the wakes formed behind the elements.

Towards the back of the 10h forest, within-canopy turbulence begin to increase rapidly, particularly in the R4 model where $\sigma_U$ increases at a rate of approximately 0.5 m s$^{-1}$ per m downwind. The rate of increase in $\sigma_U$ near the back of R3 is similar to the rate observed within the canopy of the 20h forest, being of the order of 0.1 m s$^{-1}$.
Fig. 4.10b. Streamwise profiles of longitudinal turbulence velocity, $\sigma_u$, in and above a $10$h forest at heights of 0.25h, 0.75h and 1.25h, as a function of canopy density.

The magnitude of $\sigma_u$ in the lee of the $10h$ forest is greater than the corresponding value within the canopy. In general, values of $\sigma_u$ in the forest lee are larger behind a forest of greater canopy density. For example, at a leeward distance of 9h, $\sigma_u$ near the ground (0.25h) equals 0.58, 0.70 and 0.80 m s$^{-1}$ behind models R2, R3 and R4, respectively, and these values are between 40% and 90% greater than the upwind turbulence velocity, $\sigma_u$. 
4.6.3 Turbulence velocity: \( \sigma_w \)

The vertical distributions of vertical turbulence velocity, \( \sigma_w \), at locations of 5H and 15H are shown in Figs. 4.11a-c for models R2, R3 and R4, respectively. Fig. 4.11d shows the spatially-averaged profile of \( \sigma_w \) at locations of 5H and 15H in each model. A vertical profile of \( \sigma_w \) upwind of the forest at -5H is provided for reference (the pecked line in each figure).

The general features of the spatially-averaged vertical turbulence velocity profiles are as follows. Within and above the forest canopy, \( \sigma_w \) increases in magnitude relative to the value observed upwind of the forest, except in the trunk space where a decrease in \( \sigma_w \) is observed. The largest values of \( \sigma_w \) occur near the top of the canopy. Values of \( \sigma_w \) above the canopy generally increase with increasing canopy density, and an overall increase in \( \sigma_w \) is observed with increasing distance downwind from the forest leading edge.

Vertical profiles of \( \sigma_w \) are similar in shape to the profiles of \( \sigma_u \), but the relative values of \( \sigma_w \) are smaller than corresponding values of \( \sigma_u \) by a factor of about 67%.

Profiles of \( \sigma_w \) towards the back of the forest (15H) are similar in shape to those observed in the field study (Fig. 3.8a). At 15H, \( \sigma_w \) is approximately constant from the top of the canopy to a height of about 1.1\( h \), 1.2\( h \) and 1.5\( h \) in the forests of R2, R3 and R4, respectively, and \( \sigma_w \) decreases with increasing height above this level and decreases with increasing depth into the canopy. Values of \( \sigma_w \) in the trunk space are reduced in magnitude compared to corresponding values measured upwind of the forest. The attenuation of \( \sigma_w \) with depth into the canopy increases with increasing canopy density.

Values of normalized vertical turbulence velocity \( \sigma_w/U_0 \) at canopy top are 1.13, 1.17 and 1.20, and corresponding values in the trunk space (0.25\( h \)) are 0.44, 0.42, and 0.28 for models R2, R3 and R4, respectively. These values are in good agreement with data from the field study where values of \( \sigma_w/U_0 \) near the top of the canopy were about 1.0 and reduced with depth into the canopy to values of between 0.2-0.5 in the trunk space. The wind tunnel data are also in good agreement with the envelope of observations compiled by Raupach (1988a) who reported values of \( \sigma_w/U_0 \) of between 1.0 and 1.2 at canopy top, reducing to values of between 0.1 to 0.5 lower down in the canopy, for a wide range of model and real canopies.
Fig. 4.11a. Vertical distribution of vertical turbulence velocity, $\sigma_w$, for model R2 at 5H and 15H. The pecked line shows the upwind profile.

Vertical profiles of $\sigma_w$ at a given distance into the forest are more homogeneous, in a spatial sense, than corresponding profiles of $\sigma_u$. For example, near the front of the forest (5H) the ratio of maximum to minimum values of $\sigma_w$ at midcanopy (0.5h) is 1.22, 1.02 and 2.80 for models R2, R3 and R4, respectively, compared to ratios of between 1.68 to 3.68 in $\sigma_u$. The within-canopy spatial variation
Fig. 4.11c. Vertical distribution of vertical turbulence velocity, $\sigma_w$, for model R4 at 5H and 15H. The pecked line shows the upwind profile.

Fig. 4.11d. Spatially-averaged profiles of vertical turbulence velocity, $\sigma_w$, at 5H and 15H, as a function of forest density.

in $\sigma_w$ towards the back of the forest (15H) is between 10% to 25% for a given height, compared with a spatial variation in $\sigma_u$ of between 10% to 50%.

The streamwise development in vertical turbulence velocity through and above the model canopies is shown in the horizontal profiles of $\sigma_w$ over the x range -5H to 19H (Fig. 4.12a). Changes in $\sigma_w$ that occur as the air flows through and over the
Fig. 4.12a. Streamwise profiles of vertical turbulence velocity, $\sigma_w$, in and above a 20$h$ forest at heights of 0.25$h$, 0.75$h$ and 1.25$h$, as a function of canopy density.

Forest canopy are similar to the observed changes occurring in $\sigma_U$, although the magnitude of the vertical fluctuations is smaller than the corresponding longitudinal velocity fluctuations, as pointed out earlier.

The rate of increase in $\sigma_w$ is approximately the same above the canopy (1.25$h$) and within the canopy (0.75$h$) and equal to a rate of about 0.1 m s$^{-1}$ per m downwind (Fig. 4.12a). This is in accord with the observed rates of increase in $\sigma_U$ within and above the model canopy. Values of $\sigma_w$ in the trunk space (0.25$h$) remain nearly constant with increasing downwind distance into the forest. The trunk space value of $\sigma_w$ is approximately equal to the upwind value, except over the first few tree heights into the forest where a small increase in $\sigma_w$ is observed.
Vertical turbulence velocities in the lee of a smaller 10h forest are shown in the horizontal profiles of $\sigma_w$ presented in Fig. 4.12b. The streamwise development of $\sigma_w$ through the canopy and in the lee of the forest is similar to the pattern observed in $\sigma_u$, although the corresponding values of $\sigma_w$ are smaller. The magnitude of $\sigma_w$ in the lee of the 10h forest is greater than the corresponding within-canopy values. Turbulence velocities in the forest lee generally increase with increasing canopy density. For example, values of $\sigma_w$ near the ground (0.25h) at a leeward distance of 5h are 0.28, 0.41 and 0.58 m s$^{-1}$ behind models R2, R3 and R4, respectively, and these values are between 23% to 150% greater than the upwind values of $\sigma_w$. 

Fig. 4.12b. Streamwise profiles of vertical turbulence velocity, $\sigma_w$, in and above a 10h forest at heights of 0.25h, 0.75h and 1.25h, as a function of canopy density.
Contour plots of turbulence kinetic energy, $k$, have been produced from measurements of $\sigma_u$ and $\sigma_w$ within and above the model canopies (Appendix A2). The turbulence data are presented in this form in order to compare experimental data against the predictions generated using a $K$-$k$-$\varepsilon$ turbulence model. Since the transverse velocity fluctuations were not measured, values of $\sigma_v$ were approximated by the product $\sigma_u \sigma_w$ in order to compute the corresponding value of turbulence kinetic energy, $k$.

4.6.4 Turbulence Intensity: $I_u$ and $I_w$

Vertical profiles of turbulence intensity $I_u$ and $I_w$ at locations 5H and 15H downwind from the leading edge of the model forest, are shown in Figs. 4.13 a-c and 4.14a-c for models R2, R3 and R4, respectively. Figs. 4.15d and 4.15d show the spatially-averaged vertical distributions of $I_u$ and $I_w$ at locations of 5H and 15H in each model. Values of $I_u$ and $I_w$ upwind of the model at -5H are shown for reference (the pecked line in each figure).

The general features of the spatially-averaged profiles of turbulence intensity are as follows. Turbulence intensities within the forest domain increase in magnitude relative to the value observed upwind of the forest. Turbulence intensity is greatest at midcanopy levels where the largest reduction in $U$ occurs. There is a clear trend for the turbulence intensity to increase with increasing canopy density, and to increase with increasing downwind distance. For example, near the front of the forest (5H) $I_u$ reaches a maximum value at midcanopy and this is equal to 0.53, 0.59 and 0.59 in models R2, R3 and R4, respectively. Near the back of the forest (15H) $I_u$ obtains a maximum value at midcanopy equal to 0.59, 0.78 and 0.88 in models R2, R3 and R4, respectively. A comparable value of $I_w$ near the front of the forest (5H) is 0.42, 0.57 and 0.59, and near the back of the forest (15H) are 0.48, 0.75 and 0.94 in models R2, R3 and R4, respectively.

Turbulence intensity decreases with increasing height above the canopy and decreases from midcanopy with depth into the trunk space. Turbulence intensity above the canopy is seen to fall off most rapidly above model R2, which is at the widest spacing between elements. This implies that the developing inner boundary layer over a forest canopy extends to a lesser height above the forest at wider tree spacing.

In general, measured values of $I_u$ exceed measured values $I_w$ at the same height in and above the forest canopy. However, because the within-canopy turbulence
Fig. 4.13a. Vertical distribution of longitudinal turbulence intensity, for model R2 at 5H and 15H. The pecked line shows the upwind profile.

Fig. 4.13b. Vertical distribution of longitudinal turbulence intensity, for model R3 at 5H and 15H. The pecked line shows the upwind profile.

Intensities are all greater than 40% some rectification errors are inevitable in the velocity signals measured using a 3-wire probe (Legg et al, 1984). Therefore measured turbulence intensities are probably an underestimate of the actual intensity of the turbulent fluctuations, so that midcanopy observations may be low by up to about 40% at these very high turbulence intensities. Nevertheless, the results do show that
turbulence intensities within the canopy are very high, and probably exceed 100%.

Turbulence intensities, $I_U$ and $I_w$, are a measure of the relative size of the horizontal and vertical velocity fluctuations for a given local mean velocity and are therefore useful measurements for the comparison of full scale forest data. Profiles of $I_U$ and $I_w$ near the back of the forest (15H) are similar in shape to the field data (Fig.
Fig. 4.14a. Vertical distribution of vertical turbulence intensity for model R2 at 5H and 15H. The pecked line shows the upwind profile.

Fig. 4.14b. Vertical distribution of vertical turbulence intensity for model R3 at 5H and 15H. The pecked line shows the upwind profile.

3.9a,b), although measured values of $I_U$ and $I_w$ at midcanopy are all less than 100%. Near the back of the forest (15H), values of $I_U$ at canopy top height are 0.35, 0.47, and 0.59, and corresponding values of $I_w$ are 0.24, 0.31 and 0.40 in models R2, R3 and R4. These values are comparable to the field data presented in Figs. 3.9a,b where daytime values of $I_U$ at tree top height vary between 0.58 to 0.68 and corresponding
Fig. 4.14c. Vertical distribution of vertical turbulence intensity for model R4 at 5H and 15H. The pecked line shows the upwind profile.

Fig. 4.14d. Spatially-averaged profiles of vertical turbulence intensity at downwind distances of 5h and 15h, as a function of forest density.

values of $I_w$ vary between 0.34 to 0.44.

Trunk space values of $I_u$ near the back of the forest (15H), are equal to 0.26, 0.44 and 0.55, and corresponding values of $I_w$ are equal to 0.15, 0.26 and 0.31, in models R2, R3 and R4, respectively. These intensities are comparable to, but smaller than turbulence intensities measured in the trunk space at the field plots (Fig. 3.9a,b)
where values of $I_U$ were between 0.50 to 1.0, and corresponding values of $I_W$ were observed to lie between about 0.35 to 0.60. Differences between the model data and the field data are expected because the trunk space in the model canopies was more open than those canopies at the field plots.

The spatial variability of within-canopy profiles of turbulence intensities is large, particularly near the front of the forest (5H). Although turbulence intensities become more homogeneous with increasing downwind distance, the spatial variability in intensities remains significant even near of the forest (15H) where, for example, the ratio of maximum to minimum $I_U$ at midcanopy levels equals 2.1, 1.5 and 1.1 and the corresponding ratio of maximum to minimum $I_W$ equals 1.6, 1.7 and 1.6, in models R2, R3 and R4, respectively.

The spatial variability in turbulence intensity in the model canopies is greater than the spatial in intensities observed in the field plots (Figs. A1.7-A1.9). This is presumably because the steady mean wind direction in the wind tunnel means that profiles at location A (see Fig. 4.11) are consistently measured in the element wake, and this is not always the case with profiles measured in the row position at the field plots.

Contour plots of relative turbulence kinetic energy, $k_{0.5}/U$, which is analogous to a turbulence intensity, are presented in Appendix A2 for the three densities of model forest (R2, R3 and R4) with sizes of 20h and 10h. In a 20h forest, values of $k_{0.5}/U$ increase with increasing canopy density and continue to increase with increasing downwind distance, at least to 19H, at all levels within and above the model canopies (Figs. A2.1-A2.6). In the lee of the 10h model, the relative turbulence kinetic energy has a ground-level maximum at a leeward distance of about 5h behind the model, this turbulence energy is larger behind a forest of greater density.

4.6.5 Tangential momentum stress: $\overline{uw}$

Vertical profiles of tangential momentum stress, $\overline{uw}$, at locations 5H and 15H downwind of the leading edge of the 20h forest are shown in Figs. 4.15 a-c for models R2, R3 and R4, respectively. A spatially-averaged vertical profile of $\overline{uw}$ at locations 5H and 15H is presented in Fig. 4.15d. Vertical profiles of momentum stresses at -5H upwind of the model forest are shown for reference (the pecked line in each figure).

The general features of the spatially-averaged profiles of tangential momentum stress are as follows. Within-canopy and above canopy values of $\overline{uw}$ generally become
more negative than corresponding upwind values, in accord with the absorption of momentum by the canopy elements. In contrast, values of $\overline{uw}$ in the trunk space tend to be less negative than upwind values and are near zero or slightly positive. These positive momentum stresses are found in the region of the subcanopy jet and are associated with a reversal in the gradient of the wind speed ($dU/dz$).
Fig. 4.15c. Vertical distribution of tangential momentum stress, $\overline{uw}$, for model R4 at 5H and 15H. The pecked line shows the upwind profile.

Fig. 4.15d. Spatially-averaged profiles of tangential momentum stress, $\overline{uw}$, at 5H and 15H, as a function of forest density.

The magnitude of $\overline{uw}$ is greatest near the top of the canopy, where shear-turbulence is generated and velocity gradients are large. A limited constant stress layer develops above the model canopies because of the relatively small streamwise extent of the forest canopy compared to the relatively large step change in roughness at the leading edge. The magnitude of $\overline{uw}$ decreases with increasing height above the canopy.
and decreases with increasing depth into the canopy in the expected manner (Raupach, 1988a).

At a given height above the forest, $|\overline{uw}|$ generally increases with increasing canopy density, and increases with increasing distance downwind from the forest edge. This trend is reversed for profiles of $\overline{uw}$ within the canopy wherein larger values of $|\overline{uw}|$ are observed in sparser canopy arrays.

Vertical profiles of $\overline{uw}$ near the back of the model (15H) are similar in shape to the profiles of momentum stress observed in the field study (Figs. 3.6 and 3.10). A shallow region of approximately constant momentum stress is observed above the forest to a height of about 1.1$h$, 1.25$h$ and 1.5$h$ in the forests of R2, R3 and R4, respectively, and $\overline{uw}$ decreases in magnitude with increasing height above this level. This implies that the inner boundary layer developing above the canopy extends to a greater height above the forest which has a larger canopy density. The magnitude of $\overline{uw}$ decreases with depth into the canopy, as more momentum is absorbed by the canopy elements. Small positive values of $\overline{uw}$ are still evident in the trunk space at 15H for the models R2 and R3 where a reversal in $U$ gradient exists (Fig. 4.7d), whereas values of $\overline{uw}$ in the trunk space of R4 are associated with regions of a near-zero gradient in $U$ and are therefore negligible.

The spatial variation in $\overline{uw}$ is large at a given height within the canopy. For example, at a height of 0.75$h$, the ratio of maximum to minimum $|\overline{uw}|$ near the front of the canopy (5H) equals 1.6, 1.7 and 2.2, and the corresponding ratio near the back of the forest (15H) is 1.5, 1.7 and 3.5 for models R2, R3 and R4, respectively. There is a consistent trend for values of $|\overline{uw}|$ to be smaller in the wake formed behind the elements, than in the gap position between elements. This pattern indicates more momentum being absorbed by the canopy elements, than by the air space in the rows between elements and is similar to the spatial variation in profiles of $\overline{uw}$ observed in the field study (Fig. 3.10).

Within-canopy profiles of $\overline{uw}$ can be used to estimate the depth of momentum penetration into the canopy (the zero plane displacement height, $d$), using the level of mean momentum stress within the canopy (Thom, 1975). Based on this definition, and using the spatially-averaged $\overline{uw}$ profiles at 15H (Fig. 4.15d), the $d$-values were interpolated to be about 0.64$h$, 0.72$h$ and 0.78$h$ in models R2, R3 and R4, respectively. Thus a lowering of the $d$-value occurs as the canopy density is decreased.
and this implies an increase in momentum penetration into the canopy. These \(d\)-values, and the trend towards lower \(d\)'s in sparser canopies, are in good accord with estimated \(d\)-values in the field plots where daytime values were found to lie between \(0.85h\) to \(0.74h\) as canopy density was decreased.

**4.6.6 Higher Order moments**

A discussion of the basic statistics of turbulent air flow through the model forests is completed by reporting measurements of the higher order moments of skewness and kurtosis. The presentation is similar to the field data reported in section 3.5.8 except that values of mixed skewness (\(S_{uvw}\) and \(S_{uwu}\)) have also been calculated. These are the triple velocity products that arise in the conservation equations for turbulence kinetic energy and Reynolds stress, and describe the rates of turbulent diffusion of these quantities normalized by the appropriate standard deviations (Shaw and Seginer (1987)).

The influence of element density on the vertical distribution of skewness in the longitudinal \((S_{uuu})\) and vertical \((S_{www})\) velocity fluctuations and the corresponding mixed skewness values \((S_{uuw} \text{ and } S_{uwu})\) at \(15H\) is shown in Fig. 4.16. All four values generally increase in magnitude with depth into the canopy, but this trend reverses in the trunk space and near the floor of the canopy. \(S_{uuu}\) peaks near midcanopy, obtaining a maximum value of about \(0.75 (R2), 1.0 (R3) \text{ and } 1.5 (R4)\) and the corresponding values of \(S_{www}\) peak at a lower level in the canopy, and reach a larger magnitude of about \(-1.25 (R2), -1.5 (R3) \text{ and } -1.75 (R4)\).

The values of pure skewness reported here are similar in sign and magnitude to skewness values reported in the field study, and demonstrate a similar trend of becoming more skewed with increasing element density. The relatively high values of pure skewness within the model canopy provide evidence for the existence of intermittent downward moving gusts which dominates momentum transfer within and above in plant canopies. This point is examined in more detail using quadrant analyses in section 4.6.8.

Peak values of mixed skewnesses within the canopy are smaller in magnitude than the pure skewnesses and generally signed according to the order of the velocity components. Skewnesses with even powers of \(u\), that is \(S_{www}\) and \(S_{uuu}\) are generally negative and skewnesses with odd powers of \(u\), that is \(S_{uwu}\) and \(S_{uuw}\) are generally positive, within the canopy. Skewness changes sign at some height near to or just
above the top of the canopy so that skewness is near zero at canopy height.

The vertical distribution of skewness factors is similar in sign and magnitude to other measurements in artificial canopies (Raupach et al, 1986; Shaw and Seginer, 1987), in corn (Shaw et al, 1983) and in a deciduous forest (Baldocchi and Meyers, 1988a). However there are differences in the relative size of the mixed skewnesses which may be due to canopy structure and the boundary layer flow above the canopy. In the present study the magnitude of the mixed skewnesses within the canopy tends to increase with increasing element density. This observation may help to explain why Raupach et al (1986) observed only small values of $S_{UW}$ and $S_{UWW}$ within their sparse canopy (of the order of 20% of pure skewness), whereas Shaw and Seginer (1987) and

**Fig. 4.16.** Vertical profiles of skewness in and above a model forest at 15H, as a function of canopy density.
Baldocchi and Meyers (1988a) found the ratio of mixed to pure skewness closer to unity in more dense canopies.

The vertical distribution of kurtosis values for the longitudinal ($K_U$) and vertical ($K_W$) velocity fluctuations is shown in Figure 4.17. Just above the canopy values of kurtosis are fairly close to the Gaussian values of 3; $K_U$ equals 2.7 (R2), 2.7 (R3), and 2.6 (R4) and $K_W$ equals 3.2 (R2), 3.5 (R3), and 3.5 (R4). Both $K_U$ and $K_W$ increase with depth into the canopy, although this trend is reversed in the trunk space. $K_U$ generally peaks at a higher level in the canopy than does $K_W$ and both tend to increase in magnitude with increasing element density. Peak values of $K_U$ are 3.7 (R2), 6.1 (R3) and 9.2 (R4) and corresponding peak values of $K_W$ are 4.9 (R2), 10.5 (R3), and 10.9 (R4).

![Figure 4.17](image)

Fig. 4.17. Vertical profiles of kurtosis in and above a model forest at 15H, as a function of canopy density.
The wind tunnel data are in broad agreement with field observations (Fig. 3.12) with values of kurtosis exceeding the Gaussian values by factors of between 2 and 3 within the canopy. Similar results of high kurtoses within the plant canopy have been reported by Shaw and Seginer (1987) who found kurtosis values greater than Gaussian by factors of up to 4 in corn and greater than 2 in an artificial canopy. Amiro and Davis (1988) reported values of $K_w$ exceeding Gaussian by a factor of almost 3 in a dense spruce stand.

Well above the canopy, both $K_v$ and $K_w$ tend to increase with height, in accord with known behaviour of gradient boundary layers above rough surfaces (Raupach, 1981, Raupach et al, 1986). Large values of kurtosis above a rough surface occur at approximately the interface between the outer layer and the developing inner boundary layer. Assuming the inner layer has developed to the height where the kurtoses begin to increase substantially, then Fig. 4.17 demonstrates the inner layer at 15H extends to approximately $1.25h$ (R2), $1.5h$ (R3), and $1.5h$ (R4). This gives a height to fetch ratio of between 30 to 60 for the developing inner layer. Within this layer, turbulent properties of air flow are characteristic of the underlying surface and the vertical distribution of momentum stress is approximately constant with height above the canopy (Fig 4.15d).

4.6.7 Probability density distributions

Probability density distributions for the horizontal and vertical velocity components were computed by sorting the velocity fluctuations (normalized by their respective standard deviations) into 23 class intervals over the range $\pm 5\sigma$. These distributions are shown in Figs. 4.18a-c for models R2, R3 and R4, respectively, from measurements at a downwind distance of 15H. The Gaussian distribution is shown by the solid line in each figure.

The velocity distributions are similar to those reported in the field study and confirm the behaviour of higher order statistics presented above. That is, velocity distributions are all monomodal, the $u$-distribution is skewed to the left and the $w$-distribution is skewed to the right and both tend to become more peaked with increasing depth into the canopy and with increasing element density. So the velocity distribution within the model canopy is non-Gaussian and tends to become increasing more non-Gaussian as canopy density increases.
There are some differences between the field measured and wind tunnel measured velocity distributions, possibly due to anemometer errors. In particular, the 3-wire probe suffers from rectification errors in $U$ whenever the turbulence intensity exceeds about 40% (Legg et al., 1984). This means that left hand tails in the $u$-distribution will be truncated. There is some evidence to suggest that rectification errors are occurring in the $u$-distributions of the R3 and R4 models (Figs. 4.18b and c) because the probability density falls to zero at $-2\sigma_u$.

In contrast, the $w$-velocity signals of a 3-wire probe are of a high fidelity for turbulence intensities of up to 100% so that tails in the $w$-distributions easily exceed $\pm 2\sigma_w$. For example, vertical velocities in the trunk space exceeding $\pm 2\sigma_w$ occur about 5.4% (R2), 6.5% (R3), and 6.9% (R4) of the time and these extreme vertical velocities tend to be associated with downdrafts. In a Gaussian distribution, 3.3% of the events
Fig. 4.18b. Probability density distribution of $u$ and $w$ velocities in model R3 at 15H, as function of depth into the canopy. The solid line is Gaussian.

exceed $\pm 2\sigma_{w}$. So the $w$-distribution is subject to extreme events with significantly greater than Gaussian probability, as well as being negatively skewed.

The velocity distributions and the higher order statistics associated with these distributions indicate turbulence events that become more extreme and intermittent with depth into the canopy. This feature of canopy flow is examined in the quadrant analyses reported below.
Fig. 4.18c. Probability density distribution of $u$ and $w$ velocities in model R4 at 15H, as function of depth into the canopy. The solid line is Gaussian.

4.6.8 Quadrant analysis

Data for the quadrant analysis comprised $u$ and $w$ time series collected over a 20 s period at a rate of 410 Hz from measurements in and above the model canopy at a downwind distance of 15H. The instantaneous tangential momentum stress was classified according to the quadrant and magnitude of each event, in the manner described in Chapter 2.

The total stress and time fractions associated with events exceeding a given hole size are shown in Figs. 4.19 a-c for the models R2, R3 and R4, respectively. Extreme events occur within the canopy and these account for a disproportionate amount of the total tangential momentum stress. For example, above the canopy ($z=1.25h$) events exceeding 2 times the mean normalized tangential momentum stress
Fig. 4.19a. Time and stress fractions associated with tangential momentum stress at varying hole sizes, in model R2 at 15H, as a function of depth into the canopy.

occur 8.1%, 7.9% and 8.2% of the time and these events account for 52%, 46% and 48% of the total tangential momentum stress in the R2, R3 and R4 canopies, respectively. At mid-canopy levels (z=0.5h), events exceeding $H = 2$ occur 6.7%, 5.8% and 5.4% of the time and these events account for 63%, 58% and 60% of the total stress in the R2, R3 and R4 canopies, respectively. These results are in excellent agreement with the field data (Figs. 3.13a-c) and with measurements in an artificial canopy, reported by Raupach et al. (1986).

The process of momentum transfer becomes more intermittent and the events become more extreme with depth into the canopy, at least to midcanopy. That is to say the stress fraction associated with extreme events tends to increase with depth into the canopy and the corresponding time fractions tend to decrease. This observation is similar to the findings in the field study, and similar to many other studies in widely differing canopies such as in corn (Shaw et al., 1983), a deciduous forest (Baldocchi and Meyers, 1988a) and an almond orchard (Baldocchi and Hutchison, 1987). In
addition the present results, and the field results, demonstrate that turbulence events tend to become more extreme and intermittent with increasing tree density.

The vertical distribution of the magnitude of stress and time fractions associated with events at hole size zero, that is all events occurring in each quadrant, is shown in Figs. 4.25a-c for models R2, R3 and R4, respectively. These profiles agree broadly with the field observations (Figs. 3.14a-c) showing the dominance of bursts and sweeps, that is events defined as $S_{0.2}$ and $S_{0.4}$, occurring within the upper canopy. Relatively little momentum transfer occurs by way of interaction events, at least in the upper canopy. Sweep and burst events predominate at all levels from the base of the canopy to well above the canopy top with magnitudes of less than 1.0.

The ratio $S_{0.4}/S_{0.2}$ representing the ratio of momentum transfer by sweeps to that by bursts, and the corresponding ratio $T_{0.4}/T_{0.2}$ representing the relative frequency of these events, measured at heights of 0.5$h$ and 1.25$h$ is shown in Table 4.2. Within the canopy, sweeps predominate over bursts and are more intense and intermittent. So
sweeps transfer relatively more momentum than bursts and this transfer occurs in less time. These features are in broad agreement with the findings of Raupach et al (1986) who measured ratios of $S_{0.4}/S_{0.2}$ of between 1.0 and 1.31 in their artificial canopy, and Baldocchi and Meyers (1988a) who measured factors of between 1.1 and 2.3 in a deciduous forest canopy. In addition, the present data indicate that sweeps become
increasing more intense become increasingly more intermittent as canopy density is increased. The dominant events occurring above the canopy continue to be sweeps and bursts, although sweeps tend to become less important with height compared to burst events in the transfer of momentum above the canopy. A cross over point occurs near
Fig. 4.20c. Vertical profiles of the magnitude of stress and time fractions associated with the momentum stress in each quadrant at hole size zero, in model R4 at 15H.

the top of the canopy such that at heights below this point the dominant events are sweeps and $S_{0,0}/S_{0,2} > 1.0$ and $T_{0,0}/T_{0,2} < 1.0$ whereas at heights above this point the dominant events tend to be bursts and $S_{0,0}/S_{0,2} < 1.0$ and $T_{0,0}/T_{0,2} > 1.0$. The influence of tree density is to increase the relative magnitude of sweeps within and just above the canopy, as can be seen from the Table 4.2.

4.6.9 Shelter Integral

The previous sections have considered variations in the flow statistics at a specific height within the canopy or at a specific downwind distance from the forest edge. They do not take into account the integrated effect of the canopy on the turbulent air flow. One way to compare changes in velocity and turbulence inside the forest domain with 'open' conditions, is to take an integral of the mean and turbulence velocities over the region of interest, which may be the height and length of the canopy, and compare this integral with the corresponding upwind velocity profiles integrated over the same domain. A shelter integral, $\Psi$, can be defined as (Argent, 1990):

$$\Psi = \int_0^x \int_0^z (\bar{U} + 3\sigma_u) \, d(\frac{z}{h}) \, d(\frac{x}{h})$$  \hspace{1cm} (4.2)
where $X$ and $Z$ are the normalized distances and heights respectively of the domain of interest. This definition uses a gust speed which is the sum of the mean velocity ($U$) and a gust factor (3.0) times a turbulence velocity ($\sigma_v$). A gust factor of 3.0 indicates the 99 percentile velocity for a Gaussian distribution. A lower shelter integral indicates generally lower velocities and consequently indicates better shelter provided by the forest canopy. $\Psi$ has dimensions of m$^3$s$^{-1}$ and is therefore equivalent to a volume flow rate.

Shelter integrals were computed over a domain extending from the front of the forest to 19H. For the 10h forest this includes flow in the lee of the forest. Integrals were evaluated over the height of the trunk space ($Z=0.37h$) and over the height of the canopy ($Z=1.0h$) using two definitions of $\Psi$; $\Psi_1$ integrates the gust velocity and $\Psi_2$ integrates the mean velocity. Data for 3 forest densities and 2 forest sizes are presented in Table 4.3.

The canopies are named according to the convention $RrHhO$, where $Rr$ stands for the canopy density ($R2$, $R3$ and $R4$), $Hh$ stands for the downwind depth of the forest (H10 or H20) and $O$ stands for the orientation of the rows of elements with respect to the approach flow such that $O=D$ when the rows of elements are 45° or diagonal to the flow (this is the standard orientation, see Fig. 4.11) and $O=S$ when the elements are orientated at 0° or square-on to the flow.

Shelter integrals decrease in an orderly pattern with increasing canopy density, in the expected manner, in accord with trends in the overall reductions in mean wind speed through the canopy (Table 4.3). Some interesting trends relating to forest size and wind angle appear in the shelter integrals.

A 10h forest produces a similar shelter integral to a 20h forest of half the density, when evaluated over the region from the forest edge to a distance of 19h downwind. For example, $\Psi_1$ evaluated in the trunk space of model R3H10 equals about 1.18 m$^3$s$^{-1}$ (the average of S and D orientations) whereas the corresponding trunk space value of $\Psi_1$ in model R2H20 (half the density) equals about 1.17 m$^3$s$^{-1}$, and this is lower than the corresponding unsheltered value of $\Psi_1$ which equals about 1.63 m$^3$s$^{-1}$. Similarly, $\Psi_1$ evaluated in the trunk space of model R4H10 equals about 1.04 m$^3$s$^{-1}$, whereas the corresponding trunk space value of $\Psi_1$ in model R3H20 equals about 0.97 m$^3$s$^{-1}$. This result suggests that over a distance about 20h, a small forest of 10h size may produce a similar wind shelter near the ground to that produced by a 20h forest with the same number of trees.
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Table 4.3. Shelter integrals of gust speed, \( \Psi_1 \), and mean velocity, \( \Psi_2 \), evaluated in a range of model stands over the height of the trunk space \((Z=0.37)\) and the height of the canopy \((Z=1.00)\).

Shelter integrals consistently tend to be smaller when the rows are aligned with the wind. For example, \( \Psi_1 \) evaluated in the trunk space of model R2H20 equals 1.23 compared to a value of 1.11 for orientations of 0° and 45°, respectively, and these are both lower than the corresponding unsheltered value of about 1.63. This means that tree rows aligned with the mean wind direction tend to be less effective in providing...
shelter in the trunk space, presumably because of a channelling of the air flow down the tree rows.

The results in Table 4.3 demonstrate the usefulness of a shelter integral in ranking canopies in terms of their effective wind shelter. Calculation of the shelter integral for different forest planting strategies may be a useful tool, in the future, to evaluate and compare the corresponding wind shelter in different agroforest designs.

4.7 SUMMARY AND CONCLUSIONS

A comprehensive set of wind tunnel data were collected in order to examine the influence of element spacing and model dimensions on the turbulent properties of air flow through and above a model forest of widely spaced elements. Flow variables were mapped from extensive measurements of turbulence statistics obtained using an 3-hot-wire probe. The experiments covered a four fold change in elements density and a doubling of forest size from $10h$ to $20h$ in the streamwise dimension. Time series data were used to compute probability density distributions of velocity fluctuations and the technique of quadrant analysis was used to examine the relative contribution from various turbulent events to the momentum transfer process. The most significant findings from this part of the study are summarised as follows:

(i) This wind tunnel study has been successful in simulating many of the features of canopy flow identified in the field study at Cloich. Part of the success of this study is attributable to using a 3-wire probe, which enables one to take measurements with confidence within the canopy air space, where turbulence intensities are upwards of 70%.

(ii) The within-canopy, normalized vertical distributions of turbulence statistics near the back of the model canopy (15H) are in good agreement with the field data from Cloich, where the area densities are similar, and generally lie within the envelope of observations compiled by Raupach (1988a) for air flow through a wide range of model and real canopies. For example, at a downwind distance of 15h, values of $U/\bar{U}$ at the top of the canopy are between 4.83 to 3.00, and corresponding values of $\sigma_{v}/\bar{U}$ and $\sigma_{w}/\bar{U}$ are approximately 1.75 and 1.15, respectively. Other statistics like the intensity of turbulence are also in accord with the field observations.

(iii) The within-canopy velocity distributions are non-Gaussian, being highly skewed and kurtotic, and becoming progressively more non-gaussian with increasing depth into the canopy and with increasing canopy density. This observation is consistent
with the field data from Cloich, and numerous other studies in extensive plant canopies.

(iv) By examining the tangential momentum stresses using quadrant analysis, it was possible to demonstrate that most of the events occurring within the canopy crown are sweeps and bursts, with relatively little contribution from inward and outward interactions.

(v) The magnitudes of the stress fractions at hole size zero are all less than 0.5. This result is in accord with the field data from Cloich, but is a factor of between 2 to 4 smaller than corresponding measurements by Baldocchi and Meyers (1988a) in a deciduous forest of closely spaced trees. It follows that the tangential momentum stress in a sparse canopy comprises events that are of a smaller magnitude than events occurring in denser canopies.

(vi) As air flows through the leading edge of the canopy, $U$ attenuates rapidly with downwind distance. This attenuation tends to be more rapid in a denser canopy. Despite the trunk space being open below $0.37h$, significant reductions in mean velocity are observed at a downwind distance of $15h$. Velocity reductions in the trunk space are comparable to those reductions observed in the trunk space of the plots at Cloich, where the canopies are of a similar (scaled) density, being 42%, 24% and 14% of the upwind velocity in models R2, R3 and R4, respectively.

(vii) Within-canopy turbulence velocities rise rapidly at the front of the model to reach a maximum value at a distance of between $1h$ to $3h$ into the canopy, decreasing to a local minimum at $5h$, and thereafter increasing at rates comparable to the above-canopy rates of increase in turbulence velocity. This behaviour is consistent with the hypothesis that wake generated turbulence predominates near the front canopy, which is smaller scale and would therefore dissipate quickly, and this wake-turbulence gives way to larger scale shear-turbulence which become more dominant with increasing downwind distance. This has implications for the way in which the plant/airflow interactions are modelled using higher-order closure (see Chapter 5).

(viii) Mean flow in the lee of a $10h$ sized forest decreases near the ground for a distance of between $1h$ to $5h$. Thereafter $U$ recovers at a rate which is faster behind a denser canopy. At a leeward distance of $9h$ from the forest edge, velocities near the ground ($0.25h$) are still less than the upwind velocity by a factor of 0.55. So a sheltered zone of at least $9h$ exists in the lee of a sparse canopy. At midcanopy levels
(0.75h), the velocity recovery begins over the last few elements heights, but $U$ recovers to only about 65% of the upwind value at a leeward distance of 9h.

(ix) Turbulence in the lee of the model canopy tends to increase to values that are much larger than the upwind value. The trend is for turbulence velocities to be larger in the lee of canopy of greater density.

(x) By using the concept of a shelter integral, which effectively integrates the mean and turbulence velocities over the canopy domain, it was possible to rank correctly the model canopies in terms of their effective wind shelter. It is hypothesised that the shelter integral may be a useful method to evaluate and compare the corresponding wind shelter for different forest designs, as simulated by the numerical predictions.

The results presented in this chapter form a detailed and unique set of turbulence data associated with air flow through and above a model forest of widely spaced elements. The measurements have been taken for two reasons, to examine the effect of a change in element density and forest dimensions on the properties of turbulent air flow, and to produce a comprehensive and accurate set of measurements suitable for testing the predictions from a higher-order turbulence model of canopy flow. The results from this wind tunnel study are compared in the following chapter with flow predictions generated from three comparatively simple eddy-viscosity turbulence models.
5.1 INTRODUCTION

The forest/airflow interaction has an overwhelming impact on plant canopy microclimate. In order to understand canopy processes, it is essential to deal with these interactions effectively. An understanding of the various canopy processes can result from measurements and observations, and from a methodology with which to predict them quantitatively. For the present study, the most important feature of such predictions is to determine how the flow variables change in response to proposed changes in stand geometry.

A realistic canopy flow model must be based strongly on physical considerations. Equations to describe canopy flow can be derived rigorously from the conservation equations for mass, momentum and turbulence kinetic energy (Raupach and Shaw, 1982). The methods of classical mathematics do not offer a practical way of solving these equations for complex flow phenomenon. Numerical methods, on the other hand, are available to solve the resulting set of partial differential equations (Patankar, 1981b).

A numerical simulation model offers the potential to examine forest/airflow interactions for any combination of height, shape or spacing of trees, and would therefore seem the ideal tool to examine the problem of air flow through a forest canopy. Because the theory is necessarily simplified, a numerical simulation cannot generate all the details of the turbulence. There is a need for experimental support and testing of such models otherwise their ability simulate realistic conditions remains in doubt.

The predictive ability of a numerical model depends largely on two factors, the validity of the model assumptions and the robustness of the numerical method. A conceptually satisfactory model can produce worthless results if an inadequate numerical model is used, and vice versa. For this reason, a well tested, general purpose, fluid dynamics program (PHOENICS) was used as the basis for a series of canopy-flow simulations. Such an approach enables one to concentrate attention on modelling aspects of the problem, without being concerned with the numerical solution of the fundamental flow equations.
The problem considered was that of modelling turbulent air flow in and above a stand of widely spaced trees placed in an otherwise undisturbed boundary layer flow. Computations were performed in two dimensions in order to examine flow through leading and trailing edges of a forest domain. The predictions were compared with experimental wind tunnel data (Chapter 4) in order to assess their realism.

5.2 NUMERICAL PROCEDURE

This section gives a general overview of the numerical scheme employed by the PHOENICS code to set up and solve a general flow equation. Some additional aspects of the numerical procedure, such as convergence criteria, relaxation practises, and the expected accuracy of the predictions, are also discussed. Some information presented in this section is 'transparent' to the PHOENICS user, such as the way the equations are discretized and solved. However, the author feels that the inclusion of this information is necessary in order to demonstrate the link between the canopy flow models proposed in Chapter 2, and the actual equations that are being solved by PHOENICS. A description now follows of the numerical procedure used adopted by PHOENICS.

5.2.1 The general differential equation for property \( \phi \)

The numerical solution of fluid flow and other related phenomenon begins with the laws governing these processes which were expressed in mathematical form as a set of nonlinear partial differential equations in Chapter 2. Modelled forms of the flow equations describing the conservation of mass, momentum and turbulence kinetic energy obey a generalised conservation principle and can therefore be expressed in terms of a general differential equation. The general differential equation is:

\[
\frac{\partial \rho \phi}{\partial t} + \vec{U}_j \frac{\partial \rho \phi}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \Gamma_\phi \frac{\partial \phi}{\partial x_j} \right) + S_\phi
\]

(5.1)

where \( \Gamma_\phi \) is the diffusion coefficient and \( S_\phi \) is the source term, which are specific to a particular meaning of \( \phi \).

The four terms in the differential equation are the unsteady or transient term, the convection term, the diffusion terms and the source (or sink) term. The dependent variable, \( \phi \), can stand for any one of the quantities of velocity, turbulence kinetic energy or the dissipation rate of turbulence kinetic energy.
5.2.2 Numerical technique

PHOENICS is a sophisticated, general-purpose computer code designed to provide iterative numerical approximations to the solution of fluid flow and other transport phenomenon (Spalding, 1981; Rosten et al., 1983). The basic principle behind PHOENICS is the recognition that all problems involving transport of an entity are governed by conservation equations like Eq. 5.1. Consequently, the main body of the PHOENICS code is a single, general-purpose equation solver (which is not accessible to the user). The main task in using PHOENICS is to express a given equation, or set of equations, in such a way that they obey this general form.

The procedure for casting the differential equations into the general form is to manipulate them until, for the chosen variable, the transient terms, the convection and diffusion terms obey the standard form of Eq. 5.1. The coefficient of the gradient of \( \phi \) in the diffusion term is interpreted as being the expression for the diffusion coefficient, \( \Gamma_\phi \), and the remaining terms on the right hand side are collectively combined into the source term, \( S_\phi \).

The canopy flow model proposed in Chapter 2 is implemented in a relatively straightforward manner by supplying extra source terms for the canopy domain to account for the sink of momentum and the generation and dissipation of turbulence kinetic energy. Implementation of these sources using PHOENICS is discussed in section 5.4. In the meanwhile, a brief description of the calculation procedure employed by PHOENICS will be given.

5.2.3 Numerical grid and control volumes

All numerical methods treat as basic unknowns the values of the dependent variables defined at a finite number of locations (called grid points) in the calculation domain. The task of the numerical method is to provide a set of algebraic equations for these unknowns and to provide an algorithm for solving them.

For a given differential equation, the required algebraic equations can be derived and solved in many ways. These derived equations are often referred to as 'discretized' since they describe values of \( \phi \) at discrete locations. PHOENICS uses a 'finite-domain' or 'control-volume' method. A complete description of this method is given by Patankar (1981a, 1981b). The basic strategy of the control-volume approach is outlined below.
The calculation domain is first subdivided into a number of non-overlapping control volumes. There is one control volume surrounding each grid point, with the grid point located at the geometric centre. The location of a typical node 'P' and its neighbours, labelled E, W, N and S (standing for east, west, north and south neighbours, respectively) is shown in Fig. 5.1, for a two dimensional problem in the x-y plane. Values of the dependent variables $P$, $k$ and $\varepsilon$ (standing for pressure, turbulence kinetic energy and the dissipation rate for $k$, respectively) are calculated at these positions. Corresponding values of the mean velocity components $U$ and $V$ are calculated at points e and w, and n and s, respectively.

![Fig. 5.1. Staggered grid control volume for grid point P and its neighbours.](image)

This is the so called staggered-grid arrangement since the location of the velocity components is staggered relative to that of the other dependent variables. Such an arrangement was first used by Harlow and Welch (1965) to avoid the possibility of decoupling between adjacent velocities and pressures (see Patankar, 1981b). Further advantages for using the staggered grid are that (i) the velocities lie midway between the locations of the pressures that 'drive' them, which is convenient for the calculation of pressure gradients and other scalar quantities, and (ii) the velocities are directly available for calculation of convective fluxes across the faces of each control volume surrounding the point P. One consequence of the staggered-grid approach is that the velocity components are never calculated at the boundaries of the computational domain. Boundary conditions for the velocity components are not specified at the boundaries of the flow domain, but rather at the cell centres (see section (5.3.2).
5.2.4 Conservation equation for the control volume

The general differential equation (Eq. 5.1) is integrated over each control volume to obtain an algebraic equation which expresses the conservation principle that flux differences across the sides of a control volume are balanced by the source enclosed. The total flux in the \textit{ith} direction, denoted by \( J_i \), is given by the sum of a convective and a diffusive contribution,

\[
J_i = \rho \overline{U_i} \phi - \Gamma_{\phi} \frac{\partial \phi}{\partial x_i}
\]  

(5.2)

so that the corresponding steady-state form of the general differential equation is

\[
\frac{\partial J_i}{\partial x_i} = S_{\phi}
\]

(5.3)

Integration of this equation over the control volume surrounding the point \( P \) shown in Fig. 5.1 yields

\[
J_e A_e - J_w A_w + J_n A_n - J_s A_s = \overline{S_{\phi}} \Delta V
\]

(5.4)

where the \( J \)'s represent the \textit{integrated} total fluxes over the control-volume faces, that is \( J_e \) stands for \( I J_e \Delta x \) over the interface area \( A_e \), and so on; the \( A \)'s represent the areas of the corresponding cell faces (for a cartesian system in two dimensions \( A_y = A_w = \Delta y \) and \( A_n = A_s = \Delta x \)); \( S_{\phi} \) is the average source term contained within the control-volume; and \( \Delta V \) is the volume of the control-volume (here, \( \Delta V = \Delta x \Delta y \) since \( \Delta z = 1 \)).

In order that the resulting discretization equation remains (at least nominally) linear, the source terms \( S_{\phi} \) is expressed as a linear function on \( \phi_p \), namely

\[
\overline{S_{\phi}} = S_C + S_p \phi_p
\]

(5.5)

where \( S_p \) is the coefficient of \( \phi_p \), and \( S_C \) is the part of \( S_{\phi} \) that is independent of \( \phi_p \). This linearization of source terms enables the resulting set of discretization equations to be solved by techniques for linear algebraic equations.

In a similar manner, the continuity equation \((\partial U/\partial x_i = 0)\) is integrated over the control-volume to obtain

\[
F_e - F_w + F_n - F_s = 0
\]

(5.6)

where the \( F \)'s are the mass flow rates through the faces of the control volumes, that is, if \( \rho U \) at point \( e \) prevails over the cell face at \( e \), then \( F_e \) is taken to be \( (\rho U)A_e \), and
so on. This equation is then multiplied by the grid point value of the variable in
question, namely $\phi_p$, and subtracted from the conservation equation to give

$$
\left(J_o - F_o \phi_p\right) - \left(J_w - F_w \phi_p\right) + \left(J_n - F_n \phi_p\right) - \left(J_s - F_s \phi_p\right)
= (S_c + S_P \phi_p) \Delta V
$$

(5.7)

This is the discretization analogue of the generalized conservation equation, written
in a form which obeys the continuity equation.

### 5.2.5 Final discretization equation (FDE)

The task now is to manipulate Eq. 5.7 into the final algebraic form. Piecewise
profiles expressing the variation of $\phi$ between grid points are used to evaluate terms
such as $(J_o - F_o \phi_p)$ in the following manner

$$
J_o - F_o \phi_p = a_E (\phi_p - \phi_E), \quad J_w - F_w \phi_p = a_w (\phi_w - \phi_p)
$$

(5.8)

$$
J_n - F_n \phi_p = a_N (\phi_p - \phi_N), \quad J_s - F_s \phi_p = a_s (\phi_s - \phi_p)
$$

Here the $a$'s express the combined influence of convection and diffusion across the
cell boundaries, having dimensions of mass per unit time, and are calculated using

$$
a_E = D_o A(|P_o|) + [-F_o, 0], \quad a_w = D_w A(|P_w|) + [F_w, 0]
$$

(5.9)

$$
a_N = D_n A(|P_n|) + [-F_n, 0], \quad a_s = D_s A(|P_s|) + [F_s, 0]
$$

where the $D$'s are the diffusion conductances defined as $D_e = \Gamma_A / \delta x_e$ and so on, the
$P$'s are the corresponding Peclet number given by $P = F/D$, and the operator $[a, b]$ returns the maximum of $a$ and $b$.

In the present study, the cell face diffusion coefficient (e.g. $\Gamma_e$) is deduced from
harmonic averaging of the grid-point values (e.g. $\Gamma_E$ and $\Gamma_W$). The function $A(|P|)$
approximates (interpolates) the convection-diffusion flux expressions at the cell
interface. For the hybrid scheme used here (Spalding, 1972), the functional form for
$A()$ is given by $A(|P|) = [0.1 - 0.5 |P|]$. This definition ensures the $a$'s remain positive,
which is a necessary condition to ensure physical realism and overall balance of the
discretization equations (Patankar, 1981b).

We are now in a position to write out the final form for the discretization
equation in two dimensions containing the value of $\phi$ at the point $P$ in terms of the
values of $\phi$ at neighbouring grid points. The general form is
\[ a_P \phi_P = \sum_{n} a_{nb} \phi_{nb} + b \quad (5.10) \]

where the subscript \( nb \) denotes the neighbour grid points of \( P \) and the summation is to be taken over all the neighbours (there are four in the case of a two dimensional problem). The remaining terms \( a_P \) and \( b \) are given by

\[ a_P = a_E + a_W + a_S - S_P \Delta x \Delta y, \quad b = S_C \Delta x \Delta y \quad (5.11) \]

where \( b \) is a representation of all the \( \phi \) source terms contained within the control-volume. The pressure-gradient term in the momentum equations is treated explicitly, outwith the definition of 'b', and a special solution procedure linking the velocity and pressure fields is employed, as described in section 5.2.7.

5.2.6 Nonlinearity and under-relaxation

The form of Eq. 5.10 implies that these equations are linear when, in fact, the coefficients (\( a \)'s) in the equations are themselves functions of the dependent variables (\( \phi \)'s). Numerical instabilities can develop during the computations as a result of the inter-equation linkages and non-linearity of the partial differential equations. These instabilities are manifest as small oscillations of the calculated values over successive iterations which eventually lead to slow convergence or even divergence of the solutions. The cause is usually to be found in the strength of the linkages between two or more equations, which are being solved in turn rather than simultaneously.

To account for the nonlinearities and linkages between equations, successive approximations (iterations) of the nominally linear form of Eq. 5.10 are required. At the beginning of each iteration, the \( a \)'s are evaluated using known values of \( \phi \) from the previous iteration. At the end of each iteration, the updated \( a \)'s can produce quite large changes in the corresponding \( \phi \)'s causing slow convergence or even divergence of the solutions. To slow down the changes in \( \phi \), and thereby improve the rate of convergence, the technique of under-relaxation is used.

Patankar (1981a) describes the use of an under-relaxation factor (\( \alpha \)) where the new value, \( \phi_{new} \), is calculated as the weighted mean of \( \phi \) from Eq. 5.10 and the existing value, \( \phi_{old} \) from the previous iteration

\[ \phi_{new} = \alpha \phi + (1 - \alpha) \phi_{old} \quad (5.12) \]
Van Doormaal and Raithby (1984) subsequently introduced the $E$-factor formulation by rewriting $\alpha = E/(1+E)$ so that $E = \alpha/(1-\alpha)$. $E$ is interpreted as being equivalent to a 'false time step' and is related to the time required to respectively diffuse and convect a change of $\phi$ across the control volume.

The only way of choosing the best value for $E$ is by trial and error since the optimum value for $E$ is problem dependent. Van Doormaal and Raithby (1984) suggest values of $E$ in the range 4 to 10 as being common; in Patankar’s (1981a) terminology this equates to an $\alpha$ in the range 0.8 to 0.9. In PHOENICS, the recommended value of $E$ for the momentum equations is 'no larger than the width of a typical cell divided by the velocity of a typical cell'. For the $k$ and $\varepsilon$ equations, the recommended values are 'somewhat smaller than the ratio $k/\varepsilon$'.

In practice $E$ was set to the same value for all components of the velocity and turbulence variables, with a value near 1. Linear under-relaxation was applied to the pressure for all simulations, with the relaxation factor set at $\alpha_p = 0.8$ as suggested by Patankar (1981b). The choice of $E$ does not affect the results of a converged solution, only the rate of progress towards it.

5.2.7 Solution procedure

The control volume equations for the dependent variables, the $\phi$'s, are expressed in a general form given by Eq. 5.10. However, the momentum equations must be treated in a slightly different manner to the remaining $\phi$'s because of the appearance of a pressure-gradient term. Pressure represents an unknown since it is not expressible in terms of $U_i$ or the other $\phi$'s. Consequently, a direct method of determining the pressure field must be found.

This is achieved by treating the pressure-gradient as a source term, separate from the quantities $S_c$ and $S_p$ and hence 'b', and rewriting the momentum equation to show the pressure term explicitly as

$$a_o U_o = \sum a_{nb} U_{nb} + b_o + (P_p - P_e)A_o$$

$$a_n V_n = \sum a_{nb} V_{nb} + b_n + (P_p - P_n)A_n$$

(5.13)

Here, the term $(P_p - P_e)A_e$ is the pressure force acting on the $U$ control volume (see Fig. 5.1. for a definition of the $U$ control volume), $A_e$ being the area on which the pressure difference acts. A similar expression exists for the velocity component $V$. The
momentum equations can be solved only when the pressure field is given, or can be estimated in some way. A special procedure linking the pressure and velocity fields is employed.

Patankar and Spalding (1972) described a calculation procedure by which the velocity-pressure linkage is handled iteratively. The particular technique was given the name SIMPLE, standing for Semi-Implicit Method for Pressure-Linked Equations. Although SIMPLE has been used for a large number of problems over the many years since its inception, the rate of convergence is often slow and it sometimes leads to poor pressure fields. A number of enhancements to the procedure have been proposed (Patankar, 1981a; Van Doormaal and Raithby, 1984). PHOENICS calculates the flow field using SIMPLEST (standing for SIMPLE-ShorTened), which is an improved version of the SIMPLE algorithm. The complete solution procedure proceeds along the lines of SIMPLE, by the iterative repetition of the following steps.

(i) Firstly, an initial (guessed) pressure field is substituted into the momentum equations, which are then solved to give a field of intermediate velocities. In general these velocities do not satisfy the continuity equation until the correct pressures are obtained.

(ii) The second step is to correct the pressure and velocity fields so that they obey the continuity equation. The residual of the continuity equation (Eq. 5.6 for the intermediate velocities) equates to an additional mass source, $b$, in the velocity field. The procedure is to solve Eq. 5.10 for the pressure correction, $p'$, which is then added to the existing pressure field in order to reduce the mass source to zero. Any approximations made in the derivation of the pressure correction are justifiable as long as the procedure converges.

(iii) The next step is to solve the discretization equations successively for the remaining $\phi$'s, which in the present study are $k$ and $e$. Thus the full set of equations is not solved simultaneously, but rather in succession.

(iv) The final step is to regard the corrected pressure field obtained from (ii) as the new guess for the pressure field, return to step (i), and repeat the process until convergence is reached.
5.2.8 Convergence of solutions

Assuming that all coefficients \((a's)\) are known, an algebraic discretization equation can be written for each dependent variable at each grid point. Thus the total number of equations to be solved is \(N_x N_y n^4\). Furthermore, all of these equations must be solved many times. This is because the coefficients in the equations are themselves functions of the dependent variables \((\phi's)\), and must therefore be found from successive (iterative) approximations.

PHOENICS solves the discretization equations using a line-by-line solver in which successive passes of a tri-diagonal matrix solver are performed in alternate directions. The final unchanging state of the solution represents the convergence of the iterations. The converged solutions are the correct result to the non-linear equations, even though they are arrived at by the methods of linear algebra. Successive iterations continue to improve the precision of the solution, but they are usually terminated when the discretization equations are satisfied to a sufficient accuracy by the current values of the dependent variables. A residual is calculated for each grid point from

\[
R = \sum a_{nb} \phi_{nb} + b - a_p \phi_p
\]  

(5.14)

Iterations are usually stopped once the whole-field residual, that is the sum of \(R\) from all grid points, is reduced to a sufficiently small value. For the present study, this limit was taken to be 0.01% of the incoming flux of variable \(\phi\). Only when all the residuals of all the dependent variables are reduced below this value is convergence considered to occur.

5.2.9 Accuracy of solutions

Several factors affect the final accuracy of the solutions, the main ones being (i) the degree to which the solution satisfies the original partial differential equation, (ii) the degree to which the solution satisfies the discretized equations, (ii) the location and conditions imposed at the boundaries to the flow domain, (iv) the validity of the canopy flow model, and (v) the adequacy of the turbulence model. A combination of these factors results in a certain error in the solution. A discussion of the detection and possible avoidance of such errors is presented below.

Firstly, in focusing attention on values at grid points, the continuous information contained in the exact solution of the differential equations is replaced with discrete values. Discretization errors can result if the numerical grid over which
\( \phi \) is calculated is too coarse. This is because certain assumptions are made in interpolating values of \( \phi \) between grid points. As the number of grid points is increased the solution of the discretized equations is expected to approach the exact solution to the corresponding differential equations. The existence or otherwise of discretization errors can be checked by refining the numerical grid until the resulting difference in the solution becomes smaller than an acceptable limit (perhaps 1% or so).

The extent to which the current solution satisfies the discretization equations can be checked by monitoring continuously the whole-field residuals. Such observations are valuable in discriminating between solutions that are progressing towards a converged result, and solutions that are diverging or simply not converging fast enough. In the present work iterations were continued until these residuals were less than 0.01% of the incoming mass flux. For a grid of 50 by 30 points this level of numerical accuracy usually required about 100 iterations (when solving for \( P, U, V, k, e \)) and took a total computer time of around 150 CPU seconds on a VAX 6500 minicomputer running version 1.3 of PHOENICS.

The effect of an inappropriate location or specification of the boundaries conditions can be judged by adjusting these and determining the sensitivity of the solution to such changes. In the present work the boundaries were placed well away from the forest edges and, where possible, the appropriate boundary conditions were applied (see section 5.4.2) so as to avoid any detrimental effects. Therefore the boundaries were considered to be adequate and no further changes in their location or specification were considered.

The combined effect of using different canopy/airflow models and different turbulence closure schemes forms the major part of the present study and is therefore treated separately in section 5.5. Basically errors arising from (i)-(iii) above were considered to be small since the appropriate settings were (hopefully) made. The remaining errors are attributed to the performance of turbulence and canopy models. The magnitude of these errors was estimated by comparing the predictions with experimental wind tunnel data reported in Chapter 4.

Before presenting results from the simulations there are two further aspects of the model that must be addressed, that is how the model was implemented using PHOENICS, and how the boundary conditions to the forest model were prescribed.
The standard features of PHOENICS are described in section 5.3. and the non-standard features of PHOENICS associated with the forest model are described in section 5.4.

5.3 PHOENICS IMPLEMENTATION

The purpose of this section is to present a brief overview of PHOENICS in sufficient detail that the code presented in Appendix C3 can be interpreted and understood. It is not intended to be a guide to PHOENICS, which is well documented in the CHAM publications (1987a, b, c). A brief discussion of the structure and implementation of the user-access facilities of PHOENICS now follows.

5.3.1 Structure of PHOENICS

PHOENICS is a general-purpose computer package for the solution of fluid flow and other related transport phenomenon. The general philosophy behind the PHOENICS program is to create a single, versatile and economical equation solver for the laws of fluid mechanics, and of heat and mass transfer, and to provide a facility to introduce general features for standard and non-standard flows (Spalding, 1981).

The PHOENICS code consists of three basic elements namely (i) an EARTH program which is the central core program and embodies the general-purpose computational procedures, as described in section 5.2., (ii) a SATELLITE program which provides the specific problem-defining input information which is passed once to EARTH at the start of a run, and (iii) a GROUND program which is associated with the SATELLITE and completes the problem defining task. Information which varies during the computation, or which involves interaction with the calculation procedure is provided for in GROUND. The GROUND program provides a platform on which the user can incorporate non-standard features of a particular flow, like the canopy/airflow interactions.

The SATELLITE and GROUND programs share a common design being organised into a Group structure for the convenience of the user. There are 24 groups, each group dealing with a particular aspect of the problem defining task. For example, groups 3-5 deal with specification of the grid points, group 7 indicates which variables are to be solved for and how, group 9 specifies the fluid properties, group 11 sets the initial field values for all variables, group 13 defines the boundary conditions and special sources, and group 19 sets up data communication between the SATELLITE and GROUND. The remaining groups are used to specify features such as the number
of iterations required, the convergence criteria, the relaxation of variables, printout control, and the like. This structure is readily appreciated by examining the Q1 file (a particular form of SATELLITE) and the GROUND program contained in Appendix C3.

5.3.2 Data input using PHOENICS

Information for a particular flow simulation is entered in two main ways. First, a Q1 file is created in PIL (PHOENICS Input Language) consisting of a series of high-level input statements which are passed 'one-way' to the EARTH solver in the form of a binary data file. The Q1 file is the main input level and is responsible for setting up standard features of the flow. When the problem requires special coding (e.g. when the boundary conditions and sources are flow dependent and variable), then this is inserted into the GROUND program (written in FORTRAN), and a statement to activate the coding is inserted into the Q1 file.

PHOENICS adopts a fairly simple, but flexible procedure for setting up the boundary conditions to a particular flow problem. The boundary conditions are specified by way of convective and diffusive fluxes at surfaces bounding the domain. In this way, all boundary conditions are treated as a kind of source for the variable in question. The corresponding boundary conditions are not truly inserted at the boundaries, but rather at the centre of cells. This procedure means boundary conditions can be treated in much the same manner as source terms.

Phoenics treats source terms (and hence boundary conditions) in a standard way using a PATCH statement, which defines the spatial and temporal extent of a source, and a COVAL statement, which defines the associated COefficient and VALue of a source. The general form of the PATCH and COVAL commands is given by

\[
\text{PATCH(NAME, TYPE, IXF, IXL, IYF, IYL, IZF, IZL, ITF, ITL)}
\]

\[
\text{COVAL(NAME, } C, V, )
\]

where the PATCH statement is identified by 'name' and 'type' and the I's define the patch location in x, y, z coordinates and time, respectively, and the COVAL statement is identified by 'name' and dependent variable, \( \phi \). The coefficients \( (C_\phi) \) and values \( (V_\phi) \) have the effect of generating a source for the variable \( \phi \) of the form

\[
S_\phi = TC_\phi(V_\phi - \phi_p)
\] (5.15)
where $\phi_p$ is the in-cell value of $\phi$ and $T$ is a multiplier determined by the 'type' argument for the PATCH in question. The units of the sources specified in this way have dimensions $\phi \cdot \text{kg.s}^{-1}$. For example, sources of momentum must have units of $\text{kg.m.s}^2$ (i.e. Newtons). The patch 'TYPE's used in the present study are PHASEM, which is proportional to the fluid mass, and NORTH, SOUTH, EAST and WEST which are each proportional to the area of the corresponding cell wall.

The $C$'s and $V$'s in the COVAL statement specify either a numerical value or a means of calculating the corresponding coefficients and values. If the third or forth arguments of the COVAL statements are equal to GRND$i$, where $i$ is an integer in the range 1 to 9, then the $C$'s or $V$'s are calculated using special coding inserted in the corresponding group in the GROUND program.

Inside the EARTH solver, all source terms are incorporated into the general discretized equations effectively by adding the product $C_\phi V_\phi$ to the 'b' term, and adding the coefficient, $C_\phi$, to the 'a' terms. The effect on the grid-point value can be found from the following expression

$$\phi_p = \frac{(\sum a_{nb} \phi_{nb} + b + C_\phi V_\phi)}{(\sum a_{nb} + a_p + C_\phi)}$$

(5.16)

Three special coefficients used in the present study are FIXVAL, FIXFLU and ONLYMS. Their effect on the grid point value can be interpreted in the following manner, with reference to Eq. 5.16 above.

Firstly, when the boundary condition dictates that the value of $\phi_p$ should be fixed, then setting $V$ to the desired $\phi$-value, and setting $C$ to a very large value (in this case FIXVAL) will produce the desired effect.

Secondly, when the boundary condition is of a fixed-flux kind, by contrast, $C$ must be set to a very small value (in this case FIXFLU) so that it is negligible in comparison to the other terms in the denominator of Eq. 5.16 and $V$ must be chosen so that the product $CV$ equals the desired flux.

Finally, whenever mass enters a cell from outside the flow domain, values of all the dependent variables pertaining to the inflowing fluid need to be prescribed. This is achieved by specifying the mass flow rates using a pressure boundary condition, in which case $C_p$ is set to FIXFLU and $V_p$ is set to the mass flux, and remaining $\phi$'s are specified using a coefficient of ONLYMS (to indicate mass transfer only) and $V$ set to the desired value.
The above discussion completes a general overview of PHOENICS. Additional general information on the structure, capabilities and limitations of the code is given in Rosten et al (1983) and in the CHAM publications (1987a, b, c).

5.4 MODELLING PLANT CANOPY FLOW USING PHOENICS

This section describes how the canopy flow models presented in Chapter 2 were implemented using the PHOENICS computer program. The features described in this section are non-standard to version 1.3 of PHOENICS, and required special FORTRAN subroutines to be inserted into the appropriate groups of the GROUND program in order to model the boundary conditions and corresponding source/sink relationships within the forest domain. A listing of the SATELLITE and GROUND programs used in the present study is given in Appendix C3. The description of a PHOENICS-based model of canopy flow now follows.

5.4.1 Computational domain and numerical grid

A two-dimensional, cartesian coordinate system was chosen with the streamwise velocity component $U$ aligned in the $x$-direction, and the vertical velocity component $V$ aligned in the $y$-direction. This orientation is different to that normally used in micrometeorology, where the vertical velocity is usually labelled $W$ and lies in the $z$-direction. During early testing of the model, a comparison was made of the predictions from the $k$-$\varepsilon$ turbulence model computed in the $xy$-, $xz$-, and $yz$-planes. These tests yielded the same converged solution so that, in practice, the simulations could have been carried out in any plane. The simulations were performed in the $xy$-plane because this orientation made it easier to compute lengths scales necessary for the $k$-$l$ turbulence model.

The computational domain and boundary conditions simulating the cross section of the model forest are shown in Fig. 5.2. A mesh of $mn$ non-uniform rectangular cells was used, with the smaller cells ($0.1h$ high x $0.5h$ long) located near the forest edges where greater resolution was required. Away from critical regions the cell size was increased progressively by a factor of $p$, which was taken to be 1.2. In the following discussion 'size' refers to the general dimensions of the cell, whereas the height and length of each cell denote dimensions in the $y$-direction and $x$-direction, respectively.
The formula for setting the cell size was similar to that used by Richards (1989), although the implementation using PHOENICS was slightly different. The cell size was obtained by considering a region of total length $L_n$, subdivided into $n$ cells, each $p$ times longer than its neighbour. In this case, the length of the region was given by

$$L_n = s + sp + sp^2 + \ldots + sp^{n-1}$$ (5.17)

where $s$ was the size of the smallest cell, and was given by

$$s = L_n \frac{p - 1}{p^n - 1}$$ (5.18)

For the forest model, the number of cells in each region was chosen to satisfy the condition $s \leq 0.5h$. The formula to effect a progressive increase in cell size was

$$L_i = L_B + L_n \frac{p^i - 1}{p^n - 1}$$ (5.19)

where $L_B$ was the distance to the start of a region, $L_n$ was the total length of a region and $L_i$ was distance to the end point of the $i$th cell within the region. Similarly, the general formula to effect a progressive decrease in cell size was

$$L_i = L_E - L_n \frac{p^{n-i} - 1}{p^n - 1}$$ (5.20)

where $L_E$ was the distance to the end point of a region.
In order to concentrate cells near the forest edges, the flow domain was divided into several regions and Eqs. 5.19 and 5.20 were used to set the height and length of each cell, respectively.

The cell height was set in the following manner. Firstly, the vertical extent of the flow domain was set to a height of $10h$, and was defined using 15 cells below a height of $1.5h$ and 15 cells above this. Thus, the flow domain was divided into two height regions. Below $y=1.5h$, the cell height was set to a uniform value of $0.1h$, that is the forest domain comprised 10 cells in the vertical. Above $y=1.5h$, the cell height was increased progressively according to Eq. 5.19.

Setting of the cell length was more complicated because of the need to consider both the leading and trailing edges of the forest. The following scheme was adopted. Firstly, the horizontal extent of the flow domain is set to an overall length of $300h$, and the front of the forest was located at a distance of $25h$ from the inlet boundary. The flow domain was then divided into four length regions, over which the cell length was increased or decreased accordingly in order to concentrate cells near the forest edges.

The regions and cell-length settings were as follows. Upwind of the forest the cell length was decreased progressively from the inlet boundary to the leading edge of the forest; the cell length was then increased progressively from the leading edge to the midpoint of the forest; the cell length was decreased progressively from the midpoint of the forest to the trailing edge; thereafter, the cell length downwind of the forest was increased progressively over a region extending from the trailing edge of the forest to the outlet boundary. Since the minimum cell length is set at $0.5h$, a change in forest size alters the number of cells in the forest domain as well as the length of each region within the forest. Consequently, the total number of cells defining the flow domain increases with increasing forest size.

Within PHOENICS, the forest domain is specified in Group 1, and the grid point settings are effected in Groups 3 and 4, respectively, of the Q1 file (Appendix C3).

5.4.2. Boundary conditions

Once the geometry of the flow domain has been defined using a set of grid points and cells, values of the flow variables, or their gradients, must be prescribed at the boundaries of the computation domain. There are four boundaries to consider
in a two-dimensional flow simulation. These coincide with locations of an upstream boundary at which a specified inflow occurs, a free stream boundary where the flow is assumed to be undisturbed by the forest, a downstream boundary where the outflow occurs, and a ground plane. A fifth boundary condition is supplied within the forest domain, by way of additional source terms, to simulate the effects of the canopy. The practises employed for each of the boundary conditions is outlined below.

5.4.2.1. Inlet Boundary

Incoming values for all the non-zero, dependent variables pertaining to the flow must be specified at the inlet boundary. For a simulation in the xy-plane, this means prescribing vertical distributions for the velocity components and the turbulence quantities. Although pressure also appears as a dependent variable in the equations, a boundary condition for P is not specified directly; instead the mass flow rates into the domain are specified.

At the inlet boundary, it was assumed the incoming flow was in equilibrium with the ground which, as described in the next section, was treated as a rough wall characterised by a roughness length \( z_0 \). Equilibrium vertical profiles of the dependent variables were obtained by 'developing' a boundary layer over a fetch of \( 1000h \) \((=10^6z_0)\), with the calculations proceeding until the mean-flow and turbulence profiles were independent of downstream distance.

The flow domain was defined using a grid composed of 50 non-uniform cells in the x-direction; the vertical grid spacing was not changed. Although arbitrary inlet conditions could have been used, the Harris and Deaves model (1981) (as implemented by Richards, 1989) was used in order to accelerate convergence to a steady-state solution. Self similarity of the profiles was achieved after a distance of approximately \( 500h \). Downstream values of the flow variables generated in the absence of a forest canopy were subsequently used as the inlet boundary conditions in further simulations.

The inlet boundary conditions for a PHOENICS model are set in Group 13 of the Q1 file (Appendix C3). These settings involve multiple PATCH and COVAL statements for each of the dependent variables. A short FORTRAN program was written to extract the necessary profile information from a PHOENICS output file (consisting of over 2000 lines by 6 columns of data), and convert this into the corresponding inlet-boundary-condition statements in the Q1 file.
5.4.2.2. Wall boundary

It is not possible to model the complete structure of a turbulent boundary layer from the free stream into the laminar sub-layer very close to solid boundaries. Instead, wall functions are usually employed to provide the boundary conditions at solid surfaces. The primary objective in using wall functions is to model correctly the flow behaviour very near to a solid surface where the wall no-slip condition ensures that over some region of the wall layer viscous effects on the transport processes must be large. With the wall function approach the viscous sublayer is modelled by employing empirical formulae to provide near-wall boundary conditions for the momentum and turbulence transport equations.

Launder and Spalding (1974) discussed the need for wall functions and developed some for smooth surfaces. In this study, the ground has been treated as a rough wall, characterised by a roughness length $z_0$. The wall functions used are those proposed by Rosten and Worrell (1988), and the implementation follows Richards (1989).

The near-wall momentum sink

Since the $U$-velocity component is not calculated at the ground there is no need to provide a value for $U$ at the wall. However, the momentum flux to the wall must be specified. This is achieved using a skin friction factor of the form $s=U^2/U^2$ which is derived from the logarithmic-law for a rough wall. The general form of the log-law is

$$\frac{U}{U_*} = \frac{1}{\kappa} \ln(z/z_0 + 1)$$

(5.21)

where $U$ is the resultant velocity parallel to the wall, $U_*$ is the resultant friction velocity, $z$ is the height above the wall, $z_0$ is the ground roughness length, and $\kappa$ is von Karman's constant (=0.41). The skin friction factor can be rewritten directly from Eq. 5.21 as

$$s = \frac{\kappa U_*}{U \ln(z/z_0 + 1)}$$

(5.22)

Local equilibrium is assumed over the region close to the wall, since the Reynolds stresses are nearly constant. Also, in order that finite fluxes are predicted wherever $k$
is finite, the friction velocity is expressed in terms of a velocity scale derived from the local turbulent kinetic energy. Substitution for \( U \) gives the final expression for \( s \) as

\[
s = \frac{\kappa (C_\mu C_D)^{0.25} k^{0.5}}{U \ln(z/z_0 + 1)}
\]

(5.23)

The momentum flux to the wall equates with a momentum sink equal to -shear stress times wall area (with dimensions of newton). Hence, the near-wall momentum sink is calculated using \(-\rho s U_\tau A_s\), with \( s \) calculated from Eq. 5.23.

The source term for a near-wall momentum sink is implemented in Group 13 of the Qi file, by declaring a SOUTH-type patch, and setting the corresponding Coefficient and Value to \( \rho s U_\tau \) and 0.0, respectively (see Eq. 5.15). The Coefficient is set to GRND which triggers code in Group 13 of GROUND to calculate the term \( \rho s U_\tau \).

This treatment for the near-wall momentum sink is only valid when \( k \) is one of the dependent variables. When \( k \) is not solved, as in a mixing length model, an alternative expression for \( s \) must be found. In this case, the ground is modelled simply by setting the skin friction factor equal to a suitable value \((s=0.1)\) and employing a special facility within PHOENICS, of using a WALL-type patch and setting the corresponding Coefficient and Value to \(-s\) and 0.0, respectively. This has the effect of introducing a momentum source equal to \(-\rho s U_\tau A_s\) which gives the desired result.

**The near-wall turbulence source**

Since the velocity is always zero at the wall, kinetic energy removed from the mean flow is transferred into kinetic energy of the turbulent flow. Hence a rough wall acts as a source for turbulence kinetic energy. The transfer of energy from the mean flow into turbulence is approximately equal to the product (shear stress times cell face area time velocity) where the relevant area is that of the cell face opposite the wall and the velocity is the resultant velocity in the plane of that face (Rosten and Worrell, 1988). The nett source of turbulent kinetic energy for the near-wall cell includes a mean dissipation term which is obtained by assuming local equilibrium and averaging the dissipation over the cell volume. The combined sink/source relation for \( k \) at the near-wall cell is given by (Richards, 1989)

\[
S_k = \frac{(C_\mu C_D)^{0.75} k^{0.5} \ln(2d/z_0 + 1)}{2d \kappa} \left[ \frac{\kappa U}{(C_\mu C_D)^{0.25} \ln(d/z_0 + 1)} \right]^2 - k
\]

(5.24)
where $2d$ is the height of the near-wall cell. This equation is expressed in an form equivalent to the source term mechanism operating in PHOENICS (see Eq. 5.15), so that the Coefficient and Value settings are easily recognised. Eq. 5.24 leads to a near-wall value of $k$ equal to

$$k = \left( \frac{\kappa U}{(C_p C_D)^{0.25} \ln(d/z_0 + 1)} \right)^2 = \frac{U_o^2}{(C_p C_D)^{0.5}}$$

(5.25)

The near-wall turbulence source is implemented in Group 13 of the Q1 file by declaring a PHASEM-type patch for the near-wall cells and setting the corresponding Coefficient (the leading term on the right hand side of Eq. 5.24) and Value (leading term in brackets) to GRND9. These settings activate special Fortran coding in Group 13 of GROUND to calculate the Coefficient and Value terms.

The near-wall dissipation rate

The value of the dissipation rate at the centre of the near-wall cell is specified on the assumption that the rates of creation and destruction of turbulence kinetic energy at the near-wall cell are in equilibrium. Consequently, $\varepsilon$ is modelled as (Rosten and Worrell, 1988)

$$\varepsilon = \frac{(C_p C_D)^{0.75} k^{1.5}}{\kappa (d+z_0)} = \frac{U_o^3}{\kappa (d+z_0)}$$

(5.26)

The near-wall dissipation rate is set via Group 13 of the Q1 file by declaring a PHASEM-type patch for the near-wall cells and setting the corresponding Coefficient to FIXVAL and the Value to GRND. This setting activates special Fortran coding in Group 13 of GROUND to calculate near-wall dissipation rate from Eq. 5.26. A Coefficient setting of FIXVAL guarantees that the near-wall value of $\varepsilon$ is fixed to the desired Value.

5.4.2.3 Free stream boundary

Values of the dependent variables at the free stream boundary are, in principle, known from the distributions of velocity, turbulence kinetic energy, etc, in the external stream. In practice, however, this is not entirely true because disturbances due to the forest can propagate the vertical extent of the flow domain, causing a change in the $\phi$ values at the free stream boundary. In general, the extent of such a disturbance to the flow is not known beforehand, so that the free stream boundary must be located
by trial and error at a distance far enough away from the forest so that conditions imposed at the free stream do not have a significant influence on $\phi$'s computed near the forest.

The practice adopted here was to locate the free stream boundary at a height of $10h$, and to set the velocity component normal to the free stream boundary, $V$, equal to zero. This setting resulted in changes of typically less than 1% in the dependent variables at the free stream boundary and was therefore considered to be adequate.

5.4.2.1 Outlet boundary

At the outflow boundary, that is where the fluid leaves the flow domain, one knows neither the value of $\phi$ nor its flux, so that treatment for such a boundary in the manner described above seems impossible. Fortunately, no boundary condition is needed at an outflow boundary (Patankar, 1981a). Provided the downstream boundary is located where the velocity component normal to the boundary is directed everywhere outwards, then the boundary layer nature of the flow ensures that the downstream conditions have no influence on the upstream flow.

This assumption is valid providing the Peclet number is sufficiently large. Patankar (1981a) suggests a value of $P=10$ is large enough to effectively force the Coefficient of the downstream neighbour to zero, in which case the outflow has no influence on the upwind conditions. An exception to this rule is for the pressure variable, which must be prescribed at the outflow boundary in order to establish a pressure gradient across the outflow cell. A simple treatment is usually sufficient whereby the pressure at the outflow boundary is fixed to zero.

This setting for the pressure at the outflow boundary is made in Group 13 of the Q1 file by declaring an EAST-type patch at the outlet plane, and setting the corresponding Coefficient and Value to FIXVAL and 0.0, respectively. A Coefficient setting of FIXVAL guarantees the pressure at the outlet is set to 0.0.

5.4.3. Forest source/sink relations

A plant canopy acts as a sink for momentum and a source for the generation and dissipation of turbulence kinetic energy. Equations to describe the canopy/air flow interactions were developed in Chapter 2. These interactions are modelled in PHOENICS by including the appropriate source/sink relations into the corresponding
5.4.3.1 Momentum sink

The momentum sink resulting from the form drag of the canopy elements was parameterized in the usual way by using the product of an elemental drag coefficient, $C_d$, and an area density, $A$ (see Eq. 2.9). The corresponding source term for this momentum sink was modelled in PHOENICS using

$$S_{U_i} = FIXFLU \left( -\frac{\frac{1}{2}C_dA S |U_i|}{FIXFLU} - U_{i,P} \right)$$  \hspace{1cm} (5.27)$$

where $S$ was the magnitude of the velocity vector, $U_i$ was the mean velocity components ($U$ or $V$), and FIXFLU was a PHOENICS-variable equal to $10^{-10}$. Eq. 5.27 was implemented in Group 13 of the Q1 file by declaring a PHASEM-type patch over the forest domain and setting the corresponding Coefficient to FIXFLU and the Value to GRND7. This Value setting activates special Fortran coding in Group 13, section 19 of GROUND to calculate the Value given by Eq. 5.27. The Coefficient setting of FIXFLU effectively negated the effect of the within-cell velocity value, $U_{i,P}$, on the source term.

5.4.3.2 Turbulence kinetic energy source

The turbulence kinetic energy source resulting from the canopy/airflow interactions is described by Eq. 2.18. Within the canopy domain, there are two additional source terms to consider for $k$, that arising from wake production and that arising from the dissipation of shear kinetic energy within the canopy. The combined sink/source relation for $k$ is expressed as

$$S_k = C_dA U^2 |U| - 3/2C_dA |U| k$$  \hspace{1cm} (5.28)$$

For the purpose of modelling the combined source term, these two source terms were treated separately in Group 13 of the Q1 file, in the following manner. The wake production term was modelled as

$$S_{k1} = FIXFLU \left( \frac{C_dA U^2 |U|}{FIXFLU} - k \right)$$  \hspace{1cm} (5.29)$$

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by declaring a PHASEM-type patch over the forest domain and setting the corresponding Coefficient to FIXFLU and the Value to GRND8. This Value setting activated special coding in Group 13, section 20 of GROUND to calculate the required Value, and the Coefficient setting of FIXFLU guaranteed the source term was not influenced by the in-cell value of $k$.

The second term of Eq. 5.28 was modelled as

$$S_{k2} = \frac{3}{2} C_d \xi U (0.0 - k)$$

5.4.3.3 Dissipation rate sources

It is necessary to specify the value of the source terms for the dissipation rate of turbulence kinetic energy, which result from the canopy/airflow interactions. By analogy to the $k$ equation, there are two source terms to consider for $\varepsilon$, one arising from wake production and a second arising from the additional dissipation of shear kinetic energy within the canopy (see Eq. 2.40). The combined sink/source relation for $\varepsilon$ is expressed as

$$S_{\varepsilon} = \frac{C_4 \varepsilon}{k} C_d \xi U^2 |U| - \frac{3}{2} C_d \xi U \varepsilon$$  \hspace{1cm} (5.31)

These two terms were, however, treated as separate sources in Group 13 of the Q1 file, in the following manner. The wake production term was modelled as

$$S_{\varepsilon1} = \begin{cases} \text{FIXFLU} \left( \frac{C_4 \varepsilon / k \ C_d \xi U^2 |U|}{\text{FIXFLU}} - \varepsilon \right) \end{cases}$$  \hspace{1cm} (5.32)

by declaring a PHASEM-type patch over the forest domain and setting the corresponding Coefficient to FIXFLU and the Value to GRND8. This setting activates special coding in Group 13, section 20 of GROUND to calculate the required Value. The second term of Eq. 5.31 was modelled as

$$S_{\varepsilon2} = \frac{3}{2} C_d \xi U (0.0 - \varepsilon)$$  \hspace{1cm} (5.33)
by declaring a PHASEM-type patch over the forest domain and setting the corresponding Coefficient to GRND8 and the Value to 0.0. This setting activates special coding in Group 13, section 9 of GROUND to calculate the required Coefficient.

5.4.4 Turbulence modelling

The final task in the canopy flow model is that of specifying the appropriate turbulence closure scheme. Turbulence modelling using Version 1.3 of PHOENICS is based on the eddy viscosity concept, and there are three turbulence models built into the code as standard features, namely (i) a zero-equation (mixing length) model, (ii) a one-equation \((k-i)\) model, and (iii) a two-equation \((k-\varepsilon)\) model, as described in section 2.2. These models are activated by setting appropriate values for the variables ENUT (prescribing the eddy viscosity formulae) and EL1 (prescribing the length scale formulae). The particular settings for each of the turbulence models are as follows.

5.4.4.1 Zero-equation (mixing length) model

Solutions to the continuity equation and the momentum equations are activated by the statement SOLVE(P1,U1,V1) inserted into Group 7 of the Q1 file. P1, U1 and V1 represent pressure, and the two velocity components, respectively. The mixing length model is activated in Group 9 of the Q1 file by setting the eddy viscosity using ENUT=GRND2 and setting the mixing length using EL1=GRND. These settings trigger code in Group 9 of GROUND, which calculates the corresponding values. Special Fortran code was written into Group 9 of GROUND to calculate a length scale formulation, following Li et al (1985) (see Eqs. 2.20 and 2.21).

5.4.4.2 One-equation \((k-i)\) model

In the \((k-i)\) model, a further budget equation for KE (representing \(k\)) is solved and additional source terms for KE are activated. The \((k-i)\) closure scheme is triggered in Group 7 of the Q1 file by the statement SOLVE(KE), and in Group 9 of the Q1 file by setting the eddy viscosity using ENUT=GRND3 and the mixing length using EL1=GRND. Thus, \(v_i\) is modelled by Eq. 2.27, and the length scale, \(l_m\), is modelled using Eqs. 2.20 and 2.21.

Additional source terms for \(k\) are the production term (see Eq. 2.28) and the dissipation term (see Eq. 2.29). These are standard source terms within PHOENICS,
and are activated in Group 13 of the Q1 file by declaring a PHASEM-type patch over
the flow domain, and setting the corresponding Coefficient and Value equal to
GRND4. This setting selects special Fortran coding in Group 13, sections 5 and 16
of GROUND to calculate the required production and dissipation terms in the $k$
equation.

5.4.4.3 Two-equation ($k$-$\epsilon$) model

In the $k$-$\epsilon$ model an additional budget equation for $EP$ (representing $\epsilon$) is
solved, and extra source terms for $EP$ are activated. The $k$-$\epsilon$ closure scheme is
triggered in Group 7 of the Q1 file by the statement SOLVE(KE,EP), and in Group
9 of the Q1 file by setting the eddy viscosity using $ENUT=$GRND3 and the mixing
length using $EL1=$GRND4. This setting for the length scale and the eddy viscosity is
equivalent to Eq. 2.35.

Additional source terms for the production and dissipation of $k$ and $\epsilon$ (see Eq.
2.36) are activated in Group 13 of the Q1 file by declaring a PHASEM-type patch
over the flow domain, and setting the corresponding Coefficient and Value to GRND4.
This setting triggers standard coding in Group 13, sections 5 and 16 of GROUND to
calculate the required production and dissipation terms in the $k$ and $\epsilon$ equations.

5.5 RESULTS AND DISCUSSION

Implementation of the canopy flow models using PHOENICS has proved to
be more time consuming than had been anticipated and it has therefore not proved
possible to complete all the studies that could have been done, within the time
available. Much time was spent in developing interactive software routines to view the
predictions, as the outdated version of PHOENICS currently installed on ERCVAX
had no post-processing or hard-copy facilities. Some output from these graphics
routines appear in Appendix A2. Progress in obtaining predictive results was also
slowed by a lack of documentation and local software support.

Nevertheless, the method proposed has been tested in simple flow situations
and found to work satisfactorily when compared to the wind tunnel experimental data
reported in Chapter 4. The results of these comparisons are reported below.
5.5.1 Comparison of turbulence models

Experimental data from the 20h wind-tunnel model R3 were considered for the purpose of evaluating different the canopy flow models proposed in Chapter 2. The computations were carried out using a mesh of 55 by 35 grid points (see Fig. 5.3.). All calculations were done on a VAX 6250 minicomputer using version 1.3 of the PHOENICS code. The predictions from each model were obtained with the same basic code, so that the termination criteria, relaxation practices, etc, were the same as described in section 5.2. The 'exact' flow was assumed to be that obtained by taking a spatial-average of the within-canopy measurements at each location in the wind tunnel model.

![Fig. 5.3. Grid mesh used in the two-dimensional simulations of flow through and above a 20h forest.](image)

Contour plots of equal mean velocity through and above model R3 are shown in Figs. 5.4a, b, and c. These are the numerical predictions generated using the canopy flow models presented in section 5.4., and by adopting a zero-equation (mixing length), a one-equation ($k-l$) and a two-equation ($k-\varepsilon$) turbulence closure scheme, respectively. A value of $C_{4e}=1.5$ was chosen for the $k-\varepsilon$ canopy model (see section 5.5.2). Comparison of these figures with the experimental data from wind-tunnel model R3 (Fig. 5.4d) leads to the following general conclusions.

Firstly, all three models simulate general features of the mean flow. They predict an acceleration of wind above the canopy, a maximum reduction of velocity at mid-canopy, and a local jetting or maximum in velocity in the trunk space. The rapid attenuation in velocity at midcanopy near the front of the forest is well predicted...
Fig. 5.4a. Contours of mean velocity, $U$ through and above wind-tunnel model R3 predicted using a mixing length model. The forest domain is shown by the outline.

Fig. 5.4b. Contours of mean velocity, $U$ through and above wind-tunnel model R3 predicted using a $k-l$ turbulence model. The forest domain is shown by the outline.

by all three models. The relative magnitude of the velocity reduction at midcanopy levels also agrees qualitatively with the experimental observations.

Two regions in the flow domain where the three turbulence models generate different predictions are near the top of the canopy, and in the trunk space below the canopy. The mixing length and $k-l$ models both tend to over-predict velocities in the trunk space, whereas the $k-\varepsilon$ turbulence model appears to provide more realistic predictions over this region. The over-prediction of $U$ by the mixing length and $k-l$
Fig. 5.4c. Contours of mean velocity, $U$, through and above wind-tunnel model R3 predicted using a $k$-$\varepsilon$ turbulence model. The forest domain is shown by the outline.

models may be caused by the way in which the ground has been modelled.

Velocities above the canopy are over-predicted by the mixing length and $k$-$l$ models, and both models fail to predict an acceleration in flow that is observed towards the back of the forest. As a result, the mixing length and $k$-$l$ models tend to predict a relatively short transition region for the development of equilibrium velocity conditions in the top half of the canopy. This probably reflects the use of a fixed length scale across the forest domain whereas, in reality, the turbulence length scales would be steadily changing through this transition region.
In contrast, the $k$-$\varepsilon$ model generates reasonable predictions for the velocity at the top of the canopy, and also predicts an acceleration in wind speed towards the back of the forest in line with the observed mean flow behaviour through model R3 (Fig. 5.5d). Since the $k$-$\varepsilon$ model calculates length scales from the local flow conditions, it is better suited for the calculation of flow in regions where the flow is changing rapidly. This feature of the closure scheme was thought to be the reason why better predictions are generated using the $k$-$\varepsilon$ canopy model.

In general, the performance of the models in predicting mean flow ranks in order of the complexity of the turbulence model, with the $k$-$\varepsilon$ model giving a better overall agreement with the experimental data from the R3 wind-tunnel model. Poor performance of the mixing length and $k$-$l$ models may partly attributed to using a fixed length scale formulation. It is quite possible that better agreement with measurements could have been achieved by modifying the length scale. Such an approach was not considered desirable, since this then implies that the predictive ability of such models are then problem dependent. Therefore a modification to the length scale formulation was not attempted. Instead, it was concluded that the improved predictions of mean flow by the $k$-$\varepsilon$ canopy model warranted the use of the more complicated $k$-$\varepsilon$ turbulence closure scheme. This conclusion is reinforced by examining predictions of the turbulence energy.

Contours of equal turbulence kinetic energy through and over model R3 computed using the canopy flow model of section 5.4, and by adopting a $k$-$l$ and a $k$-$\varepsilon$ turbulence closure scheme, respectively, are shown in Figs. 5.5a, and b. The mixing length model does not solve for the turbulence energy, so that no predictions for $k$ are generated. Comparison of these figures with the experimental data in Fig. 5.5c reveals further the relative strengths and weaknesses of these models.

Both models simulate general features of the turbulent flow. They predict maximum turbulence energy near the top of the canopy, and a small region of increased turbulence energy just in from the leading edge of the forest which is attenuated rapidly. However, the simpler $k$-$l$ model fails to predict a progressive increase in turbulence energy that is observed above the canopy, with increasing downwind distance, being an almost symmetrical pattern with respect to the top of the canopy. A second apparent weakness in the $k$-$l$ model is that it tends to predict constant values for the turbulence energy in the top half of the canopy after a relatively short transition region, and gives rise to unreasonable high values for the
Fig. 5.5a. Contours of turbulence kinetic energy, $k$ through and above wind-tunnel model R3 predicted using a $k$-$l$ turbulence model. The forest domain is shown by the outline.

Fig. 5.5b. Contours of turbulence kinetic energy, $k$ through and above wind-tunnel model R3 predicted using a $k$-$\varepsilon$ turbulence model. The forest domain is shown by the outline.

turbulence energy well above the canopy. In contrast, the $k$-$\varepsilon$ model gives a much improved prediction of the overall pattern of turbulence energy through and above model R3, and yields values that are in good agreement with the experimental data.

Both models generally overpredict the turbulence energy well above the canopy. This overprediction in $k$ results partly from the fact that the upwind profiles of turbulence energy were not matched between the wind tunnel and the simulation model. Velocity profiles in the wind tunnel were generated using a grid of rods and
therefore had uncharacteristically low values of turbulence energy. In contrast, when a velocity profile was generated by the numerical model to match that in the wind tunnel simulations, the resulting turbulence energy was higher and possibly more realistic. This difference in approach flow turbulence energy makes an absolute assessment of the accuracy of the $k-l$ and $k-\varepsilon$ models difficult. However, it is clear from the comparison with experimental observations that the more sophisticated $k-\varepsilon$ canopy model yields predictions that are closer to the experimental results.

The predictive ability of the $k-\varepsilon$ canopy model is somewhat surprising, considering the complex nature of the flow through the model canopy. It should be pointed out, however, that a value of $C_d=2.0$ was used in all these simulations. This is a factor of two higher than the measured single-element drag coefficient (Fig. 4.3) and is counter to the usual practice of adopting a 'sheltered value' for $C_d$ of between 0.2 and 0.5 of the single-element value (Thom, 1971). The so-called 'shelter parameter' has evolved from extensive observations in reasonably-closed canopies, both at full scale and model scale, which show that the drag coefficient of a canopy element is reduced below that of a single element.

Because $C_d$ is often unpredictable beforehand, most numerical models obtain results by 'optimising' the value of $C_d$ to fit experimental data, usually ending up with a drag coefficient of between 0.3 and 0.6. An exception to this, is the predictions of Wilson (1988) who required a $C_d$ of 2.3 in order to achieve agreement with experimental data from a relatively-open artificial canopy of Raupach et al (1986). In
their wind tunnel experiment, Raupach et al (1986) measured the corresponding in situ value of $C_d$ to be 1.6. In a personal communication to the author, Wilson stated that he would not be surprised if the single-element drag coefficient had to be multiplied (by 1/2 or 2) in order to achieve good agreement with experimental observations (J.D. Wilson, pers. comm., 1990).

The reason why a larger drag coefficient had to be used in the present study remains unclear. However, part of the reason may have been because the area density, $A$, of the model canopy was not measured in the usual way. $A$ was taken to be the projected frontal area of the model tree crown (the shadow area) rather than the total projected area of the bristles; the latter area is probably much greater. Since it is the product $C_dA$ that generates the canopy flow terms in the numerical model, any underestimate in $A$ must be balanced by a corresponding increase in $C_d$ to simulate the same effect.

In summary, the $k$-$\varepsilon$ canopy model produced more realistic flow predictions than the simpler mixing length and $k$-$l$ canopy models. Consequently, only the $k$-$\varepsilon$ model was considered further. Detailed comparisons with experimental data are presented in following sections to cover specific aspects of the $k$-$\varepsilon$ model, that is the appropriate choice for the $C_{4e}$ parameter and the validity of the model over a range of canopy densities and forest sizes.

5.5.2 Optimisation of the $C_{4e}$ Parameter

Predictions from the $k$-$\varepsilon$ model depend on an appropriate choice for the parameter $C_{4e}$, which is an empirical coefficient used to describe the dissipation rate of wake generated turbulence energy. In developing the canopy flow model, it was suggested the value of $C_{4e}$ should be less than 2.0, since this term must parameterize some higher-order terms which were necessarily omitted from the model.

In order to establish an appropriate value for this parameter, a series of sensitivity tests were carried out by comparing predictions using different values of $C_{4e}$ with the experimental data from the wind-tunnel model R3 at 20$h$. In addition, sensitivity tests were also performed using the experimental data from R2 and R4 in order to establish the constancy, or not, of $C_{4e}$ over a range of area densities, in this case $A$ being varied by a factor of four. The results are presented as vertical profiles of mean wind speed and turbulence kinetic energy at distances of 5$h$ and 15$h$.
Fig. 5.6a. Profiles of mean velocity $U$ predicted using a $k$-$\varepsilon$ turbulence model, as a function of $C_4$. Circles are spatially-averaged experimental data from wind-tunnel model R2.

Fig. 5.6b. Profiles of mean velocity $U$ predicted using a K-$k$-$\varepsilon$ turbulence model, as a function of $C_4$. Circles are spatially-averaged experimental data from model R3.

downwind from the leading edge of the forest.

Figs. 5.6a, b and c demonstrate the influence of a change in $C_4$ over the range 1.4 to 1.6, on the predicted vertical profiles of mean wind speed in and above wind-tunnel models R2, R3 and R4, respectively. In general, the predictions of $U$ are in
Fig. 5.6c. Profiles of mean velocity $U$ predicted using a K-k-ε turbulence model, as a function of $C_4$. Circles are spatially-averaged experimental data from model R4.

very good agreement with point-averaged experimental data, yielding a characteristic 'S' shaped velocity profile which is progressively diminished in magnitude with increasing distance into the forest. Predictions of mean velocity are only mildly influenced for values of $C_4$ in the range 1.4 to 1.6. Predictions at 15h are slightly better than those at 5h, although this probably reflects the fact that local variability in mean velocity is large near the leading edge of a canopy of widely spaced elements.

The influence of a change in $C_4$ on the vertical profiles of turbulence kinetic energy predicted in and above models R2, R3 and R4, is shown in Figs. 5.7a, b and c, respectively. Reasonable predictions of turbulence energy are generated using a value of $C_4 = 1.5$, with the predictions being in fair agreement with the spatially-averaged experimental data. Clearly, the parameter $C_4$ has a much greater influence on predictions of turbulence energy than on the corresponding predictions of mean velocity.

A small change in $C_4$ over the range 1.4 to 1.6 leads to a large change in the predictions of turbulence energy near the leading edge of the forest. However, the sensitivity of the predictions to such changes in $C_4$ is reduced somewhat with increasing distance into the forest. The predictions of turbulence energy at 15h being only mildly influenced (of the order of 10% at the top of the canopy) by changes in
Fig. 5.7a. Profiles of turbulence kinetic energy, $k$, predicted using a $k$-$\epsilon$ turbulence model, as a function of $C_{4e}$. Circles are spatially-averaged data in wind-tunnel model R2.

Fig. 5.7b. Profiles of turbulence kinetic energy, $k$, predicted using a $k$-$\epsilon$ turbulence model, as a function of $C_{4e}$. Circles are spatially-averaged data in wind-tunnel model R3.

$C_{4e}$, particularly for the denser R4 model forest. Since the $C_{4e}$ parameter controls the dissipation of wake-generated turbulence, this parameter is expected to have the largest effect on the predictions in the region where the production of wake-turbulence is greatest, that is near the front of the forest.
Fig. 5.7c. Profiles of turbulence kinetic energy, $k$, predicted using a $k$-$\epsilon$ turbulence model, as a function of $C_{4c}$. Circles are spatially-averaged data in wind-tunnel model R4.

An absolute assessment of the accuracy of the predictions of turbulence energy is made difficult by the fact that different values of $k$ have been used in the approach flow upwind of the wind tunnel and numerical forests. The use of different upstream conditions undoubtedly leads to different levels of turbulence energy at heights well above the canopy, and outside the region of influence of the forest, as exemplified by the disparity between measurements and predictions at a height of $2.5h$, especially near the leading edge. Nevertheless, predictions of turbulence energy from just above the canopy to deep within the canopy are in reasonable agreement with the spatially-averaged experimental data.

The agreement between the predictions of the $k$-$\epsilon$ canopy model and the spatially-averaged experimental data from the wind-tunnel models R2 to R4 was better than had been expected, since the within-canopy flows were predicted without specifying a priori anything about the wind speed or turbulence energy above the canopy. In this respect, the two-dimensional model is quite different from a one-dimensional model where it is conventional to 'tie' the values of velocity, turbulence energy and shear stress to those values expected above the canopy.

Because the adoption of K-theory is a potential weakness in the present model, an examination was made of the agreement between predicted and measured vertical
Fig. 5.8a. Profiles of tangential momentum stress, $\overline{uw}$, predicted using a $k$-$\varepsilon$ turbulence model, as a function of $C_{4e}$. Circles are spatially-averaged data in wind-tunnel model R2.

Fig. 5.8b. Profiles of tangential momentum stress, $\overline{uw}$, predicted using a $k$-$\varepsilon$ turbulence model, as a function of $C_{4e}$. Circles are spatially-averaged data in wind-tunnel model R3.

profiles of tangential momentum stress. Results are presented in Figs. 5.8a-c for wind-tunnel models R2, R3 and R4, respectively. A value of $C_{4e}$=1.5 once again yields a vertical profile, this time for $\overline{uw}$, that is consistent with experimental observations of tangential momentum stress within the model canopies for a four-fold change in $A$. 

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Fig. 5.8c. Profiles of tangential momentum stress, $\overline{uw}$, predicted using a $k$-$\varepsilon$ turbulence model, as a function of $C_{4e}$. Circles are spatially-averaged data in wind-tunnel model R4.

Predictions of $\overline{uw}$ well above the canopy are different to the measured values, as would be expected since the incoming stress profiles are not the same in regions outside the influence of the forest. Fig 5.8c demonstrates excellent predictions of $\overline{uw}$ towards the back of model R4, to a height of at least $2h$.

In the light of these results, a value of $C_{4e}=1.5$ seems appropriate to cover the range of area densities examined in the wind tunnel models, and to give reliable estimates of mean wind speed and turbulence energy through and above these canopies. However, this is not to say the same value of $C_{4e}$ is appropriate for a closed-canopy. In comparing the accuracy of the R2 and R4 predictions, that is comparing the performance of the model with increasing area density, the results suggest that $C_{4e}$ may be a mildly-decreasing function of $A$ since a value of $C_{4e}=1.5$ provides a good 'fit' to the experimental data of R2 and R3, whereas a value of 1.4 tends provides a better fit to R4 data.

5.5.3 Air flow through the leading edge

The predictive ability of the $k$-$\varepsilon$ canopy model is confirmed in the vertical profiles presented above. The model predictions are further validated by taking horizontal transects through the forest edge at several height in and above the forest.
Fig. 5.9a. Streamwise profiles of $U$ in and above a $20h$ forest predicted using a $k$-c turbulence model. Circles are spatially-averaged data from wind-tunnel model R2.

canopy. A knowledge of the pattern of wind reduction through the forest edge is important for a several reasons including, for example, an assessment of the maximum wind speed reduction that may be achieved for a given forest density, and also in estimating the distances over which these reductions occur. In this section, the results are presented using a series of horizontal transects at heights of $0.25h$, corresponding to the trunk space, $0.75h$ corresponding to a mid-canopy level, and $1.25h$ above the
Fig. 5.9b. Streamwise profiles of $U$ in and above a $20h$ forest predicted using a $k$-$\varepsilon$ turbulence model. Circles are spatially-averaged data from wind-tunnel model R3.

canopy, extending from a location $-5H$ upwind of the forest through to the trailing edge of the forest located at $20H$.

Predictions of mean wind speed through and above models R2, R3 and R4 are presented in Figs. 5.9a, b and c, respectively. The low sensitivity of the predictions to changes in $C_4$, is in general accord with the vertical profile data. The predictions of mean velocity are weakly dependent on $C_4$ over the range 1.4 to 1.6. The overall
Fig. 5.9c. Streamwise profiles of $U$ in and above a $20h$ forest predicted using a $k$-$\varepsilon$ turbulence model. Circles are spatially-averaged data from wind-tunnel model R4.

Predictions are in excellent agreement with the spatially-averaged velocity data in all three models. These data provide further evidence of the ability of the $k$-$\varepsilon$ canopy model to predict the pattern of mean velocity through a canopy of widely spaced elements.

Corresponding predictions of turbulence energy through and above models R2, R3 and R4 are presented in Figs. 5.10a, b and c, respectively. The sensitivity of these
Fig. 5.10a. Streamwise profiles of turbulence kinetic energy, $k$, predicted in a 20$h$ forest using a $k$-$\varepsilon$ turbulence model. Circles are spatially-averaged data from wind-tunnel model R2.

Predictions to a change in $C_{4e}$ is probably best demonstrated by presenting the data in this manner. These predictions show clearly that predictions of turbulence energy are highly sensitive to the choice of $C_{4e}$. This parameter controls the dissipation of wake-generated turbulence energy, and has a large influence on the initial rise in turbulence energy at the leading edge of the canopy. With increasing distance into the forest, the dip and subsequent rise in turbulence energy within the canopy, are
predicted to occur at rates that are relatively independent of the value of $C_{4e}$.

As discussed above, a value of $C_{4e}=1.5$ gives rise to the best predictions of turbulence energy across the range of area densities covered by the wind tunnel data. This question of which value of $C_{4e}$ to use needs clarification, especially if this model is to be applied to plant canopies outside the range of area-densities examined here.
Fig. 5.10c. Streamwise profiles of turbulence kinetic energy, $k$, predicted in a 20$h$ forest using a $k$-$\varepsilon$ turbulence model. Circles are spatially-averaged data from wind-tunnel model R4.

One feature of the predictions is that for some choices of $C_{4e}$ the turbulence energy above the canopy is predicted to decrease, which is counter to observations. This is especially true in the region near the front of the forest and above immediately the canopy, whenever the value of $C_{4e}$ is too large. An example of this is illustrated in Figs. 5.10a, b and c where, for a value of $C_{4e}=1.6$, turbulence energy above the canopy is predicted to decrease near the leading edge. This decrease in turbulence
energy is possibly because the dissipation rate for the turbulence energy is too large near the top of the canopy, and hence the value of $C_{4e}$ is too high (see Eq. 2.44).

In some situations, for example in simulating flow through canopies of a higher density, knowledge of this feature of the model may be used to advantage in determining the appropriate value for $C_{4e}$. For example, if $C_{4e}$ is set too high then a dip will be observed in the turbulence energy in the vicinity of the leading edge, immediately above the canopy. On the other hand, if $C_{4e}$ is set too low then the corresponding rise in turbulence energy at the leading edge becomes too large. This situation is demonstrated in Figs. 5.10a and b when the value of $C_{4e}$ is set equal to 1.4 (too low) and set equal to 1.6 (too high). Thus, the appropriate value for $C_{4e}$ lies somewhere between these two values.

The constancy of the parameter $C_{4e}$ is questionable since a value of $C_{4e}=1.4$ appears to give a better 'fit' to the observations in model R4. A preliminary test to simulate flow through a denser canopy (two times the area density of R4, results not presented) required a value of $C_{4e}=1.3$ in order to produce plausible looking results, strengthening the hypothesis that $C_{4e}$ is a mildly decreasing function of area density.

In summary, the $k$-$\varepsilon$ canopy model gives realistic predictions of mean velocity and turbulence energy through the leading edge of the forest, providing the appropriate setting is chosen for $C_{4e}$. For the widely space elements used in the wind tunnel models, a value of $C_{4e}=1.5$ seems appropriate.

The more difficult problem of modelling flow in the forest lee is considered in the next section. This problem is included to assess the performance and generality of the present $k$-$\varepsilon$ canopy model.

5.5.4 Air flow through the trailing edge

A sizeable sheltered region exists downwind of any forest. The purpose of this section is to examine the validity of the proposed $k$-$\varepsilon$ canopy model in predicting the size of this sheltered zone. For predictive purposes, this represents an extremely complicated flow since we are trying to model both the influence of both the leading and trailing edges of the forest. The size and magnitude of the corresponding shelter in the forest lee will undoubtedly be influenced by the approach flow conditions and the realism of the predictions through the leading edge of the forest canopy. Therefore difference are expected between predictions and corresponding experimental observations of lee-flow.
For the purpose of validating the $k$-$\epsilon$ model, predictions of air flow through the trailing edge of the forest are compared with experimental data in models R2, R3 and R4, the model size being reduced to $10h$. The 'exact' flow was taken to be the spatially-averaged measurements at each location within the canopy domain, over the $x$-range $-5H$ upwind of the model and extending a distance of $9H$ in the lee of the model. The turbulent flow was modelled using a grid of 50 by 35 points as shown in Fig. 5.11.

![Fig. 5.11. Grid mesh used in two-dimensional simulation of flow through and above a $10h$ forest.](image)

Horizontal transects of mean velocity through a canopy of $10h$ extent are shown in Figs. 5.12a, b and c for models R2, R3 and R4, respectively. Predictions of mean velocity show qualitative agreement with the experimental data. But quantitatively, the predictions show poorer agreement with the measured data, particularly in the strong shear layer near the top of the canopy and in the near-wake and redeveloping regions. Velocity reductions within the canopy are predicted reasonable well, showing good agreement with experimental data for a four-fold change in canopy density. In general, the rate of recovery behind the canopy is also in good agreement with the observations, although the magnitude of the velocity reduction in the forest-lee is somewhat overpredicted.

Corresponding estimates of turbulence energy through the canopy are shown in Figs. 5.13a, b and c for models R2, R3 and R4, respectively. Predictions for the development of turbulence energy through the leading edge of the canopy in good agreement with the experimental data when a value of $C_{4\epsilon}=1.5$ is used. However, the
Fig. 5.12a. Streamwise profiles of $U$ in and above a $10h$ forest predicted using a $k$-$\varepsilon$ turbulence model. Circles are spatially-averaged data from wind-tunnel model R2.

The subsequent pattern of turbulence energy through the trailing edge of the forest (located at $x=10h$) shows poorer agreement with measured values. In the near-lee of the forest, values of turbulence energy are somewhat overpredicted. For example, in the region near to the floor predictions of turbulence energy are almost a factor of 2 larger than the corresponding experimental data. Possible causes for this overprediction of $k$ may be the modelled form of the $\varepsilon$-equation, which is highly empirical in nature, or the
Fig. 5.12b. Streamwise profiles of $U$ in and above a $10h$ forest predicted using a $k$-$\varepsilon$ turbulence model. Circles are spatially-averaged data from wind-tunnel model R3.

In general, the standard $k$-$\varepsilon$ turbulence model used in this study gives qualitative predictions for most turbulence flows. However, for the bench-mark problem of turbulent flow over a backward facing step, a problem similar to the one considered here, the standard $k$-$\varepsilon$ turbulence model gives highly diffusive results, generally underpredicting the reattachment length (the size of the sheltered zone) by...
about 30 per cent, and giving rise to an overshoot in turbulence energy in the near wake of the step (Nallasamy, 1985). This overshoot in turbulence energy is evident to at least 5H behind the step. A similar behaviour for $k$ is observed in the present study, in the predictions of turbulence energy in the near-wake behind the canopy.

The poor performance of the $k$-$\varepsilon$ model is often attributed to the parameterization of the $\varepsilon$ rate equation. Several modified forms of the equation have
been proposed. Chen and Kim (1988) have suggested adding a second time scale to the production term in the $\varepsilon$-equation, in order to improve the response over regions where rapid changes in turbulence energy production and dissipation rates occur. The extended $k-\varepsilon$ closure scheme of Chen and Kim (1988) gives improved performance in predicting both the size of the sheltered zone and the development of turbulence energy in the near wake of the backward facing step. This closure scheme was
Fig. 5.13b. Streamwise profiles of turbulence kinetic energy, $k$, in a 10$h$ forest predicted using a $k$-$\varepsilon$ turbulence model. Circles are spatially-averaged data from wind-tunnel model R3.

therefore considered as a way of improving the flow predictions in the near-wake region behind the model canopy. Unfortunately, when combined with the sink/source terms for the canopy domain, the simulations failed to reach a converged solution, despite the use of heavy under-relaxation on the $\varepsilon$-equation. Further tests were abandoned because of time.
Fig. 5.13c. Streamwise profiles of turbulence kinetic energy, $k$, in a 10$h$ forest predicted using a $k$-$\varepsilon$ turbulence model. Circles are spatially-averaged data from wind-tunnel model R4.

In the absence of comparable data in the far-wake of the model canopies, it is not possible to comment on the accuracy of the predictions well downwind of the forest, nor to comment on the accuracy of the predicted size of the sheltered zone in the lee of the forest. It is worth noting, however, that shelter predictions of air flow through a wind break by Wilson (1985), using both a $k$-$\varepsilon$ model and a full stress transport model, underestimated the rate of return towards the upstream equilibrium
state, and gave unsatisfactory predictions of the far wake. The discrepancy between measured and modelled velocity-recovery was attributed to a failure of the models to predict the sharp speed up zone observed above a fence. Similar underestimates of velocity above the model canopy are evident in the flow predictions presented here. It is quite possible that this will also result in poor predictions of velocity and turbulence energy well downwind of the forest.

5.6 SUMMARY AND CONCLUSIONS

The problem considered was that of modelling turbulent airflow in and above a small forest block placed in a otherwise undisturbed boundary layer flow. Computations were performed in two dimensions in order to study flow through the forest edges. The aerodynamics of a forest canopy were modelled using the spatially-averaged flow equations presented in Chapter 2, in which the forest canopy was modelled by a sink term in the momentum equations and additional source terms in the budget equations for turbulence kinetic energy and its rate of dissipation.

Three turbulence models were considered by adopting the eddy-viscosity concept and using either a zero equation (mixing length model), a one-equation (k-l model) or a two equation (k-ε) turbulence model to close the equation set. Once formulated, the flow equations were solved using a general-purpose fluid dynamics model (PHOENICS) by substituting the appropriate sink/source terms into the corresponding equations. The predictions were compared with the wind tunnel data described in Chapter 4. The main conclusions of this modelling study are:

(i) The conventional treatment of plant/airflow interactions using rigorously derived budget equations for momentum and turbulence energy (Raupach and Shaw, 1982), was found to be inadequate in this two-dimensional study of canopy flow, leading to predictions of k that were grossly inconsistent with experimental wind tunnel data in a range of model canopies (data not presented). It was concluded that an additional dissipation term was needed to model correctly the k-budget equations within a plant canopy. Some semi-empirical theory was developed in an attempt to generate more realistic predictions (Chapter 2).

(ii) Three simple turbulence closure schemes were examined, each one based on an eddy viscosity model of the Reynolds stresses. The k-ε closure scheme proved to be the most accurate, yielding very satisfactory agreement with observations of mean
velocity and turbulence energy through the leading edge of a canopy of widely spaced elements with minimal specification of an area density, $A$, a drag coefficient, $C_d$, and suitable optimization of a single parameter, $C_{4c}$. Predictions using the simpler mixing length and $k-l$ closure schemes were found to be distinctly inferior.

(iii) The unconventional treatment of the $k$-budget equation, and the corresponding modification to the $\varepsilon$-equation in the $k-\varepsilon$ canopy model seems justified by the very good agreement between predictions and experimental wind tunnel data, for a four-fold change in canopy density. A value of $C_{4c}$ equal to 1.5 was found to give the best fit to the experimental data for a four-fold change in canopy density. This value for $C_{4c}$ is recommended for modelling turbulent air flow through plant canopies of similar, scaled canopy density.

(iv) Reasonable predictions were generated for the mean velocity in the forest-lee, but corresponding predictions of turbulence energy were found to be rather less satisfactory. The poorer performance of the $k-\varepsilon$ model in the near-wake region behind the forest, was attributed to the performance of the $\varepsilon$ equation. Attempts to improve the predictions in the forest-lee by modifying the $\varepsilon$-equation failed to resolve the problem. It is possible that a higher-order model for turbulence closure is needed.

(v) The good agreement between observations and predictions of flow through a range of model canopies means this numerical model is potentially suitable for simulating turbulent air flow through a forest of widely spaced trees. However, there are doubts concerning the validity of such predictions in the forest-lee born out by the poorer predictions of turbulence energy behind the model canopies.

(vi) A potential weakness in the present model lies in the dissipation rate equation and the use of the modelling parameter $C_{4c}$, since this parameter is a mild function of area density, assuming a value in the narrow range of 1.4 to 1.6 for the canopy densities considered here. This feature of the model raises a potential problem in considering air flow through canopies that have an area density outside the range studied here.

(vii) In making predictions in full-sized forest canopies, a number of grey areas to the present model need to be resolved. For example, questions like 'What is the appropriate drag coefficient for a forest tree?' and 'What is the appropriate value of the $C_{4c}$ parameter?' will arise in scaling the predictions to a real forest. These questions can only be answered if the appropriate forest data are collected. Data from
the Cloich forest study (Chapter 3) were not considered suitable because of the unknown boundary conditions for flow into the site.

The authors experience has been that Version 1.3 of PHOENICS is not very user friendly. It is hoped that the presentation in this Chapter will go some way towards explaining PHOENICS to other users who may contemplate its use to model environmental flows.
CHAPTER 6.
CONCLUSIONS AND RECOMMENDATIONS.

6.1 INTRODUCTION

This research aims to improve our understanding of plant canopy aerodynamics by addressing the problem of wind flow through a forest of widely spaced trees. This problem is currently of particular relevance to the UK where agroforestry practices are being advocated as a viable means of taking surplus agricultural land out of food production, by planting trees at wide spacing for the production of high grade timber. At the same time as producing timber, pasture growing beneath the tree canopy would be utilized by livestock. One of the important potential benefits of agroforestry is in providing shelter to livestock during adverse weather conditions. A good understanding and accurate prediction of canopy air flow, and a knowledge of animal energy expenditure, are necessary in order to quantify these benefits.

The two basic questions this thesis sets out to answer are firstly, "What effect does a forest of widely spaced trees have on the air flow within and above the canopy?", and secondly, "Can these effects be modelled in order to predict the wind field in a given forest canopy". In order to answer these questions, a series of field and wind tunnel experiments was conducted in widely spaced tree and model canopies, respectively, and a higher-order turbulence closure model was developed to predict canopy flow.

This chapter summarizes the research findings and explores the linkages between the field and wind tunnel studies, and the fluid dynamics modelling to answer the question of whether we can use these techniques to study successfully turbulent flow in vegetative canopies. Finally, some recommendations are suggested for areas of further work.

6.2 SUMMARY AND CONCLUSIONS

This thesis combines work in three complementary areas of research into the interactions between a plant canopy and the turbulent air flow, namely field experiments, wind tunnel experiments, and numerical experiments. Before summarising these experimental studies and presenting the main scientific conclusions resulting from them, some important aspects relating to the anemometry will first be discussed.
6.2.1 Instrumentation

In any experimental investigation of turbulent air flow it is important to measure as accurately as possible the velocity fluctuations. Prior to taking measurements in the respective canopies, the performance of the anemometry was tested. In the case of the field study, the test was done by comparing measurements from the propeller anemometers against similar data from a sonic anemometer. In the case of the wind tunnel study, the test was done by comparing the measurements from the 3-wire anemometer against a known flow. The findings are summarized below.

(a) Field anemometry

The requirements of the field study were to obtain measurements of the vertical distribution of the turbulence properties. This meant using an array of suitable anemometers, each capable of resolving the three components of the instantaneous wind vector. Gill UVW propeller anemometers were chosen as the basic tool in the field study because of their proven reliability as turbulence sensors and their relatively low cost. It was possible to purchase six of these anemometers for the study. An intercomparison was made between within-canopy measurements using a propeller anemometer and a sonic anemometer, the latter instrument being recognised as 'ideal' and therefore suitable for a reference.

In order to get good agreement between the measurements from the two anemometers, it was necessary to tilt the vertical arm of the propeller array by an angle of $45^\circ$ into the mean flow. By tilting the propeller array in this manner, and subsequently rotating the data, the anemometer was able to measure $U$ and $\sigma_w$ to within 3% and $\overline{uw}$ to within about 1% of their true within-canopy value, as given by simultaneous sonic anemometer measurements. Similar comparisons of other second order statistics showed $\sigma_U$ to be underestimated by about 7% and $\sigma_V$ to be overestimated by about 7%. Experimental measurements of means and variances associated with velocity fluctuations within the forest canopy, are considered to be reliable.

Possible errors in turbulence statistics up to second order due to the propeller anemometry are relatively small, and could be corrected for using these relationships, although this was not done. It is concluded that Gill UVW anemometer arrays should always be tilted in order to improve the reliability of the data.
(b) Wind tunnel anemometry

The anemometer requirements for the wind tunnel study were to be able to resolve fluctuations in the horizontal and vertical components of the instantaneous velocity vector at high turbulence intensities. To meet this requirement a 3-hot-wire probe was fabricated and a simple procedure was developed to calibrate and operate the anemometer. Unlike in the field study, it was not possible to test the probe in situ against measurements of an ideal instrument. Instead, the response of the probe was tested in a known flow by examining the 3-wire output for a range of horizontal and vertical mean velocities, at a background turbulence intensity of about 5%.

Horizontal mean velocity measured using the 3-wire probe was compared against the corresponding value using a pitot-static tube and found to be within 1% for velocities over the range 1 to 7 m s\(^{-1}\). No comparison was possible below a velocity of 1 m s\(^{-1}\) because the wind tunnel did not run at these low velocities. Vertical mean velocities measured by rotating the 3-wire probe in the vertical plane through a range of measured angles revealed a significant offset of between about -0.1 to -0.2 m s\(^{-1}\). A procedure was developed to correct the vertical mean velocities, and associated errors in the second order statistics, whereby the 3-wire probe was shown to have an acceptance angle of at least ±45°.

A 3-wire probe gives better measurements of turbulence statistics in two-dimensions than would have been obtained with a conventional X-wire probe. Given the increased fidelity of the velocity signals from a 3-wire probe, and the relative ease with one can be constructed and operated, it is concluded that any wind tunnel measurements within model canopies, or in regions of high turbulence intensity, should consider using a 3-wire probe.

6.2.2 Field experiment

A field experimental study was undertaken to examine the effect of stand density on the vertical distribution of turbulence statistics, and associated turbulence properties, in and above a forest of widely spaced conifer trees. The trees were 8 m tall Sitka spruce, at spacings of 4 m, 6 m and 8 m between tree centres, and are referred to as the wide (TW), medium (TM) and narrow (TN) plots, respectively. The most significant findings from this part of the study were:
- An approximately four-fold decrease in stand density, corresponding to a doubling of tree spacing from 4 m to 8 m, opened up considerably the forest canopy and resulted in much greater wind penetration into the wider spaced tree canopy.

- When expressed as a fraction of mean wind speed in the open, mean velocity at the same height in the forest trunk space was 46% (wide), 29% (medium) and 16% (narrow), respectively. So significant reductions in mean wind speed in the trunk space were achieved using trees at wide spacings.

- Tangential momentum stress decreases with depth into the canopy as momentum is absorbed by the tree canopy. By analyzing the depth of momentum penetration, using the height of the mean momentum stress within the canopy, daytime $d$-values were estimated to be $0.74h$, $0.80h$ and $0.85h$ in the wide, medium and narrow plots, respectively. Corresponding nocturnal values were significantly higher ($0.89h$, $0.89h$, $0.88h$) as a result of thermal stability.

- Highest levels of turbulence intensity occur at midcanopy, and these peak values tend to increase with increasing canopy density. Peak values of longitudinal turbulence intensity are 0.70, 0.80 and 1.78, and corresponding peak values of vertical turbulence intensity are 0.52, 0.65 and 1.48 in the wide, medium and narrow plots, respectively.

- Examination of the tangential momentum stress using quadrant analysis shows the predominant events occurring within the canopy crown are sweeps and bursts, with relatively little contribution from inward and outward interactions.

- Turbulent events become more extreme and intermittent with increasing depth into the canopy and with increasing tree density. However, turbulence events occurring within a forest of widely spaced trees are less extreme than those occurring in closed stands.

- Within-canopy velocity fluctuations are non-Gaussian, being highly skewed and kurtotic, and become progressively more so with increasing depth into the tree canopy and with increasing tree density.

- Velocity spectra within the canopy display dominant peaks at wavenumbers which increase with depth into the canopy and which increase with increasing tree density.

- Spectral slopes for $u$-spectra in the upper canopy are near $-2/3$, indicating the existence of an inertial subrange. Slopes of $u$-spectra in the trunk space approach -0.9
in the medium and narrow plots suggesting a bypass of the normal eddy cascade process is occurring.

- Turbulence length scales are a decreasing function of height in the canopy and tend to decrease with increasing canopy density. Horizontal length scales are greater than vertical length scales and are comparable to the height of the canopy.

6.2.3 Wind tunnel experiment

A wind tunnel experimental study was established to examine the effect of stand density on the horizontal and vertical distribution of turbulence statistics in and above a 1:75 scale model forest of widely spaced elements. The model forests were at spacings of 1/3h (R4), 1/2h (R3) and 2/3h (R2), and at two sizes, 10h and 20h. The most significant findings from this part of the study are summarised as follows:

- The wind tunnel study was successful in producing a comprehensive and unique set of turbulence data for air flow through and above a model forest of widely spaced elements. Many of the features of canopy flow identified in the field study were simulated successfully. The within-canopy, normalized vertical distributions of turbulence statistics near the back of the model canopy (15h) were in good agreement with data from the field experiment.

- By examining the tangential momentum stresses using quadrant analysis, it was possible to demonstrate that most of the events occurring within the canopy crown are sweeps and bursts, with relatively little contribution from inward and outward interactions. This observation is in good agreement with the field observations and suggests that within-canopy sweep and burst events can be simulated realistically in wind tunnel models. Such events are probably generated by the velocity shear at or just above the canopy.

- The magnitudes of the stress fractions at hole size zero are all less than 0.5. It follows that the tangential momentum stress in a sparse canopy comprises events that are of a smaller magnitude those occurring in denser canopies where stress fractions as large as 2.0 have been observed (Baldocchi and Meyers, 1988a).

- The corresponding $d$-values were estimated from the vertical profiles of tangential momentum stress at a distance of 15h in a 20h forest, and found to be 0.64h, 0.72h and 0.78h in models R2, R3 and R4, respectively. This confirms that a four-times decrease in canopy density results in much greater wind penetration into sparser canopies.
- Mean flow was reduced rapidly with distance from the leading edge and this attenuation was found to increase with increasing canopy density. Despite the trunk space being open below 0.37h, significant reductions in mean velocity are observed at downwind distance of 15h, being 42%, 24% and 14% of the upwind velocity in models R2, R3 and R4, respectively.

- A rapid rise in turbulence energy was observed at midcanopy as air flowed through the leading edge of the forest, and this rise peaked at distances of between 1h to 3h into the forest. Turbulence energy decreased with further distance into the forest, reaching a local minimum at around 5h, and thereafter increasing towards the back of the forest, at rates comparable to the above-canopy rates of increase in turbulence velocity.

- Mean flow in the lee of a 10h sized forest continued to decrease near the ground for a distance of between 1h to 5h and thereafter recovered at a rate which was faster behind a denser canopy. At a leeward distance of 9h mean velocity near the ground was about 0.55% of the upwind approach flow. So a significant sheltered zone exists in the lee of a forest of widely spaced trees.

- Turbulence energy in the lee of the model canopy tended to increase to values much larger than found upwind of the forest. The trend was for turbulence energy to be larger in the lee of a denser canopy.

- The concept of a shelter integral was used to rank correctly the model canopies in terms of their effective wind shelter. It is hypothesised that the shelter integral may be a useful method to evaluate and compare the corresponding wind shelter for different forest designs, as simulated by the numerical predictions.

- From the wind tunnel results is has been possible to show that wind flow through a forest of widely spaced trees is dominated by advective edge effects which are observed to distances of between 10h and 20h, depending on canopy density. It is therefore concluded that the flow regime is more complicated than can be handled by a simple 1-dimensional treatment.

6.2.4 Numerical experiment

A numerical study was carried out in two-dimensions to predict turbulent air flow in and above a small forest stand placed in an otherwise undisturbed rural boundary layer flow. The governing partial differential equations for the conservation of mass, momentum, turbulence kinetic energy and its rate of dissipation were solved
using a well-tested fluid dynamics program called PHOENICS. The most significant findings of this part of the study are:

- The conventional theoretical treatment of plant/airflow interactions was found to be inadequate in this two-dimensional study of canopy flow, leading to predictions of $k$ that were grossly inconsistent with experimental wind tunnel data in model forest canopies. In particular, predictions of $k$ using conventional theory were found to increase continuously with increasing downwind distance. It was concluded that an additional dissipation term was needed to model correctly the $k$-budget equations.

- An alternative treatment was adopted for the $k$-budget equation by adding an additional semi-empirical sink term to account for the dissipation of shear-generated to wake-generated turbulence kinetic energy.

- Three simple closure schemes were examined, each one based on an eddy-viscosity model for the Reynolds stress terms, and the $k$-$\varepsilon$ model was found to be the most promising when compared against the experimental wind tunnel data. Predictions using the simpler mixing length and $k$-$\lambda$ models were distinctly inferior. These models use a constant mixing-length inside the canopy, which is both difficult to prescribe and conceptually in error.

- Very satisfactory agreement was reached between predictions from the $k$-$\varepsilon$ canopy flow model and observations of $U$ and $k$ through the leading edge of the model canopies, with minimal specification of an area density, $A$, a drag coefficient, $C_d$, and suitable optimization of a single parameter, $C_\varepsilon$, in the $\varepsilon$-budget equation. It was concluded that the satisfactory performance of the numerical model justifies the unconventional treatment of the $k$- and $\varepsilon$-budget equations within the canopy.

- The agreement between predictions and measurements in the lee of a forest are fairly good in terms of mean velocity for a range of canopy densities. However, the predictions of turbulence energy in the near-wake region behind the model canopy is rather less satisfactory. The poorer performance of the $k$-$\varepsilon$ model in the forest lee is attributed to the performance of the $\varepsilon$-equation. Attempts to improve the performance of the predictions by modifying the $\varepsilon$-equation have so far failed to resolve the problem. A further examination of the problem using a 2nd-order stress transport model is probably warranted.
6.2.5 Linkages between various experiments

In order to examine linkages between the various experimental and numerical studies, vertical profiles of normalised mean velocity, turbulence kinetic energy, and tangential momentum stress at a downwind distance of $15h$ are reproduced in Figs. 6.1 to 6.5.

Some discrepancy between the field data, the wind tunnel data and the numerical predictions is to be expected because of unknown influences at the field site, associated with surrounding topography and poorly-defined boundaries, and known differences in canopy density in the trunk space. Nevertheless these comparisons demonstrate reasonable agreement in measured and predicted distributions of mean velocity and turbulence kinetic energy for a four-fold change in canopy density. Several important conclusions which can be drawn from the comparisons are discussed below.

- Predictions of $U/U_T$ are in good agreement with wind tunnel data, considering the large spatial-variation of the within-canopy measurements (Fig. 6.1). The influence of a four-fold change in canopy density produces a similar change in the velocity gradients at the top of the canopy, for all three studies. Wind speeds in the trunk space show the expected result that the forest canopy has a lower trunk space velocity than observed in the model data, and this is because the trunk space is less open in the forest plots.

- A four-fold change in tree density does not, however produce a distinct separation in wind speed profiles in the forest data as that observed in the corresponding model data and predictions, when velocities are normalized by $U/U_\star$ (Fig. 6.2). The wind tunnel data and numerical predictions remain in good agreement as to the influence of a 4-times decrease in canopy density on the behaviour of $U/U_\star$, but the field data show almost no change in above canopy profiles of $U/U_\star$ for a halving of canopy density (from TM to TW). This is somewhat surprising, but may be an artifact of the small plot size and complex pattern of the surrounding surface roughness at the field site.

- In terms of a bulk drag coefficient defined by $C_d=(U_\star/U)^2$ at canopy height, predicted $C_d$'s are 0.054, 0.080 and 0.132, compared to corresponding values of 0.043, 0.064 and 0.113 in the wind tunnel models R2, R3 and R4, respectively. The corresponding drag coefficient for a conventional forest canopy is usually assumed to be 0.1. The numerical model gives fairly good predictions for $C_d$. These values are
Fig. 6.1. Vertical profiles of normalized mean velocity, $U/U_*$, from field, wind tunnel and numerical experiments, for a four fold change in canopy density.

Fig. 6.2. Vertical profiles of normalized mean velocity, $U/U_*$, from field, wind tunnel and numerical experiments, for a four fold change in canopy density.

comparable to estimates of $C_d$ implied from measurements of aerodynamic conductance at the forest site, where values of 0.04, 0.06 and 0.08 were derived in the wide, medium and narrow plots, respectively, using a mass exchange method for the evaporation of water from a wet canopy (Teklehaimanot, 1990).
Fig. 6.3. Vertical profiles of turbulence energy, $k/U_r^2$, from field, wind tunnel and numerical experiments, for a four fold change in canopy density.

Fig. 6.4. Vertical profiles of turbulence energy, $k/U_r^2$, from field, wind tunnel and numerical experiments, for a four fold change in canopy density.

When normalized by $U_r^2$, experimental data and the predictions of turbulence kinetic energy are in good agreement, especially in the upper canopy and to heights just above the canopy top (Fig. 6.3). However, values of turbulence energy measured above canopy R2 ($z > 1.3h$) are lower than predicted. This disparity between
measurements and predictions reflects the fact that at a downwind distance of 15\(h\), the inner boundary layer over model R2 has only developed to a height of about 1.3\(h\). Therefore values of \(k\) above 1.3\(h\) are strongly influenced by the upwind conditions, in which values of \(k\) are known to be lower in the wind tunnel.

- The unpredictable influence of different upwind conditions is thought to explain why, in the field observations, a halving in tree density (from TM to TW) has not produced the same effect on turbulence above the forest canopy as was observed by halving the canopy density (from R3 to R2) in the wind tunnel and numerical experiments (Fig. 6.3). It seems probable that the vertical distribution in turbulence kinetic energy that has developed above the medium plot has subsequently travelled downwind over the change in roughness from TM to TW with very little corresponding change in turbulence energy following this change in roughness. This behaviour is thought to reflect the relatively small plot size. A similar explanation is suggested for the profiles of mean velocity above the wide and medium plots, where no significant differences were observed in the above canopy profiles.

- Experimental data and the predictions of turbulence kinetic energy are in good agreement near the top of the canopy, when normalized by \(U_*^2\) (Fig. 6.4). Values of \(k/U_*^2\) at \(z=h\), lie within a narrow range of 2.6 to 3.2. The influence of canopy density on within-canopy profiles of \(k\) are in good qualitative agreement. There is a tendency, however, for the numerical model to under-predict turbulence energy deep within the canopy when compared to the experimental data. This underprediction may be partly due to the adoption of an eddy-viscosity closure model for the Reynolds stresses.

- The vertical distribution of tangential momentum stress, normalized by the value at the top of the canopy, is shown in Fig 6.5, for the field, wind tunnel and numerical experiments, respectively. Again, good qualitative agreement is obtained between all three experiments in terms of the effect of a 4-times decrease in canopy density on the observed profiles. Decreasing the canopy density opens up the canopy and allows for a greater penetration of momentum into the canopy, and this leads to an increase in within-canopy values of \(\overline{uw}/U_*^2\) in a sparser canopy. A constant stress layer is observed above the forest canopy, and this constant layer is predicted by the numerical model. However, the wind tunnel data show a more rapid decrease in \(\overline{uw}\) above models R2 and R3, which is thought to be associated with the lower turbulence levels in the approach flow into the wind tunnel model.
Fig. 6.5. Vertical profiles of tangential momentum stress from field, wind tunnel and numerical experiments, for a four fold change in canopy density.

- A closer inspection of the within-canopy profiles of momentum stress reveals some potential weaknesses with the numerical model. When compared with the experimental data in each of the model canopies, the numerical model tends to under-predict the magnitude of $\overline{uw}$ within the canopy, and in the trunk space region, tends to predict positive stresses where negative stresses are observed. Because the predictions of $\overline{uw}$ are made using velocity gradients and positive coefficients (the eddy viscosity), that is they adopt K-theory, the numerical model cannot predict counter gradient momentum fluxes which may occur within the canopy. However, since advective effects are still evident in the trunk space at $15h$ and are a possible cause of the subcanopy jet, other factors may explain equally well this discrepancy. For example, improper spatial averaging of the $\overline{uw}$ profiles within the canopy or measurement errors in $\overline{uw}$ at high turbulence intensities.

In conclusion, the results from these three independent studies have provided good qualitative and in some cases good quantitative agreement regarding the effect that a forest of widely spaced trees has on the air flow through and above the canopy. The additional knowledge gained from the wind tunnel study, in terms of the streamwise development of mean and turbulence velocities through the canopy, has been invaluable in validating the numerical model to the point where it is now of potential use in predicting the pattern of air flow through widely spaced tree canopies.
There are a number of refinements that could be made to the model, and a number of areas for further work. These are discussed in the following section.

6.3 RECOMMENDATIONS FOR FUTURE WORK

One of the aims of the present study was to develop and test a numerical model of turbulent air flow that could be used to predict wind shelter in a forest of widely spaced trees. In that respect this thesis has achieved its stated objective. Further work is needed in order to apply this model to the problem of predicting the benefits of shelter to animals in an agroforestry system. To address this problem, we need a better understanding of animal energy expenditure. Experiments are in progress at MLURI to establish relationships between wind speed and energy expenditure in sheep. It is planned to combine these relationships with predictions from the present model to assess alternate agroforestry designs in terms of the possible shelter benefits they can provide to the sheep. This represents a small step towards the design of an optimum agroforestry system.

This thesis has concentrated on the problem of air flow through widely spaced tree canopies. Because of the general purpose nature of the PHOENICS code, the present canopy flow model can be modified easily for the purpose of predicting air flow in two-dimensions through other canopies, such as agricultural crops. However, given the semi-empirical nature of turbulence modelling it seems likely that additional field or wind tunnel data would be needed in order to validate such predictions.

A useful feature of the PHOENICS code is the ability to solve flow problems using a curvilinear grid. This feature allows the possibility of examining the effect of topography on air flow through plant canopies. This represents a challenging area in environmental fluid dynamics, and an important one in terms of understanding forest microclimate since forests are seldom, if ever, located on flat, level, extensive sites.

An immediate concern with the present air flow model, if it were to be applied to closed forest stands or dense agricultural crops, is the inability of the model to predict counter gradient fluxes. This inability stems from the adoption of an eddy-viscosity approach to model the Reynolds stresses. An investigation of alternative approaches to turbulence modelling, for example by adopting a second-order closure model to solve for the Reynolds stress terms, represents a useful and necessary advancement on the present work. Stress transport models have already demonstrated more realistic predictions of one-dimensional velocity and turbulence profiles through
plant canopies (Wilson and Shaw, 1977), although the extension to two-dimensions has yet to be shown. Further work on developing a two-dimensional stress-transport model for air flow is recommended.

Wind is only one aspect of the canopy microclimate. With a model to describe air flow, we are in the attractive position of being able to begin to examine the wider role plants play in modifying the microclimate by developing models for the transport of scalars, like heat and water vapour, and the exchange of gases, like carbon dioxide, within the plant canopy.

These models require as inputs the respective source distributions for the scalars, such as the distribution of leaf temperature, water vapour fluxes etc. within the canopy, and they need to be based on a rigorous set of governing equations describing the distribution and transport of such scalars. This is not an easy task, for it requires the addition of further submodels in order to establish the scalar source distributions.

Providing these source distributions are known, or can be estimated, PHOENICS is equipped with the mathematical framework necessary to advect, diffuse and otherwise redistribute scalars through the canopy using eddy-viscosity turbulence closure. However there are doubts, as have already been expressed, regarding the validity of an eddy-viscosity approach to modelling canopy transport processes since such models can not describe counter-gradient fluxes which are known to occur within plant canopies.

In order to solve the problem of scalar transport in a plant canopy, and in order to develop a more realistic model or turbulent air flow within the canopy, a higher-order closure model (of at least second-order) is required. PHOENICS is not immediately amenable to solving such problems, but can be modified in order to do so (see Malin and Younis, 1989). Further work on developing a second order turbulence model to include the transport of scalars in two dimensions is recommended.

6.4 CONCLUDING REMARKS

Lack of time has meant that only a few numerical simulation runs could be performed with the present canopy flow model. These runs were restricted to a validation study using experimental data from the wind tunnel model. No comparative full-scale predictions were carried out so there is no way of judging the accuracy of
the numerical predictions at full-scale. However, since the wind tunnel data were well-predicted and as these data were in good qualitative and quantitative agreement with the field data, it seems reasonable to suggest that the numerical model is amenable to predictions at full-scale. It is therefore concluded that the model derived as a result of this thesis is potentially suitable for predicting turbulent air flow in a forest of widely spaced trees.
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APPENDIX A1.

VERTICAL PROFILES OF NORMALIZED TURBULENCE VELOCITY COMPONENTS FROM THE FIELD STUDY AT CLOICHT.

The following figures show the spatial and nocturnal variation in vertical profiles of normalized turbulence velocity components measured in and above a forest of 8 m tall Sitka spruce trees, at spacings of 8 m (TW), 6 m (TM) and 4 m (TN) between tree centres. Three normalizations have been used by dividing the turbulence velocity components by the mean velocity at tree top height, $U_T$ (Figs. A1.1 to A1.3), dividing by the friction velocity at tree top height, $U_\ast$ (Figs. A1.4 to A1.6), and by dividing by the local mean velocity, $U$ (Figs. A1.7 to A1.9). Spatially-averaged vertical profiles of normalized turbulence velocity calculated by taking the arithmetic mean of measurements in the row and gap positions are presented in section 3.5.5.
Fig. A1.1 Spatial variation in vertical profiles of longitudinal turbulence velocity normalized by mean velocity at tree top height. Error bars represent one standard deviation (n > 100).

Fig. A1.2 Spatial variation in vertical profiles of lateral turbulence velocity normalized by mean velocity at tree top height. Error bars represent one standard deviation (n > 100).
Fig. A1.3 Spatial variation in vertical profiles of vertical turbulence velocity normalized by mean velocity at tree top height. Error bars represent one standard deviation (n > 100).

Fig. A1.4 Spatial variation in vertical profiles of longitudinal turbulence velocity normalized by friction velocity at tree top height. Error bars represent one standard deviation (n > 100).
Fig. A1.5 Spatial variation in vertical profiles of lateral turbulence velocity normalized by friction velocity at tree top height. Error bars represent one standard deviation (n > 100).

Fig. A1.6 Spatial variation in vertical profiles of vertical turbulence velocity normalized by friction velocity at tree top height. Error bars represent one standard deviation (n > 100).
Fig. A1.7 Spatial variation in vertical profiles of longitudinal turbulence intensity. Error bars represent one standard deviation (n > 100).

Fig. A1.8 Spatial variation in vertical profiles of lateral turbulence intensity. Error bars represent one standard deviation (n > 100).
Fig. A1.9 Spatial variation in vertical profiles of vertical turbulence intensity. Error bars represent one standard deviation (n > 100).
APPENDIX A2.

CONTOUR PLOTS OF MEASUREMENTS AND PREDICTIONS OF TURBULENT AIR FLOW THROUGH AND ABOVE A MODEL FOREST OF WIDELY SPACED ELEMENTS.

The following figures are contour plots of horizontal wind speed and turbulence kinetic energy measured in the wind tunnel models and predicted using the K-$k$-$\varepsilon$ canopy flow model. Results and predictions are reported for three forest densities (R2, R3 and R4), at two forest sizes (dimensions of 20$h$ and 10$h$ in the streamwise direction). The wind tunnel data have been spatially-averaged by taking the arithmetic mean of three measurements within the model canopy.

The flow field is mapped over a domain spanning the distance interval $-5h$ to $20h$ in the horizontal and spanning the height interval $0h$ to $2.5h$ in the vertical. Measurements are mapped using a grid of 13 by 17 points and predictions are mapped using a grid of 24 by 21 points over this subdomain.

Relative velocity is defined by taking the ratio of the downwind mean horizontal velocity ($U$) to the upwind reference velocity at the same height ($U_v$), which coincided with a location $5h$ upwind of the leading edge of the forest. Relative turbulence kinetic energy is defined by taking the ratio of the square root of the turbulence energy ($k^{0.5}$) to the local mean horizontal velocity ($U$).
Fig. A2.1 Contours of measured wind speed and turbulence kinetic energy through and above model R2 (20h). Flow is left to right and 6 m s\(^{-1}\) at z=2.5h.
Fig. A2.2 Contours of predicted wind speed and turbulence kinetic energy through and above model R2 (20h). Flow is left to right and 6 m s$^{-1}$ at $z=2.5h$. 

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Fig. A2.3 Contours of measured wind speed and turbulence kinetic energy through and above model R3 (20h). Flow is left to right and 6 m s$^{-1}$ at $z=2.5h$. 
Fig. A2.4 Contours of predicted wind speed and turbulence kinetic energy through and above model R3 (20h). Flow is left to right and 6 m s\(^{-1}\) at \(z=2.5h\).
Fig. A2.5 Contours of measured wind speed and turbulence kinetic energy through and above model R4 (20h). Flow is left to right and 6 m s$^{-1}$ at z=2.5$h$. 
Fig. A2.6  Contours of predicted wind speed and turbulence kinetic energy through and above model R4 (20h). Flow is left to right and 6 m s\(^{-1}\) at \(z=2.5h\).
Fig. A2.7 Contours of measured wind speed and turbulence kinetic energy through and above model R2 (10h). Flow is left to right and 6 m s$^{-1}$ at $z=2.5h$. 
Fig. A2.8 Contours of predicted wind speed and turbulence kinetic energy through and above model R2 (10h). Flow is left to right and 6 m s\(^{-1}\) at \(z=2.5h\).
Fig. A2.9 Contours of measured wind speed and turbulence kinetic energy through and above model R3 (10h). Flow is left to right and 6 m s\(^{-1}\) at z=2.5h.
Fig. A2.10  Contours of predicted wind speed and turbulence kinetic energy through and above model R3 (10h). Flow is left to right and 6 m s\(^{-1}\) at z=2.5h.
Fig. A2.11  Contours of measured wind speed and turbulence kinetic energy through and above model R4 (10h). Flow is left to right and 6 m s$^{-1}$ at $z=2.5h$. 
Fig. A2.12 Contours of measured wind speed and turbulence kinetic energy through and above model R4 (10/i). Flow is left to right and 6 m s\(^{-1}\) at \(z=2.5h\).
APPENDIX A3

PERFORMANCE OF THE WIND TUNNEL

The uniformity of the wind tunnel jet was examined by measuring values of $U$ and $\sigma_U$ at different locations in an empty tunnel, using a single hot-wire anemometer. These measurements were taken in order to define a suitable working section for the wind tunnel.

Fig. A3.1 shows vertical profiles of $U$ and $\sigma_U$ at distances of between 2 m and 5 m downstream from the turbulence grid, measured along the tunnel centre line. At a given height above 0.1 m, streamwise changes in $U$ down the centre of the jet were less than 5%. However, near the floor of the tunnel (below 0.1 m) values of $U$ decreased by about 10% with increasing downwind distance. Similarly, streamwise changes in $\sigma_U$ were of the order of 10% at heights above 0.1 m, whereas near the floor $\sigma_U$ increased by up to 20% with increasing downwind distance. The velocity profiles were therefore only approximately steady down the centre of the jet between the distances of 2 m to 5 m downstream from the turbulence grid.

Fig. A3.2 shows transverse profiles of $U$ across the width of the jet, at heights of 0.05 m, 0.15 m and 0.3 m. A systematic variation in $U$ was observed across the jet and this variation was not symmetric with respect to the centre line of the wind tunnel. The cross-stream variation in $U$ was similar at the three measurement heights and was probably caused by a spreading of the jet as it flowed across the open table and recirculated within the room.

In order to minimise the effects of this cross-stream variation in $U$, all measurements in the forest canopies were taken at a position close to the centre line of the wind tunnel. At these locations, velocity profiles in the empty tunnel were approximately steady with $U$ decreasing by about 10% and $\sigma_U$ increasing by about 20% near the tunnel floor. These changes were nevertheless considerably smaller than any changes occurring when the model forests were placed in the flow.

Observations of $U$ and $\sigma_U$ will differ by an unknown amount from values that would otherwise have been observed had the jet been steady. It was hoped that by consistently measuring near the tunnel centre such differences, due to the inadequacies of the wind tunnel, would small.
Fig. A3.1. Vertical profiles of mean velocity, $U$, and turbulence velocity, $\sigma_u$ near the tunnel centre line, at different distances downstream from the turbulence grid.

Fig. A3.2. Profiles of mean velocity, $U$, across the width of the jet, $y$, at different distances downstream from the turbulence grid, $x$, and at different heights, $z$. 
APPENDIX B1.
PERFORMANCE TEST OF THE PROPELLER ANEMOMETERS.

B1.1 INTRODUCTION

The Gill UVW 3-propeller anemometer was chosen as the basic tool to measure turbulence statistics in the forest because of its proven reliability and relatively low cost. However, the propeller anemometer is not without its idiosyncrasies (Wyngaard, 1981). Of particular importance for this application is the non-ideal cosine response to off-axis winds and the inevitable stalling of propellers at low wind speeds. For a wind angle of $45^\circ$ to the propeller axis, errors of 13% in mean velocity occur as a result of the non-cosine response (Drinkrow, 1972). The percentage error increases with increasing wind angle so that a vertically-orientated propeller, which spends most of its time at or near to $90^\circ$ to the mean flow, is subject to the largest errors. In addition to a decreased sensitivity at large wind angles, a vertical propeller frequently changes its direction of rotation as the flow reverses from updraft to downdraft conditions. Thus the response of a vertical propeller is particularly limited by the inertia and consequent stalling of the propeller.

The instrument response can be improved and the quality of the turbulence statistics enhanced by using special computational and operational methods, namely correcting for the non-cosine response of the propellers during processing (Horst, 1972), and tilting the anemometer into the wind so that none of the propellers are vertical (Bowen and Teunissen, 1986). The ability of such 'correction' procedures to adequately compensate for the response limitations of the anemometer can be tested in the field by comparing velocity statistics against those from an ideal instrument.

The sonic anemometer is an appropriate standard against which to test the performance of the propeller anemometer. Intercomparisons have been reported by Horst (1973), Bowen and Teunissen (1986) and others, for turbulence statistics measured above fairly homogeneous sites. These studies demonstrate an improved performance by 'cosine correcting' the data and 'tilting' the anemometer. However, intercomparisons have not been done within a forest canopy where the turbulence is more intense and where the response limitations may have an even greater effect on the measurements. Such an intercomparison study was undertaken.

The suitability of using a propeller anemometer array within a forest canopy of widely spaced trees was examined by comparing velocity statistics from a 3-
component sonic anemometer (Kaijo-Denki WA200) with those from a 3-component propeller anemometer (Gill UVW type, model 08274 polystyrene propeller). In addition, the cosine response of a model 08274 propeller was examined in a wind tunnel. The results from these tests are reported below.

**B1.2 COSINE CORRECTION**

The non-cosine response of the propeller presents the major limitation to the accuracy of the Gill UVW anemometer at frequencies below about 0.3Hz (Horst, 1973). These errors can be corrected for, or at least minimised, using a computation method first described by Horst (1972). The procedure is to calculate direction cosines from ‘raw’ measurements of the 3 velocity components, apply corrections to the data to account for the non-ideal cosine response of the propellers, and then calculate new direction cosines from the corrected velocity components. An iterative scheme is adopted until the results converge; the calculations terminate when successive direction cosines agree to within 0.02 or when a maximum of 6 iterations have been performed.

The above procedure implies a knowledge of the directional response of the propeller. The propeller has in the past been tested extensively in the wind tunnel to determine its (cosine) response to winds from various angles of attack (wind angle) (Holmes, 1964; Pond et al., 1979). A table of multiplying factors is usually supplied with the instrument to enable the user to correct the velocity signals for deviation from the cosine. The validity of such correction factors was tested by examining the cosine response of the propellers in the Civil Engineering wind tunnel. The tunnel was operated at a nominal velocity of 6 m s⁻¹ and turbulence intensity of about 10%. A single propeller arm was mounted in a level position so that air flow was into the propeller; this orientation serves to define $U$ at a wind angle of 0 degrees. The wind angle was varied by rotating the propeller arm about the horizontal plane in increments of between 2 and 5 degrees using a protractor device to measure wind angle. A mean value of $U$ at each wind angle was calculated from a 20s time series of measurements taken at 5Hz.

The results of this performance test demonstrate clearly a deviation from the ideal cosine behaviour (Fig. B1.1). The response is very nearly symmetrical for wind angles either side of the stall angle (90°) so that no significant difference is found in the response to wind from the front ($\theta<90^\circ$) and from behind the propeller ($\theta>90^\circ$). This means that it is possible to determine a universal correction factor that is valid.
Fig. B1.1. Directional response of model 08274 Gill propeller (pecked line); the ideal cosine response is shown by the solid line.

Fig. B1.2. Correction factor for the non-cosine response of the model 08274 Gill propeller (pecked line); the manufacturers calibration curve is shown by the solid line.

for positive and negative values of velocity, and this correction can be applied to correct each velocity component of the Gill UVW array.

The correction factor is determined by the ratio of the true velocity component at a wind angle \( \theta \) \((U \cos(\theta))\) to the velocity measured by the propeller anemometer. Data in Fig. B1.1 have been replotted in Fig. B1.2 in order to calculate a correction
factor. The results are in close agreement with the manufacturers calibration curve (R.M. Young Co., USA) for the model 08274 propeller (the solid line in Fig. B1.2). The main difference occurs when the propeller is near to stalling. However, since the velocity component for wind angles near 90° is small, the difference between suggested and observed correction factors does not have a large effect on corrected velocities. The velocity residuals (difference between measured and true velocity) are thereby reduced to a tolerable level using the standard correction curve (Fig. B1.3). Consequently, the manufacturers calibration has been used to correct for the non-cosine response of the propeller anemometers.

B1.3 THRESHOLD RESPONSE

An axial wind of approximately 0.2 m s⁻¹ is required to overcome the starting friction and turn the propeller. Consequently, the propellers stall whenever the velocity is less than about 0.2 m s⁻¹ or whenever the axial velocity component reverses direction. The threshold response can be improved by altering the orientation of the anemometer. For the $U$ and $V$ components an improved response can be achieved by orientating the anemometer so that the two horizontal arms are at an angle of 45° to the mean wind direction (Horst, 1973).
Overcoming the poor threshold response is more a difficult problem for the vertical propeller because the vertical velocity component changes direction frequently and this causes the propeller to stall more often, leading to a loss of small-amplitude $w$-fluctuations (Wieringa, 1972). The response of the $W$ component can be improved by tilting the vertical propeller at an angle of 45° into the mean wind (Horst, 1973; Bowen and Teunissen, 1986) in order to minimise the stall time of the propellers.

A performance test of a 'tilted' Gill UVW anemometer was carried out at the Cloich agroforestry site using a Kaijo-Denki 3-component sonic anemometer as the reference instrument. Both anemometers were supported on booms that extended approximately 1.5 m to windward of a triangular TV-type tower. The lateral separation between anemometers was about 2 m. Measurements were taken in the wide and medium sites with the anemometers mounted in the trunk space at a height of 2 m, and at mid-canopy at a height of 6 m.

Unfiltered time series data were captured at 8Hz over an interval of 25 minutes and stored on floppy disc for later analysis. The data processing involved a 3-d coordinate rotation of the data to force mean vertical ($W$) and lateral ($V$) components to zero. A cosine correction was performed on the velocity data from the Gill anemometer, and means and variances of the 3 velocity components were computed in the standard way.

The results the intercomparison test are shown in Figs. B1.4-B1.6. The turbulence statistics are plotted on the same graph so the results from measurements at 2 heights in two different canopies allows for an intercomparison in effectively 4 different flow regimes. There is some scatter in the data, as would be expected, since the within-canopy flow statistics exhibit a large local variability, and it is unlikely the two anemometers were placed in exactly the same flow. The intercomparison of turbulence statistics has been done by merging the results from measurements at different heights and forest densities into one data set.

Based on over 10 hours of field data at each location, the performance of the 'tilted' Gill anemometer relative to the sonic anemometer for each turbulence statistic is as follows (note: the linear regression has been forced through zero):

\[
\begin{align*}
U_{GILL} &= 0.977 \ U_{SONIC}; \quad SE=0.15 \\
\sigma_{U,GILL} &= 0.932 \ \sigma_{U,SONIC}; \quad SE=0.10 \\
\sigma_{V,GILL} &= 1.073 \ \sigma_{U,SONIC}; \quad SE=0.08 \\
\sigma_{W,GILL} &= 0.973 \ \sigma_{U,SONIC}; \quad SE=0.03
\end{align*}
\]
Fig. B1.4. Intercomparison of $U$ statistics; W stands for 'wide' site, M stands for 'medium' site and 2 m and 6 m are the measurement heights. The same nomenclature is used in Figures B1.5-B1.8.

Fig. B1.5. Intercomparison of longitudinal turbulence velocity, $\sigma_U$.

$$\bar{u}w_{GILL} = 1.010 \bar{u}w_{SONIC}; \quad SE=0.06$$

So the 'tilted' Gill anemometer is within 3% for $U$ and $\sigma_w$, and within 1% for the tangential Reynolds stress $\bar{u}w$, but measures lower values of $\sigma_U$ (by about 7%) and higher values of $\sigma_V$ (by about 7%). The performance of the 'tilted' Gill in the forest canopy is similar to the comparisons of $U$, $\sigma_U$ and $\sigma_V$ above a fairly homogeneous site,
as described by Bowen and Teunissen (1986), although Bowen and Teunissen (1986) measured 7% lower values of \( \sigma_v \) using a 'tilted' Gill. The performance of the 'tilted' Gill in the forest canopy is much better than the comparisons of \( \sigma_w \) and \( uv \) described by Bowen and Teunissen (1986), who measured 25% lower values of \( \sigma_w \) and 18% lower values of \( \overline{uv} \).
Given the local variability of the flow statistics in the forest canopy is large, so that some scatter is expected in the results, this intercomparison serves gives us some confidence that the turbulence measurements taken at the Cloich field study using a 'tilted' Gill are reliable.
APPENDIX B2
HOT-WIRE ANEMOMETERS AND THE 3-HOT-WIRE PROBE

B2.1 INTRODUCTION

The single hot-wire anemometer is one of the principle ways of obtaining quantitative information on turbulent flows although it does have certain limitations. The main drawback is that the accuracy of measurement depends largely on the turbulence intensity of the flow, decreasing as the level increases above some limiting value. A single hot-wire anemometer responds to the magnitude of the instantaneous wind vector, but it is unable to resolve individual velocity components, nor the direction of flow.

The conventional method of obtaining simultaneous measurements of more than one velocity component is to employ a X-wire anemometer. The X-wire probe resolves unambiguously two components of the velocity vector whenever the turbulence intensity of the flow is below about 20% and when no flow reversal occurs. However, the accuracy of the X-wire probe results decreases noticeably as turbulence intensity increases beyond 20% (Tutu and Chevray, 1975). A X-wire probe was judged unsuitable for measurements within the forest canopy, where turbulence intensities are likely to be higher than 50% (Cionco, 1972).

Kawall et al. (1983) developed a 3-hot-wire probe for measuring two-component velocity statistics in highly turbulent flows. A similar 3-hot-wire probe was developed independently by Legg et al. (1984). The 3-wire probe is essentially a normal hot-wire mounted next to a conventional X-wire. This probe is capable of measuring streamwise and vertical velocities with a high degree of accuracy for turbulence intensity levels of up to 70% (Kawall et al., 1983).

In the present study, the horizontal and vertical components of the velocity vector were measured with a 3-wire probe using the digital technique described by Kawall et al. (1983). Details of the construction and operation of the 3-wire probe are given in the following section. Since the single hot-wire forms the cornerstone of any 3-wire probe, a description of a single hot-wire and the governing response equations will first be given.
B2.2 THE HOT-WIRE ANEMOMETER

In this investigation Disa type P01 and P55 miniature hot-wire probes were used in a constant temperature mode. These probes have a 5 μm diameter platinum filament and were heated to a temperature of approximately 250 °C. The principle of operation of a hot-wire is as follows.

As air blows across the filament, heat is lost from the wire and it cools. The electrical resistance of the platinum filament changes with temperature, so that fluctuations in wire temperature caused by changes in airflow are registered as changes in wire resistance. The wire resistance was measured using a Disa type 55M01 hot-wire bridge unit. This unit compensates for changes in wire resistance by supplying an instantaneous feedback voltage to maintain the wire at a constant resistance, and hence a constant temperature. Fluctuations in the airflow were registered directly as variations in wire voltage.

King's cooling law is widely used to relate the output voltage from a hot wire, $E$, to an effective cooling velocity, $U_{\text{eff}}$, using

$$E^2 = A + BU_{\text{eff}}^n \quad (B2.1)$$

where $A$ and $B$ are calibration constants which must be determined individually for each wire. In Eq. B2.1 $U_{\text{eff}}$ stands for the velocity that the wire actually 'sees'. Fig. B2.1 represents the instantaneous velocity vector contained in the hot-wire plane.

![Fig. B2.1. Velocity vector resolution for a single hot-wire.](image)

Whenever turbulence levels are small, the effective cooling velocity is equal to the flow velocity perpendicular to the wire, so that $U_{\text{eff}} = U_N$. This expression is no longer valid if the hot-wire is employed in turbulent flows where the instantaneous velocity vector is continuously changing its angle relative to the hot-wire. In this case
the velocity components parallel to the wire axis, $U_r$, and binormal to the wire axis, $U_b$, contribute to the cooling of the wire. A more general expression, has been proposed by Jorgensen (1971)

$$U_{\text{eff}} = \left( U_N^2 + k^2 U_T^2 + h^2 U_B^2 \right)^{\frac{1}{2}} \quad \text{(B2.2)}$$

where $k$ and $h$ are sensitivity parameters of the wire. $k$ depends primarily on the length-to-diameter ratio ($l/d$) of the wire (Champagne et al, 1967) and is almost independent of the velocity (Jorgensen, 1971). $h$ describes the unsteadiness of the heat transfer at the periphery of the hot wire due to different flow conditions. In practice, $k$ is set equal to a value of 0.2 for a wire with $l/d=250$ (Champagne, 1967) and $h$ is set to a value of 1.0 as suggested by Legg et al (1984).

Eq. B2.2 describes the relationship between $U_{\text{eff}}$ and the individual velocity components. When used in conjunction with Eq. 4.1, this expression provides a mathematical framework to calculate the instantaneous velocity vector. Assuming the constants $A$ and $B$ and the sensitivity parameters $k$ and $h$ are already known, Eq. B2.2 still contains 3 unknowns ($U_N$, $U_T$ and $U_B$) which cannot be resolved using a single wire. A multi-wire probe is therefore required in order to resolve more than one velocity component. Details of the response equations for a 3-wire probe to measure 2 velocity-components in a high-turbulence flow are given below.

B2.3 THE 3-HOT-WIRE ANEMOMETER

In the 3-wire probe developed by Kawall et al (1983) and Legg et al (1984), all 3 wires lie in the plane parallel with the flow and perpendicular to the boundary (Fig. B2.2). The wire normals are at angles of approximately 45°, -45°and 0° to the mean flow direction. In the present study, a 3-wire probe was formed using a conventional X-wire probe (Disa type P51) mounted beside a single hot-wire probe (Disa type P01). The separation between the two outermost wires was about 2.5 mm. This configuration was chosen to measure velocity components parallel to the mean flow ($U$ component, x direction) and perpendicular to the boundary ($W$ component, z direction).

Analysis of the 3-wire probe follows Kawall et al (1983). On the basis that (a) the length of the three hot wires and the distance between them is sufficiently small, so that all three wires sense the same velocity vector, and (b) the wires are orientated with $\theta_1 = -\theta_2 = 45^\circ$, and $\theta_3 = 0^\circ$, the resulting hot-wire response equations follow
Fig. B2.2. Orientation of hot wires in a 3-hot-wire probe, with respect mean direction of flow.

from Eq. B2.2 as

\[ E_1^2 = A_1 + B_1 \left( V_2 (U_t - W_t)^2 + V_2 k^2 (U_t + W_t)^2 + V_t^2 \right)^{\frac{1}{2n}} \] (B2.3)

\[ E_2^2 = A_2 + B_2 \left( V_2 (U_t + W_t)^2 + V_2 k^2 (U_t - W_t)^2 + V_t^2 \right)^{\frac{1}{2n}} \] (B2.4)

\[ E_3^2 = A_3 + B_3 (U_t^2 + k^2 W_t^2 + V_t^2)^{\frac{1}{2n}} \] (B2.5)

In these equations the subscripts 1 and 2 refer to the inclined wires (wires no. 1 and no. 2 in Fig. B2.2) and subscript 3 refers to the normal wire (wire no. 3 in Fig. B2.2); \( E_i \) is the instantaneous voltage for the ith hot-wire \( (i=1,2,3) \); \( U_t \) is the 'true' component of the instantaneous velocity vector in the x- or streamwise direction, \( V_t \) is the component in the y- or spanwise direction, and \( W_t \) is the component in the z- or vertical direction; \( A_i \) and \( B_i \) are parameters of the system which are determined by means of a least squares regression analysis of the velocity calibration data (see later); \( n \) is a power index which is taken as 0.45 (Collis and Williams, 1959); \( k \) is the axial sensitivity of the wires, assumed to be constant with a value of \( k=0.2 \) for wires with a length to diameter ratio of \( l/d=250 \) (Champagne et al, 1967); and \( h \) is assigned a value of unity.

The optimum estimates of \( U_t \) and \( W_t \) that are obtainable by means of the present 3-wire response equations are given by

\[ U_3 = \left| U_t \right| = \left( \frac{Z + (Z^2 + (Z_2-Z_1)^2)^{\frac{1}{2n}}}{2(1-k^2)} \right)^{\frac{1}{2}} \] (B2.6)
\[ W_3 = W_t = \frac{Z_2 - Z_1}{2(1 - k^2)U_3} \]  

(B2.7)

where \( Z_1, Z_2, Z_3 \) and \( Z \) are given by the following relations

\[ Z_1 = \left( \frac{E_1^2 - A_1}{B_1} \right)^{2/n} \]  

(B2.8)

\[ Z_2 = \left( \frac{E_2^2 - A_2}{B_2} \right)^{2/n} \]  

(B2.9)

\[ Z_3 = \left( \frac{E_3^2 - A_3}{B_3} \right)^{2/n} \]  

(B2.10)

\[ Z = 2Z_3 - (Z_1 + Z_2) \]  

(B2.11)

In principal values of \( U_t \) and \( W_t \), can be found from measurements of \( U_3 \) and \( W_3 \). In practice however, the performance of a 3-wire probe using Eqs. B2.6 and B2.7 is degraded, especially in high-intensity turbulent flows, because of a combination of factors which are explained below.

The analysis using Eqs. B2.6 and B2.7 assumes \( U_3 \) is positive. Sometimes \( U_3 \) may become negative, especially in high-intensity turbulent flows when flow reversal occurs. In this case the 3-wire probe is subject to rectification errors since it cannot resolve the flow whenever \( U_3 < 0 \). Kawall et al (1983) indicate that these errors will occur whenever the turbulence intensity exceeds about 40%, but that good estimates of \( U_3 \) are still obtained with turbulence levels of up to 70%.

In addition, the accuracy of the results is reduced by actual and unpredictable variations in the 'constant' \( A_n \), that arise whenever the turbulence intensity exceeds about 15%. Such variations occur because the parameter \( A_n \) is a function of wind angle (see Fig. 2, Kawall et al, 1983).

Finally, Eqs. B2.6 and B2.7 are derived on the assumption that the wires angles are \( \theta_1 = -\theta_2 = 45^\circ \) and \( \theta_3 = 0^\circ \), whereas the real wire angles will inevitably be slightly misaligned. For example, wires that are initially straight are known to distort when heated and to be deflected by the airstream (Perry, 1982). Providing deviations in \( \theta_1 \) and \( -\theta_2 \) from \( 45^\circ \), and \( \theta_3 \) from \( 0^\circ \) are less than \( \pm 1^\circ \) there will be no adverse effect on the accuracy of the estimates of \( U_3 \) and \( W_3 \) (Kawall et al, 1983).

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B2.4 CALIBRATION PROCEDURE FOR THE 3-WIRE PROBE

Calibration of the 3-wire probe was performed at the upstream end of the wind tunnel, where the turbulence intensity was low ($\sigma_u/U = 0.5\%$). A single hot-wire response equation was used to determine the parameters ($A_i$ and $B_i$) of each wire.

The procedure was to align each wire normal to the flow, so that it was cooled principally by the mean velocity component. This alignment was done by positioning the wire approximately normal to the flow, by eye, and slowly adjusting the position by way of a rotary turntable to obtain the maximum hot-wire voltage for a given velocity.

Once aligned normal to the flow, the hot-wire voltage was measured over a range of velocities between 1 to 7 m s$^{-1}$. The tunnel speed could not be maintained steady below 1 m s$^{-1}$ so that no calibration data was obtained for these low velocities. A reference velocity, $U$, was measured using a pitot-static tube which was placed beside the hot-wire, but separated by a lateral distance of 0.1 m. The pitot tube was connected to an electronic micromanometer which measured the dynamic pressure ($\Delta P$) of the flow. This is the difference between the total and static pressure. Wind speed, $U$, was calculated as:

$$U = \left( \frac{2\Delta P}{\rho_a} \right)^2 \quad (4.12)$$

where $\rho_a$ is the (dry) air density, which was calculated from the universal gas law,

$$\rho_a = \frac{P}{RT_a} \quad (4.13)$$

where $R$ is the universal gas constant (8.314 J mol$^{-1}$ K$^{-1}$) and both atmospheric pressure ($P$) and air temperature ($T_a$) were monitored.

The hot-wire voltage, $E_i$, was related to the velocity of flow normal to the wire using King’s cooling law (Eq. B2.1), where the effective cooling velocity was taken to be the reference (free stream) velocity, $U$. The cooling effect of the other velocity components was considered to be negligible.

The parameters ($A_i$ and $B_i$) of the system were obtained from a linear regression of $E_i^2$ against $U^n$ using 15 calibration points over the velocity range 1.0 m s$^{-1}$ to 7 m s$^{-1}$. The power index, $n$, was assigned a constant value of 0.45, as suggested by Collis and Williams (1959). An examination of the goodness of fit for values of
\( n \) equals 0.40, 0.45 and 0.50 usually showed any of these values of \( n \) to give an excellent linear fit to the calibration data \((r^2 \geq 0.999, \text{ se} \leq 0.2\%)\) over this velocity range. But a value of \( n = 0.45 \) gave an intercept value that was close to \( E^2 \) observed in 'zero' flow and was therefore considered to be the most appropriate value.

A calibration was not performed at velocities of less than 1 m s\(^{-1}\) because a pitot tube becomes inaccurate over this range and also because the tunnel did not run at these low velocities. A Turbo-Pascal computer program to calibrate hot-wires against a pitot tube is in Appendix C3.1. A typical calibration curve is shown in Fig. B2.3.

![Typical calibration curve for a Disa type P01 hot-wire operated at a constant temperature of 250 °C.](image)

**B2.5 OPERATION OF THE 3-WIRE PROBE**

Each wire of the 3-wire probe was connected to a standard bridge circuit (Disa type M01) and operated at a constant temperature of 250 °C. In order to calculate \( U_1 \) and \( W_1 \), digital versions of the analog signals \( U_3 \) and \( W_3 \), defined by Eqs. B2.6 and B2.7, were determined in the following manner.

At the beginning of each day, individual hot-wires of the 3-wire probe were calibrated to determine the parameters \( A_i \) and \( B_i \). Then, providing the temperature did not change by more than \( \pm 2 \) °C during a run (it never did), analog signals from the 3-wire probe were sampled to produce digital voltages \( E_1 \), \( E_2 \) and \( E_3 \). These digital voltages were then transformed into the data sequences \( Z_{1j}, Z_{2j}, Z_{3j}, Z_j \ (j=1, \ldots, n) \) and the digitized signals \( U_{3j} \) and \( W_{3j} \) were calculated. A computer program to compute and process 3-wire probe velocity signals is in Appendix C3.2.
APPENDIX B3.
PERFORMANCE TEST OF THE 3-WIRE PROBE.

B3.1 Introduction

A 3-hot-wire probe was used to measure turbulence statistics in the model forests for two main reasons. A multi-wire probe is needed to resolve instantaneous velocity components and a 3-wire probe is more reliable than a conventional X-wire probe in high intensity turbulent flows. However, since the 3-wire probe was not available commercially, a 'one-off' probe was fabricated by mounting a single hot-wire next to a conventional X-wire, and computer software was developed to interpret the velocity signals of the new probe (Appendix C2). A simple test was carried out at the start of the study to check the software routines by examining the response of the 3-wire probe to different velocities and different wind angles. The results of these tests are given below.

B3.2 RESPONSE OF THE 3-WIRE PROBE

A performance test of the 3-wire probe was carried out in a low-intensity turbulent air stream ($I_u=5\%$). The tests were designed to examine both the linearity and directional response of the probe. For each test a reference velocity, $U_r$, was measured using a pitot tube mounted next to, and at the same height as the 3-wire probe, but separated by a lateral distance of 0.2 m. Simultaneous values of $U_3$ and $W_3$ were measured with the 3-wire probe in the standard way using a time series of 8192 points collected over a time interval of about 20 s, as described in Chapter 4.

The performance of the probe over the velocity range 1 m s$^{-1}$ to 6 m s$^{-1}$ is shown in Fig. B3.1. A linear regression of $U_3$ on $U_r$ yields a slope of 1.011 and an intercept value of -0.017 m s$^{-1}$ ($r^2=100\%$, se= 0.02 m s$^{-1}$). The results demonstrate that $U_3$ varies linearly with $U_r$, and that the measurements of $U_3$ lie within about 1% of $U_r$. Given the accuracy of the pitot measurements is probably no better than 2% (the quoted accuracy of the micromanometer used to measure the dynamic pressure of the pitot tube) values of $U_3$ yield a reliable measure of longitudinal velocity, at least when the turbulence intensity is low. At velocities of less than about 1 m s$^{-1}$ velocity measurements using a pitot tube are unreliable, so the performance of the probe at low velocities can not be examined in this way. Nevertheless, a value for $U_3$ in nominally 'still' air is less than 0.01 m s$^{-1}$, so the offset in the $U_3$ measurements can be assumed.
to be small.

A significant non-zero value is observed in the measurements of \( W_3 \) (Fig. B3.2). The results demonstrate that \( W_3 \) varies linearly with \( U_T \), and \( W_3 \) becomes increasingly more negative with increasing \( U_T \). A linear regression of \( W_3 \) on \( U_T \) yields a slope of -0.0298 and an intercept value of -0.047 m s\(^{-1}\) \((r^2=98.1\%, \text{se}=0.006 \text{ m s}^{-1})\). So about 98% of the variation in \( W_3 \) is explained by changes in \( U_T \). A similar anomaly in \( W_3 \) was reported in the vertical velocity measurements of Raupach et al (1986). This anomaly was attributed to flow distortion about the probe, as predicted by Legg et al (1984). Since the offset in \( W_3 \) is significantly less than zero, mean vertical velocities must be corrected for using measured values of \( U_3 \) during post processing of the data. The correction formula used to recover values of \( U_T \) and \( W_T \) from measurements of \( U_3 \) and \( W_3 \) is given in Table B3.1.

The directional response of the probe was examined by varying the elevation angle over a range of \(-45^\circ\) to \(45^\circ\), at increments of \(5^\circ\), and measuring \( U_3 \) and \( W_3 \) at a single reference velocity of 4 m s\(^{-1}\). The elevation angle, \( \theta_T \), was measured using an electronic level meter (stated accuracy ±0.5°). \( \theta_3 \) was calculated from \( \theta_3 = \arctan(W_3/U_3) \), using values of \( U_3 \) and \( W_3 \) corrected with the formulas in Table B3.1. The angular response is linear over the range of \(-45^\circ\) to \(45^\circ\) (Fig. B3.3). A linear regression of \( \theta_3 \) on \( \theta_T \) yields a slope of 0.994 and an intercept value of -1.09° \((r^2=99.8\%, \text{se}=1.19^\circ)\). The intercept value is comparable to the standard error of the estimate and has subsequently been neglected. These results confirm the angular response of the 3-wire probe is significantly better than a X-wire probe which loses
Fig. B3.2. Performance test of the 3-wire probe: mean velocity, \( W_3 \).

\[
W_3 = -0.047 - 0.0298 U_t
\]

Fig. B3.3. Directional response of the 3-wire probe.

Accuracy at angles greater than about 23° (Perry, 1982). Hence values of \( \sigma_w \) measured with a 3-wire probe are likely to be of a higher fidelity.

**B3.3 ERRORS ANALYSIS FOR \( \sigma_u \) AND \( \sigma_w \) AND \( \overline{uw} \).**

A significant offset is observed in the measurements of \( W_3 \). This leads to contamination errors in estimates of velocity variances, and in the higher order moments of the velocity fluctuations. Assuming the errors in \( U_T \) and \( W_T \) are linear functions of \( U_3 \) and \( W_3 \), errors in the velocity variances and higher order terms can be corrected for, providing the necessary uncorrected statistics are known. The likely
error in measured values of \( \sigma_U, \sigma_W \) and \( uw \) due to errors in \( U_3 \) and \( W_3 \) can be examined in the following way.

Consider the true mean velocity \( U_T \) and \( W_T \) to be linearly related to the measured mean values of \( U_3 \) and \( W_3 \) by equations of the form:

\[
\overline{U_3} = a + b \overline{U_T} \quad \text{(B3.1)}
\]
\[
\overline{W_3} = c + d \overline{W_T} + e \overline{U_T} \quad \text{(B3.2)}
\]

Next, assume the same relationship holds true for the instantaneous velocity, so that true instantaneous values of \( U_T \) and \( W_T \) are related to instantaneous values of \( U_3 \) and \( W_3 \) by equations of the form:

\[
U_3 = a + b U_T \quad \text{(B3.3)}
\]
\[
W_3 = c + d W_T + e U_T \quad \text{(B3.4)}
\]

The true velocity fluctuations, \( u_T \) and \( w_T \), are then related to the measured velocity fluctuations, \( u_3 \) and \( w_3 \), by equations of the form:

\[
u_3 = U_3 - \overline{U_3} = b(U_T - \overline{U_T}) = bu_T \quad \text{(B3.5)}
\]
\[
w_3 = W_3 - \overline{W_3} = dw_T - eu_T \quad \text{(B3.6)}
\]

Eqs. B3.5 and B3.6 can be used to derive a relationship between measured variances and the true values as:

\[
\overline{u_3^2} = b^2 \overline{u_T^2} \quad \text{(B3.7)}
\]
\[
\overline{w_3^2} = d^2 \overline{w_T^2} + 2de \overline{u_T} \overline{w_T} + e^2 \overline{u_T^2} \quad \text{(B3.8)}
\]
\[
\overline{u_3 w_3} = bd \overline{u_T} \overline{w_T} + be \overline{u_T^2} \quad \text{(B3.9)}
\]

Rearranging Eqs. B3.7, B3.8 and B3.9 and substituting for the coefficients \( b, d \) and \( e \) leads to expressions for the measurements errors in the variance and covariance terms. Corresponding correction equations are given in Table B3.1 below.

Offset errors in the measurement of \( W_3 \) result in errors of only a few percent in the variance terms. These errors have subsequently been ignored. The only significant error in the operation of the 3-wire probe is in the vertical velocity; these velocities can be corrected using the expression in Table B3.1. This error analysis
\[ U_T = 0.017 + 0.989 U_T \quad (r^2 = 100.0\%, \text{se} = 0.021) \]
\[ W_T = 0.047 + 1.00 W_3 + 0.0295 U_3 \quad (r^2 = 98.4\%, \text{se} = 0.006) \]
\[ \sigma_u^2 = 0.978 \sigma_{u_3}^2 \]
\[ \sigma_w^2 = \sigma_{w_3}^2 - 0.0596 u_3 w_3 \]
\[ \bar{u}w = 0.989 \bar{u}_3 \bar{w}_3 - 0.0295 \sigma_{u_3}^2 \]

Table B3.1. Correction formula to account for errors in 3-wire probe response.

should hold for turbulence intensities of less than about 40%.

At much higher turbulence intensities of 100%, errors of up to 20% are predicted to occur in measurements of \( U \) and \( \sigma_u \), and errors approaching 40% are predicted in the measurements of \( \bar{u}w \), due to rectification errors and signal distortion of the 3-wire probe (Legg et al., 1984). Errors in \( \sigma_w \) are predicted to be negligible. Legg et al (1984) provide theoretical curves which can be used to further correct for the response error of the 3-wire probe at high turbulence intensities. However, Raupach et al (1986) concluded the theoretical analysis of Legg et al (1984) overestimates errors in 3-wire probe measurements and they did not correct their results. Consequently, none of the data in the present study have been corrected as suggested by Legg et al (1984). Instead, only offset errors in \( W_3 \) have been corrected for using formulae in Table B3.1.
APPENDIX C1.
LISTING PROGRAMS TO PROCESS VELOCITY DATA FROM FIELD MEASUREMENTS.

C1.1 CR10 program

Main Program: Table I

<table>
<thead>
<tr>
<th>LOC</th>
<th>CODE</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.0</td>
<td>Sample rate set at 1Hz</td>
</tr>
<tr>
<td>1</td>
<td>92 0 20 11</td>
<td>SET F1 to initiate sampling every 20mins</td>
</tr>
<tr>
<td>2</td>
<td>91 11 30</td>
<td>IF (TIME-TO-GO) THEN DO</td>
</tr>
<tr>
<td>3</td>
<td>18 1 1440 98</td>
<td>READ TIME (98) = min of hour</td>
</tr>
<tr>
<td>4</td>
<td>37 98 0.01667 98</td>
<td>READ HOUR (97) = hour of day</td>
</tr>
<tr>
<td>5</td>
<td>18 2 8784 97</td>
<td>GET DAY (97) = day of year</td>
</tr>
<tr>
<td>6</td>
<td>37 97 0.04166 97</td>
<td>CHECK BATTERY (96) = battery voltage</td>
</tr>
<tr>
<td>7</td>
<td>34 97 0.5 97</td>
<td>INITIALIZE VARIABLES</td>
</tr>
<tr>
<td>8</td>
<td>45 97 97</td>
<td>(20)..(25) = direction cosines</td>
</tr>
<tr>
<td>9</td>
<td>32 97</td>
<td>(26)..(31) = mean velocities</td>
</tr>
<tr>
<td>10</td>
<td>10 96</td>
<td>(99) = reset loop counter, max 1080</td>
</tr>
<tr>
<td>11</td>
<td>87 0 6</td>
<td>MAIN LOOP: 1080 at 1Hz (=18 minutes)</td>
</tr>
<tr>
<td>12</td>
<td>30 1.0 0 20C</td>
<td>MEASURE UVW (50)..(55)= 2 Gills UVW</td>
</tr>
<tr>
<td>13</td>
<td>30 0.0 0 26C</td>
<td>(17C) = raw velocity Gill#1</td>
</tr>
<tr>
<td>14</td>
<td>95</td>
<td>(6C) = direction cosine Gill#1</td>
</tr>
<tr>
<td>15</td>
<td>30 0.0 0 99</td>
<td>CORRECT UVW for Gill#1</td>
</tr>
<tr>
<td>16</td>
<td>87 1 1080</td>
<td>(50C) = corrected UVW for Gill#1</td>
</tr>
<tr>
<td>17</td>
<td>90 6</td>
<td>save direction cosine for Gill#1</td>
</tr>
<tr>
<td>18</td>
<td>32 99</td>
<td>CORRECT UVW for Gill#2</td>
</tr>
<tr>
<td>19</td>
<td>1 6 5 1 50 0.01768 0</td>
<td>(53C) = corrected UVW for Gill#2</td>
</tr>
<tr>
<td>20</td>
<td>87 0 3</td>
<td>save direction cosine for Gill#2</td>
</tr>
<tr>
<td>21</td>
<td>31 50C 17C</td>
<td>SAVE UVW #1=(101C), #2=(104C)</td>
</tr>
<tr>
<td>22</td>
<td>31 20C 6C</td>
<td>(26C) = sum UVW's</td>
</tr>
<tr>
<td>23</td>
<td>95</td>
<td>IF (TIME-TO-STOP) DO</td>
</tr>
<tr>
<td>24</td>
<td>86 1</td>
<td>RESET F1 -(TIME-TO-STOP=.TRUE.)</td>
</tr>
<tr>
<td>25</td>
<td>87 0 3</td>
<td>SET F2 --&gt; (DATA-READY=.TRUE.)</td>
</tr>
<tr>
<td>26</td>
<td>31 14C 50C</td>
<td>END</td>
</tr>
<tr>
<td>27</td>
<td>31 6C 20C</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>31 53C 17C</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>31 23C 6C</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>86 1</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>87 0 3</td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>31 14C 53C</td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>31 6C 23C</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>54 6 50 1 101C 1</td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>87 0 6</td>
<td></td>
</tr>
<tr>
<td>38</td>
<td>33 26C 50C 26C</td>
<td></td>
</tr>
<tr>
<td>39</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>89 99 3 1080 30</td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>86 21</td>
<td></td>
</tr>
<tr>
<td>42</td>
<td>86 12</td>
<td></td>
</tr>
<tr>
<td>43</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td>44</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>95</td>
<td></td>
</tr>
</tbody>
</table>

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**Main Program:**

<table>
<thead>
<tr>
<th>LOC</th>
<th>CODE</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>46</td>
<td>91 12 30</td>
<td>If (DATA-READY) DO</td>
</tr>
<tr>
<td>47</td>
<td>87 0 6</td>
<td>AVERAGE UVW (26C) = mean UVW's</td>
</tr>
<tr>
<td>48</td>
<td>38 26C 99 26C</td>
<td>STORE UVW (52C) = mean UVW for Gill#1</td>
</tr>
<tr>
<td>49</td>
<td>95</td>
<td>(72C) = mean UVW for Gill#2</td>
</tr>
<tr>
<td>50</td>
<td>87 0 3</td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>31 26C 52C</td>
<td></td>
</tr>
<tr>
<td>52</td>
<td>31 29C 72C</td>
<td></td>
</tr>
<tr>
<td>53</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td>54</td>
<td>87 0 2</td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>90 3</td>
<td></td>
</tr>
<tr>
<td>56</td>
<td>31 26C 32</td>
<td>(32) = mean U</td>
</tr>
<tr>
<td>57</td>
<td>31 27C 33</td>
<td>(33) = mean V</td>
</tr>
<tr>
<td>58</td>
<td>86 2</td>
<td>CALCULATE (\theta) (34) = wind angle ((\theta))</td>
</tr>
<tr>
<td>59</td>
<td>31 34 27C</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>34 27C 90 26C</td>
<td></td>
</tr>
<tr>
<td>61</td>
<td>48 26C 26C</td>
<td></td>
</tr>
<tr>
<td>62</td>
<td>48 27C 27C</td>
<td>(26C) = (\cos\theta)</td>
</tr>
<tr>
<td>63</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td>64</td>
<td>86 22</td>
<td>RESET F2 (\rightarrow) (DATA-READY=.FALSE.)</td>
</tr>
<tr>
<td>65</td>
<td>86 13</td>
<td>SET F3 (\rightarrow) (DATA-PROCESS=.TRUE.)</td>
</tr>
<tr>
<td>66</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td>67</td>
<td>91 13 30</td>
<td>IF (DATA-PROCESS) DO</td>
</tr>
<tr>
<td>68</td>
<td>86 3</td>
<td>ROTATE UVW from Gill#1</td>
</tr>
<tr>
<td>69</td>
<td>86 4</td>
<td>ANALYSE UVW from Gill#1</td>
</tr>
<tr>
<td>70</td>
<td>54 10 4 1 55 1</td>
<td>STORE STATISTICS (55..(64) = Gill#1</td>
</tr>
<tr>
<td>71</td>
<td>31 29 26</td>
<td>Repeat for Gill#2</td>
</tr>
<tr>
<td>72</td>
<td>31 30 27</td>
<td></td>
</tr>
<tr>
<td>73</td>
<td>87 0 3</td>
<td></td>
</tr>
<tr>
<td>74</td>
<td>54 1080 104C 6 101C 6</td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td>76</td>
<td>86 3</td>
<td>ROTATE UVW from Gill#2</td>
</tr>
<tr>
<td>77</td>
<td>86 4</td>
<td>ANALYSE UVW from Gill#2</td>
</tr>
<tr>
<td>78</td>
<td>54 10 4 1 75 1</td>
<td>STORE STATISTICS (75..(84) = Gill#2</td>
</tr>
<tr>
<td>79</td>
<td>31 97 50</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>31 97 70</td>
<td>(97) = day</td>
</tr>
<tr>
<td>81</td>
<td>31 98 51</td>
<td></td>
</tr>
<tr>
<td>82</td>
<td>31 98 71</td>
<td>(98) = time</td>
</tr>
<tr>
<td>83</td>
<td>86 10</td>
<td>SET OUTPUT</td>
</tr>
<tr>
<td>84</td>
<td>70 15 50</td>
<td>OUTPUT DATA for Gill#1</td>
</tr>
<tr>
<td>85</td>
<td>86 10</td>
<td></td>
</tr>
<tr>
<td>86</td>
<td>70 15 70</td>
<td>OUTPUT DATA for Gill#2</td>
</tr>
<tr>
<td>87</td>
<td>86 23</td>
<td>RESET F3 (\rightarrow) (DATA-PROCESS=.FALSE.)</td>
</tr>
<tr>
<td>88</td>
<td>95</td>
<td>END</td>
</tr>
</tbody>
</table>

**Subroutines:**

<table>
<thead>
<tr>
<th>LOC</th>
<th>CODE</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>85 1</td>
<td>CORRECT UVW from Gill anemometer</td>
</tr>
<tr>
<td>2</td>
<td>87 0 6</td>
<td>iterate 6 times</td>
</tr>
<tr>
<td>3</td>
<td>30 0 0 0 13</td>
<td>calculate correction factor (2)</td>
</tr>
<tr>
<td>4</td>
<td>87 0 3</td>
<td>(1) = old direction cosine</td>
</tr>
<tr>
<td>5</td>
<td>31 6C 1</td>
<td></td>
</tr>
</tbody>
</table>
### Table III (cont.)

<table>
<thead>
<tr>
<th>LOC</th>
<th>CODE</th>
<th>COMMENT</th>
</tr>
</thead>
</table>
| 6   | 89 1 4 0.25 30 | If \( \cos \theta < 0.25 \) then correction factor = 1.25  
else |
| 7   | 30 1.25 0 2    | correction factor = 1.25  
else |
| 8   | 94             | correction factor = 1.25  
else |
| 9   | 89 1 3 0.96 30 | If \( \cos \theta \geq 0.96 \) then correction factor = 1.0  
else |
| 10  | 30 1.0 0 2     | correction factor = 1.25  
else |
| 11  | 94             | correction factor = 1.25  
else |
| 12  | 55 1 1 2 1.3307 -0.21609 0 -0.13607 0 0 | correction = 'a cubic' |
| 13  | 95             | (14C) = corrected UVW |
| 14  | 95             | (13) = \( u^2 + v^2 + w^2 \) * |
| 15  | 36 17C 2 14C   | exit if no wind |
| 16  | 36 14C 14C 12  | exit if no wind |
| 17  | 33 13 12 13    | exit if no wind |
| 18  | 95             | (3C) = new direction cosine |
| 19  | 39 13 13       | (3C) = \( \sqrt{u^2 + v^2 + w^2} \) |
| 20  | 89 13 1 0.0 31 | \( \theta_{old} = \theta_{new} \) |
| 21  | 87 0 3         | \( \theta_{old} = \theta_{new} \) |
| 22  | 38 14C 13 3C   | (9C) = \( \theta_{old} \) |
| 23  | 43 3C 3C       | (9C) = \( \theta_{old} \) |
| 24  | 35 3C 6C 9C    | (9C) = \( \theta_{old} \) |
| 25  | 43 9C 9C       | (9C) = \( \theta_{old} \) |
| 26  | 95             | (3C) = \( \sqrt{u^2 + v^2 + w^2} \) |
| 27  | 89 9 3 0.02 30 | (4C) = \( \sqrt{u^2 + v^2 + w^2} \) |
| 28  | 89 10 3 0.02 30 | (4C) = \( \sqrt{u^2 + v^2 + w^2} \) |
| 29  | 89 11 3 0.02 30 | (4C) = \( \sqrt{u^2 + v^2 + w^2} \) |
| 30  | 87 0 3         | (4C) = \( \sqrt{u^2 + v^2 + w^2} \) |
| 31  | 31 3C 6C       | (4C) = \( \sqrt{u^2 + v^2 + w^2} \) |
| 32  | 95             | (4C) = \( \sqrt{u^2 + v^2 + w^2} \) |
| 33  | 95             | (4C) = \( \sqrt{u^2 + v^2 + w^2} \) |
| 34  | 95             | (4C) = \( \sqrt{u^2 + v^2 + w^2} \) |
| 35  | 95             | (4C) = \( \sqrt{u^2 + v^2 + w^2} \) |
| 36  | 95             | (4C) = \( \sqrt{u^2 + v^2 + w^2} \) |
| 37  | 33 15 16 12    | Gills are tilted \( \therefore \) rotate VW by 45°  
(15) = V  
(16) = W |
| 38  | 35 15 16 13    | Gills are tilted \( \therefore \) rotate VW by 45°  
(15) = V  
(16) = W |
| 39  | 37 12 0.70711 1 5 | (15) = V  
(16) = W |
| 40  | 37 13 0.70711 1 6 | (15) = V  
(16) = W |
| 41  | 95             | (15) = V  
(16) = W |
| 42  | 85 2           | calculate \( \tan^\theta \) for \( 0^\circ < \theta < 45^\circ \)  
\( \tan \theta = \frac{V}{U} \) |
| 43  | 38 33 32 34    | \( \tan \theta = \frac{V}{U} \) |
| 44  | 43 34 34       | (34) = \( |\tan \theta| \) |
| 45  | 89 34 3 1.0 30 | (34) = \( |\tan \theta| \) |
| 46  | 42 34 34       | (34) = \( |\tan \theta| \) |
| 47  | 55 1 34 34 59.007 -10.002 -4.0428 0 0 | \( \approx \tan^\theta \pm 0.01 \) deg  
approx \( \tan^\theta \pm 0.01 \) deg  
approx \( \tan^\theta \pm 0.01 \) deg |
| 48  | 34 34 -90.0 34 | approx \( \tan^\theta \pm 0.01 \) deg  
approx \( \tan^\theta \pm 0.01 \) deg  
approx \( \tan^\theta \pm 0.01 \) deg |
| 49  | 37 34 -1 34    | approx \( \tan^\theta \pm 0.01 \) deg  
approx \( \tan^\theta \pm 0.01 \) deg  
approx \( \tan^\theta \pm 0.01 \) deg |
| 50  | 94             | approx \( \tan^\theta \pm 0.01 \) deg  
approx \( \tan^\theta \pm 0.01 \) deg  
approx \( \tan^\theta \pm 0.01 \) deg |
| 51  | 55 1 34 34 59.007 -10.002 -4.0428 0 0 | approx \( \tan^\theta \pm 0.01 \) deg  
approx \( \tan^\theta \pm 0.01 \) deg  
approx \( \tan^\theta \pm 0.01 \) deg |
| 52  | 95             | approx \( \tan^\theta \pm 0.01 \) deg  
approx \( \tan^\theta \pm 0.01 \) deg  
approx \( \tan^\theta \pm 0.01 \) deg |
| 53  | 89 32 3 0.0 30 | endif  
If \( U \geq 0.0 \) then  
If \( V < 0.0 \) then |
| 54  | 89 33 4 0.0 30 | endif  
If \( U \geq 0.0 \) then  
If \( V < 0.0 \) then |
| 55  | 37 34 -1.0 34  | endif  
If \( U \geq 0.0 \) then  
If \( V < 0.0 \) then |
| 56  | 95             | endif  
If \( U \geq 0.0 \) then  
If \( V < 0.0 \) then |

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**Table III (cont.)**

<table>
<thead>
<tr>
<th>LOC</th>
<th>CODE</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>57</td>
<td>94</td>
<td>else</td>
</tr>
<tr>
<td>58</td>
<td>89 33 3 0.0 30</td>
<td>If ( V \geq 0.0 ) then</td>
</tr>
<tr>
<td>59</td>
<td>37 34 -1.0 34</td>
<td>quadrant 2</td>
</tr>
<tr>
<td>60</td>
<td>34 34 180 34</td>
<td>else</td>
</tr>
<tr>
<td>61</td>
<td>94</td>
<td>quadrant 3</td>
</tr>
<tr>
<td>62</td>
<td>34 34 180 34</td>
<td>rotate UV by ( \theta^\circ ) so ( V_{\text{bar}}=0 )</td>
</tr>
<tr>
<td>63</td>
<td>95</td>
<td>(5) ( = U_{\text{bar}} )</td>
</tr>
<tr>
<td>64</td>
<td>95</td>
<td>(3) ( = U_{\cos \theta} + V_{\sin \theta} )</td>
</tr>
<tr>
<td>65</td>
<td>95</td>
<td>(4) ( = V_{\cos \theta} - U_{\sin \theta} )</td>
</tr>
<tr>
<td>66</td>
<td>85 3</td>
<td>(5) ( = U_{\text{rotated}} )</td>
</tr>
<tr>
<td>67</td>
<td>30 0 0 5</td>
<td>( (101C) = u' )</td>
</tr>
<tr>
<td>68</td>
<td>87 0 1080</td>
<td>( (103C) = w' )</td>
</tr>
<tr>
<td>69</td>
<td>90 6</td>
<td>Calculate ( E(u^2), E(u^3), E(u^4) )</td>
</tr>
<tr>
<td>70</td>
<td>36 101C 26 1</td>
<td>( (4C) \ldots (13C) ) ( = ) means</td>
</tr>
<tr>
<td>71</td>
<td>36 102C 27 2</td>
<td>loop through the values</td>
</tr>
<tr>
<td>72</td>
<td>33 1 2 3</td>
<td>( (4) = \Sigma u w )</td>
</tr>
<tr>
<td>73</td>
<td>36 102C 26 1</td>
<td>( (5C) = \Sigma u^2 )</td>
</tr>
<tr>
<td>74</td>
<td>36 101C 27 2</td>
<td>( (8C) = \Sigma u^3 )</td>
</tr>
<tr>
<td>75</td>
<td>35 1 2 4</td>
<td>( (11C) = \Sigma u^4 )</td>
</tr>
<tr>
<td>76</td>
<td>31 3 101C</td>
<td>( (101C) = U_{\text{rotated}} )</td>
</tr>
<tr>
<td>77</td>
<td>31 4 102C</td>
<td>( (102C) = V_{\text{rotated}} = v' )</td>
</tr>
<tr>
<td>78</td>
<td>33 3 5 5</td>
<td>( (5) = \text{sum } U )</td>
</tr>
<tr>
<td>79</td>
<td>95</td>
<td>( (101C) ) ( = u' )</td>
</tr>
<tr>
<td>80</td>
<td>38 5 99 5</td>
<td>( (103C) ) ( = w' )</td>
</tr>
<tr>
<td>81</td>
<td>87 0 1080</td>
<td>(5) ( = U_{\text{bar}} )</td>
</tr>
<tr>
<td>82</td>
<td>90 6</td>
<td>(4C) \ldots (13C) ( = ) means</td>
</tr>
<tr>
<td>83</td>
<td>35 101C 5 101C</td>
<td>loop through the values</td>
</tr>
<tr>
<td>84</td>
<td>35 103C 28 103C</td>
<td>( (5C) = E(u^2) ) etc</td>
</tr>
<tr>
<td>85</td>
<td>95</td>
<td>( (14) = \sigma_i )</td>
</tr>
<tr>
<td>86</td>
<td>95</td>
<td>( (14) = \sigma_i )</td>
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Subroutines:

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<th>LOC</th>
<th>CODE</th>
<th>COMMENT</th>
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<tr>
<td>111</td>
<td>36</td>
<td>5C 5C  16</td>
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<tr>
<td>112</td>
<td>31</td>
<td>14 5C</td>
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<tr>
<td>113</td>
<td>38</td>
<td>8C 15 8C</td>
</tr>
<tr>
<td>114</td>
<td>38</td>
<td>11C 16 11C</td>
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<tr>
<td>115</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td>116</td>
<td>95</td>
<td></td>
</tr>
</tbody>
</table>

C2.2 Time series analysis program

```fortran
C program tstat89.for
C
C .. VERTICAL VARIATIONS IN TURBULENT STATISTICS ..
C
C for time series analysis of windspeed and turbulence data
C generated from gill and sonic u-v-w anemometers

REAL*8 UVW(18,25000), T(6,25000), STATS(18,6), SR
INTEGER N, NCHAR, CHAN, NANEMO, NGILL, NSON, NTEMP
CHARACTER*45 FILNAM, ANS
LOGICAL KEEPON
DATA VDU/5/, CONS/6/, CHAN/32/

COMMON /WIND/N, UVW, NANEMO, NTEMP, STATS, NCHAR, FILNAM, CHAN, SR,
T

C subroutine references
C gilicor - cosine correction for gill u-v-w
C gilirot - rotate u-v-w components
C rotate - horizontal rotation for mean v=0
C statistics - mean, std, Sk, Kr in u-v-w
C - u°, <u'w'>
C - <w'T'>
C quadrant - quadrant analysis of momentum stress
C spectrum - velocity spectra

10 WRITE(CONS,*), 'INPUT FILENAME (.DAT ASSUMED) ?',
READ(VDU,99100) NCHAR,FILNAM
OPEN(UNIT=31,FILE=FILNAM(1:NCHAR)//' .DAT',TYPE='OLD',READONLY,ERR=10)
OPEN(UNIT=41,FILE=FILNAM(1:NCHAR)//' .OUT',TYPE='NEW',RECORDSIZE=132)
WRITE(CONS,*), 'INPUT NUMBER OF GILLS, SONICS AND TEMPS',
READ(VDU,*), NGILL, NSON, NTEMP
NANEMO=NSON+NGILL
WRITE(CONS,*), 'INPUT SAMPLE RATE (HZ) ?',
READ(VDU,*), SR
J=1
KEEPON=.TRUE.
DO WHILE(KEEPON)
IF(NTEMP.GT.(0.0)) THEN
READ (31,*),END=20 DUMMY, (UVW(I,J), I=1,3*NANEMO),
```

283
ELSE READ (31,*,END=20) DUMMY, (UVW(I,J), I=1,3*NANEMO)
END IF
J=J+1 GOTO 30
20 KEEPON=.FALSE.
c22 WRITE(CONS,*) 'ERROR AT LINE ',J
30 CONTINUE END DO

N=J-1 WRITE(CONS,*) 'NUMBER OF DATA POINTS = ',N

apply corrections to U-V-W for non-cosine response of Gill's
IF(NGILL.GT .0) THEN
CALL GILLCOR(NGILL)
CALL GILLROT(NGILL)
WRITE(CONS,*) 'END OF WIND CORRECTION'
ENDIF

rotate coordinates so that V-mean is zero
 WRITE(CONS,*) 'COORDINATE ROTATION (Y/N)'
READ(VDU,99100) IN, ANS
 IF((ANS.EQ.'Y').OR.(ANS.EQ.'y')) THEN
CALL STATISTICS
CALL ROTATE
WRITE(CONS,*) 'END OF CO-ORDINATE ROTATION'
ENDIF

remove the mean and calculate turbulence statistics (mean, sk and kr)
CALL STATISTICS
WRITE(41,9090) (STATS(3*KK-2,2)/STATS(3*KK-2,1), *
(STATS(3*KK-2,1), I=1,6),KK=1,NANEMO)
WRITE(41,9090) (STATS(3*KK-1,2)/STATS(3*KK-1,1), *
(STATS(3*KK-1,1), I=1,6),KK=1,NANEMO)
WRITE(41,9090) (STATS(3*KK ,2)/STATS(3*KK-2,1), *
(STATS(3*KK ,1), I=1,6),KK=1,NANEMO)
WRITE(41,909)  

perform quadrant analysis
CALL QUADRANT

calculate the power spectrum of U, V, W velocities
CALL SPECTRUM

calculate the autocorrelation function of U, V, W velocities
CALL AUTOCORR

99100 FORMAT (Q,A)
99110 FORMAT (A)
9090 FORMAT(1X,7F8.3)
END

SUBROUTINE GILLCOR(NGILL)
C
C apply correction to U-V-W velocities of the Gill
C using cosine-response corrections from Horst (1972)
C ************************************************************************modified 890814************************************************************************
REAL*8 ANGLE(6), UVW(18,15000), STATS(18,6), U(3), *
S, SR, T(6,15000), CORFAC(6)
INTEGER I, J, K, II, JJ, KK, N, NCHAR, NANEMO, CHAN
CHARACTER*45 FILNAM
DATA VDU/5/, CONS/6/
COMMON /WIND/N, UVW, NANEMO, NTEMP, STATS, NCHAR, FILNAM, CHAN, SR,
* T
  IF(NGILL.EQ.0) RETURN
  DO 50 KKK=1,NGILL
     NC = 0
     ANGLE(1)=1.0
     ANGLE(2)=1.0
     ANGLE(3)=1.0
     DO 40 I=1,N
       DO 60 D060 J=1,3
          IF(ANGLE(IJ).LT.(0.25)) CORFAC(IJ)= 1.25
          IF(ANGLE(IJ).GE.(0.96)) THEN
             CORFAC(IJ)= 1.0
          ELSE
             CORFAC(IJ)= 1.3307-0.2176*ANGLE(IJ)-0.13607*(ANGLE(IJ)**3)
          ENDIF
          U(IJ)=UVW(3*KKK-3+II,1)*CORFAC(IJ)
       CONTINUE
     S = SQRT(U(1)**2 + U(2)**2 + U(3)**2)
     IF(S.EQ.0) GOTO 35
     DO 70 II=1,3
        ANGLE(II+3)=U(I)/S
     IF(ABS(ANGLE(4)-ANGLE(1))-.02) 10,10,20
        IF(ABS(ANGLE(5)-ANGLE(2))-.02) 15,15,20
        IF(ABS(ANGLE(6)-ANGLE(3))-.02) 30,30,20
        NC=NC+1
        IF(NC=NC) 30,30,25
       ANGLE(1)=ANGLE(4)
       ANGLE(2)=ANGLE(5)
       ANGLE(3)=ANGLE(6)
       GOTO 5
     UVW(3*KKK-2,1)= U(1)
     UVW(3*KKK-1,1)= U(2)
     UVW(3*KKK 1,1)= U(3)
  NC=0
  CONTINUE
  CONTINUE
  RETURN
END

C...........................................................................
SUBROUTINE GILLROT(NGILL)
C...........................................................................
c rotate coordinates of all Gills by 45 degrees in the VW plane
C
REAL*8 UVW(18,15000), STATS(18,6), THETA, U, V, W, SR, T(6,15000)
INTEGER I, J, K, II, JJ, KK, N, NCHAR, NANEMO, CHAN
DATA VDU/5/, CONS/6/
COMMON /WIND/N, UVW, NANEMO, NTEMP, STATS, NCHAR, FILNAM, CHAN, SR,
T
IF(NGILL.EQ.0) RETURN
DO 120 KKK=1,NGILL
  100 IF(NGILL.EQ.0) RETURN
DO 120 J=1,N
W=UVW(3*KK,J)
V=UVW(3*KK-1,J)
UVW(3*KK,J) = (V-W)*0.70711
UVW(3*KK-1,J) = (V+W)*0.70711
120 CONTINUE
RETURN
END

SUBROUTINE ROTATE
C apply a 1-d coordinate rotation making U the streamwise velocity component
c and V the lateral component
REAL*8 UVW(18,25000), STATS(18,6), UBAR, VBAR, SR, T(6,25000),
U, V, THETA, PHI
INTEGER N, NANEMO, NCHAR, NTEMP, CHAN
CHARACTER*45 FILNAM
DATA VDU/5/, CONS/6/
COMMON /WIND/N, UVW, NANEMO, NTEMP, STATS, NCHAR, FILNAM, CHAN, SR,
T
DO 30 KK=1,NANEMO
UBAR = STATS(3*KK-2,1)
VBAR = STATS(3*KK-1,1)
PHI = ATAN2D( VBAR, UBAR)
WRITE(41,9090)KK, UBAR, VBAR, PHI
9090 FORMAT(I X,15,3F8.3)
DO 20 J=1,N
IF( (UVW(3*KK-1,J).EQ.0).AND.(UVW(3*KK-2,J).EQ.0) ) GOTO 20
THETA = ATAN2D( UVW(3*KK-1,J), UVW(3*KK-2,J))
U = SQRT( UVW(3*KK-1,J)**2 + UVW(3*KK-2,J)**2 )
UVW(3*KK-1,J) = U*SIND(THETAPHI)
20 UVW(3*KK-2,J) = U*COSD(THETAPHI)
30 CONTINUE
WRITE(41,*)
RETURN
END

SUBROUTINE STATISTICS
C
REAL*8 XMIN, XMAX, XBAR, XSTEP, XX(25000), WTUM, WT(25000),
S2, S3, S4, STATS(18,6), UVW(18,25000), T(6,25000), SR
INTEGER N, NANEMO, NCHAR, CHAN, IWT, IFAIL, ISPACE, ITYPE, MULTY,
N1, NSTEPX, NSTEPY, VDU, NTEMP
CHARACTER*45 FILNAM
DATA VDU/5/, CONS/6/
COMMON /WIND/N, UVW, NANEMO, NTEMP, STATS, NCHAR, FILNAM, CHAN, SR,
T
DO 1000 KK=1,3*NANEMO+NTEMP
IFAIL = 1
IWT = 0
IF(KK.LE.(3*NANEMO)) THEN
DO 10 I=1,N
10 XX(I)=UVW(KK,I)
ELSE
DO 101 I=1,N
101 XX(I)=T(KK-3*NANEMO,I)
c calculate mean of time series
    CALL G01AAF(N, XX, IWT, WT, XBAR, S2, S3, S4, XMIN, XMAX, WTSUM, IFAIL)
    IF ( IFAIL ) 15,15,210
15    STATS(KK,1)=XBAR
    STATS(KK,2)=S2
    STATS(KK,3)=S3
    STATS(KK,4)=S4
    STATS(KK,5)=XMIN
    STATS(KK,6)=XMAX
1000  CONTINUE
210  CLOSE(32)
RETURN
END

SUBROUTINE QUADRANT
C-----
c performs conditional sampling on the Reynolds stresses (Raupach et at 1986)
c and calculate the stress and time fractions
c II= quadrant: burst=2, sweep=4, outward and inward interactions = 1,3 resp.
c JJ= pointer to hole size
REAL*8 UVW(18,25000), STATS(18,6), UWFRAC(6,5,10), TFRAC(6,5,10),
  U, W, UW, UWSUM, HOLE(10), T(6,25000)
INTEGER N, NANEMO, NCHAR, CHAN, VDU
CHARACTER*45 FILNAM
COMMON /WIND/N, UVW, NANEMO, NTEMP, STATS, NCHAR, FILNAM, CHAN, SR,
  T
DATA VDU/5/, CONS/6/
DATA HOLE/0,.5,1,1.5,2,2.5,5,7.5,10,12.5/
OPEN (UNIT=CHAN, FILE=FILNAM(1:NCHAR)//' .QUAD', TYPE='NEW',
  RECORDSIZE=132 )
DO 200 KK=1,NANEMO
      UWSUM=0.0
      DO 50 II=1,5
      DO 50 JJ=1,10
          UWFRAC(KK,II,JJ)=0.0
      50        TFRAC(KK,II,JJ)= 0.0
      DO 60 I=1,N
          UWSUM = UWSUM + (UVW(3*KK2,I)STATS(3*KK,1)) * 	 *(UVW(3*KK, I) STATS(3*KK ,1))
100 CONTINUE
287
C    WRITE(CONS,9999)
DO 170 JJ=1,10
DO 150 II=1,4
TFRAC(KK,IIJJ)=TFRAC(KK,IIJJ)/N
150 UWFRAC(KK,IIJJ)=UWFRAC(KK,IIJJ)/STATS(3*KK-2,2)/STATS(3*KK,2)/N
C    WRITE(CONS,9998) HOLE(JJ), (UWFRAC(KK,IIJJ), II=1,4),
C      (TFRAC(KK,IIJJ), II=1,4)
C    WRITE(CHAN,9998) HOLE(JJ), (UWFRAC(KK,IIJJ), II=1,4),
     (TFRAC(KK,IIJJ), II=1,4)
170 CONTINUE
200 CONTINUE
9999 FORMAT(1X/, 48H RESULTS FROM CONDITIONAL SAMPLING OF STRESSES
      ,1X/, 40H SIZE S1 S2 S3 S4 ,
      32H T1 T2 T3 T4 )
9998 FORMAT(1X,9F8.4)
CLOSE(CHAN)
RETURN
END
C------------------------------------------------------------------------
SUBROUTINE STRESS
C------------------------------------------------------------------------
REAL*8 XMIN, XMAX, UWBAR, UVBAR, VWBAR, XSTEP, XX(25000), WTSUM,
      WT(25000), S2, S3, S4, STATS(18,6), UVW(18,25000), T(6,25000), SR
INTEGER N, NANEMO, NCHAR, CHAN, IWT, IFAIL, VDU, NTEMP
CHARACTER*45 FILNAM
DATA VDU/5/, CONS/6/
COMMON /WIND/N, UVW, NANEMO, NTEMP, STATS, NCHAR, FILNAM, CHAN, SR,
      T
DO 100 KK=1,NANEMO
   c calculate time-averaged Reynolds Stress -<u'w'>
   DO 50 J=1,N
      50 XX(J) = (UVW(3*KK-2,J)-STATS(3*KK-2,1))* (UVW(3*KK,J)-STATS(3*KK,1))
      IFAIL=1
      IWT=0
      CALL GOIAAF(N, XX, IWT, WT,UWBAR, S2, S3, S4, XMIN, XMAX, WTSUM, IFAIL)
      IF ( IFAIL ) 15,15,100
      15 WRITE(41,9090) UWBAR, s2
      9090 FORMAT(IX, 2F8.3)
100 CONTINUE
   c calculate time-averaged Reynolds Stress -<v'w'>
   DO 501 J=1,N
      501 XX(J) = (UVW(3*KK-1,J)-STATS(3*KK-1,1))*(UVW(3*KK,J)-STATS(3*KK,1))
      IFAIL=1
      IWT=0
      CALL G01AAF(N, XX, IWT, WT,VWBAR, S2, S3, S4, XMIN, XMAX, WTSUM, IFAIL)
      IF ( IFAIL ) 151,151,1001
151 WRITE(41,9090) VWBAR, s2
1001 CONTINUE
   c calculate time-averaged Reynolds Stress -<u'v'>
   DO 502 J=1,N
      502 XX(J) = (UVW(3*KK-2,J)-STATS(3*KK-2,1))*(UVW(3*KK-1,J)
      * -STATS(3*KK-1,1))
      IFAIL=1
      IWT=0
288
CALL G01AAF(N, XX, IWT, WT, UVBAR, S2, S3, S4, XMIN, XMAX, WTSUM, IFAIL)
IF (IFAIL) 152,152,1002
152 WRITE(41,9090) UVBAR, S2
1002 CONTINUE
WRITE(41,*)
WRITE(CONS,*)
RETURN
END

SUBROUTINE SPECTRUM

C
REAL*8 UVW(18,16000), STATS(18,6), PX, PW, STA(4), UG(32000),
* ASP(18,16000), SR, T(6,16000), F(16000), FF(200), FN(200),
* FS(200)
INTEGER N, NANEMO, NCHAR, CHAN, IFAIL, KC, L, LG, MTX, MW, NX, VDU
CHARACTER*45 FILNAM
DATA VDU/5/, CONS/6/
COMMON /WIND/N, UVW, NANEMO, NTEMP, STATS, NCHAR, FILNAM, CHAN, SR,
* T
COMMON /SPEC/ASP

DO 1000 KK=1,3*NANEMO+NTEMP
IF(KK.GT.(3*NANEMO)) THEN
   DO 401 I=1,N
      UG(I) = T(KK-3*NANEMO,I) - STATS(KK,1)
      UG(N+I) = 0.0
   401 CONTINUE
ELSE
   DO 40 I=1,N
      UG(I) = UVW(KK,I)-STATS(KK,1)
      UG(N+I) = 0.0
   40 CONTINUE
ENDIF
C set parameters for call to routine g13cbf
C mean correction and 10% taper (total over both ends)
   MTX = 2
   PX = 0.10
C smoothing window as 2pi/MW hz with a square window
   MW = N/8
   PW = 1.0
C kc and l are order of fft and frequency division of smoothed
C spectral estimates as 2*pi/l
   KC = 4*N
   L = N
   LG = 0
C *********************** lg=1 means logged output ***********************
   IFAIL = 1
   CALL G13CBF (N, MTX, PX, MW, PW, L, KC, LG, UG, NG, STA, IFAIL )
   IF (IFAIL.EQ.0) GOTO 400
   WRITE(CONS,99400) FILNAM, IFAIL
   GOTO 420
C calculate a block average over about 40 log-freq bands
400 DO 410 II=1,1101
   FF(II) = 0
   FS(II) = 0
410 FN(II) = 0
C ng = [I/2] + 1
   DO 600 I=1,NG
   A= LOG10(REAL(I)*SR/REAL(L))
600 CONTINUE
IF(UG(I).GT.(0.0)) B= LOG10(UG(I))
II = 1+ 10*(A +4)
FF(II) = FF(II) + A
FS(II) = FS(II) + B
c FF(II) = FF(II) + 10**a
c FS(II) = FS(II) + 10**b
600 FN(II) = FN(II) + 1

I=1
DO 110 II=1,101
IF(FN(II).GT.(0.0)) FF(II) = FF(II)/FN(II)
IF(FN(II).GT.(0.0)) FS(II) = FS(II)/FN(II)
IF(FF(II).NE.(0.0)) THEN
ASP(KK,I) = FS(II)
F(I) = FF(II)
c ASP(KK,I) = log10(FS(II))
c F(I) = log10(FF(II))
I=I+1
ENDIF
110 CONTINUE
NNG = I-1
1000 CONTINUE
WRITE(CONS,99410) FILNAM

OPEN (UNIT=CHAN, FILE=FILNAM(1:NCHAR)//'.ASPU', TYPE='NEW')
WRITE(CHAN,99420) (STATS(KK,1), KK=1,3*NANEMO,3)
WRITE(CHAN,99420) (STATS(KK,2), KK=1,3*NANEMO,3)
DO 1100 I=1,NNG
WRITE(CHAN,99420) (ASP(KK,I), KK=1,3*NANEMO,3)
CLOSE (CHAN)

OPEN (UNIT=CHAN, FILE=FILNAM(1:NCHAR)//'.ASPV', TYPE='NEW')
WRITE(CHAN,99420) (STATS(KK,1), KK=2,3*NANEMO,3)
WRITE(CHAN,99420) (STATS(KK,2), KK=2,3*NANEMO,3)
DO 1110 I=1,NNG
WRITE(CHAN,99420) (ASP(KK,I), KK=2,3*NANEMO,3)
CLOSE (CHAN)

OPEN (UNIT=CHAN, FILE=FILNAM(1:NCHAR)//'.ASPW', TYPE='NEW')
WRITE(CHAN,99420) (STATS(KK,1), KK=3,3*NANEMO,3)
WRITE(CHAN,99420) (STATS(KK,2), KK=3,3*NANEMO,3)
DO 1120 I=1,NNG
WRITE(CHAN,99420) (ASP(KK,I), KK=3,3*NANEMO,3)
CLOSE (CHAN)

99400 FORMAT (27HOSPECTRAL ESTIMATE FAILED , 20A, 91-10IFAIL =,
99410 FORMAT (32HOSPECTRAL ESTIMATE COMPLETE FOR , 40A)
99420 FORMAT (7F8.4)
99419 FORMAT (71 7 10.6)
420 RETURN

C-----------------------------------------------------------------------------
SUBROUTINE AUTOCORR
C-----------------------------------------------------------------------------
REAL*8 UVW(18,16000), XX(16000), R(200), STATS(18,6), XM, XV,
* AUTO(18,200), T(6,16000)
INTEGER N, NANEMO, NCHAR, CHAN, IFAIL, NK, VDU, KK
CHARACTER*45 FILNAM
DATA VDU/5/, CONS/6/, NK/200/

C-----------------------------------------------------------------------------
COMMON /WIND/N, UVW, NANEMO, NTEMP, STATS, NCHAR, FILNAM, CHAN, SR, T

DO 30 KK=1,3*NANEMO
  IFAIL = 1
  DO 10 I=1,N
     XX(I)=UVW(KK,I)
     CALL G13ABF(XX, N, NK, XM, XV, R, STAT, IFAIL)
     IF (IFAIL.NE.0) GOTO 30
    DO 20 I=1,NK
       AUTO(KK,I)=R(I)
  30 CONTINUE

OPEN (UNIT=CHAN, FILE=FILNAM(1:NCHAR)//'.ACFU', TYPE='NEW',
     RECORDSIZE=132)
  DO 50 I=1,NK
     WRITE(CHAN,99320) I,(AUTO(KK,I), KK=1,3*NANEMO,3)
  50 CLOSE (CHAN)

OPEN (UNIT=CHAN, FILE=FILNAM(1:NCHAR)//'.ACFV', TYPE='NEW',
     RECORDSIZE=132)
  DO 60 I=1,NK
     WRITE(CHAN,99320) I,(AUTO(KK,I), KK=2,3*NANEMO,3)
  60 CLOSE (CHAN)

OPEN (UNIT=CHAN, FILE=FILNAM(1:NCHAR)//'.ACFW', TYPE='NEW',
     RECORDSIZE=132)
  DO 70 I=1,NK
     WRITE(CHAN,99320) I,(AUTO(KK,I), KK=3,3*NANEMO,3)
  70 CLOSE (CHAN)

99300 FORMAT (1X,40H1AUTOCORRELATION ROUTINE HAS FAILED FOR , 30A)
99310 FORMAT (1X,40H1AUTOCORRELATION ROUTINE COMPLETED FOR , 30A)
99320 FORMAT (1X,13,6F10.6)
RETURN
END
APPENDIX C2.

LISTING OF TURBO PASCAL PROGRAMS TO CALIBRATE HOT-WIRES AND TO COMPUTE AND PROCESS 3-WIRE PROBE VELOCITY SIGNALS.

C3.1 Calibration program

PROGRAM calibrate;

(to calibrate a X-wire and hot-wire against a pitot tube)

{-------------------------------------------------------------}

CONST
  nsamples = 1500;
  nobs = 15;
VAR
  ch: char;
  x,y: array[1..20] of real;
  a1,b1,rsq,se: real;
  e1,e1sum: real;
  c2,c2sum: real;
  e3,e3sum: real;
  p0,p0sum: real;
  Ta,Tref,Pref,Tcor: real;
  a,b,c,d: real; {dummy variables}
  u,v1,v2,v3: array[1..20] of real;
  i,j,ii,jj: integer;
  measure: boolean;

{-------------------------------------------------------------}

FUNCTION ADSAMPLE (channel:INTEGER): INTEGER;
VAR
  ii: integer;
BEGIN
  PORT [$782] := (channel SHL 4) + 2; { channel selection and clear software-clock bit }
  PORT [$782] := (channel SHL 4) + 3; { channel selection and setting of software-clock bit }
  FOR ii:=1 TO 6 DO
    BEGIN
      END;
  ADSAMPLE := ((PORT[$781] AND $0F) SHL 8) + PORT[$780];
END;

{-------------------------------------------------------------}

PROCEDURE ZEROPITOT;
(to set the zero point on the pitot tube.. anything less than about 1 m/s is inaccurate (about 0.5 on pitot))

VAR
  measure: boolean;
BEGIN
  jj := 2;
  clrscr;
  measure := true;
  WHILE measure DO
    BEGIN
go to xy(1,1);
write('zero pitot and press return to sample');
readln(ch);
p0sum := 0;
FOR i := 1 to nsamples DO
BEGIN
  p0 := 0.92 + 50.1003*(adsample(0)/2048.0 - 1);\ [N/m²]
p0sum := p0sum + p0;
delay(10);
END;
jj := jj + 1;
p0 := p0sum/nsamples;
gotoxy(1,jj);
write('pitot = ', p0:7:3);
write(' Is the zero OK (y/n)?');
readln(ch);
if ord(ch) in [89,121] then measure := false;
END;
END;

{---------------------------------------------------------------}
PROCEDURE SAMPLE;
{ approx 100Hz to measure each sample }
BEGIN
  PORT[$783] := $92; \{Initialization of A/D Board\}
  PORT[$788] := $9B; \{Initialization ports A..C as inputs\}
  p0sum := 0;
  e1sum := 0;
  e2sum := 0;
  e3sum := 0;
FOR i := 1 to nsamples DO \{ sample at approx 100 Hz FOR 2 chan\}
BEGIN
  p0 := 0.92 + 50.1003*(adsample(0)/2048.0 - 1); \[N/m²]
  e1 := 3.53033 + 1.24933*(adsample(1)/2048.0 - 1); \[Volts\]
  e2 := 3.52427 + 1.26442*(adsample(2)/2048.0 - 1);
  e3 := 3.52154 + 1.22438*(adsample(3)/2048.0 - 1);
p0sum := p0sum + p0;
e1sum := e1sum + e1;
e2sum := e2sum + e2;
e3sum := e3sum + e3;
delay(9);
END;
p0 := p0sum/nsamples;
e1 := e1sum/nsamples*tcor;
e2 := e2sum/nsamples*tcor;
e3 := e3sum/nsamples*tcor;
write(chr(7));
END;

{---------------------------------------------------------------}
PROCEDURE REGRESSION;
{calculate a least-squares regression equation FOR E² vs U\(^{0.45}\) }
{where U\(^{0.45}\) is stored in x[..] and E² is stored in y[..] }
VAR
  sumx, sumy, sumxx, sumyy, sumxy: real;
xbar, ybar, sx, sy: real;
BEGIN
sumx := 0.0;
sumy := 0.0;
sumxx := 0.0;
sumyy := 0.0;
sumxy := 0.0;
FOR jj := 1 to nobs DO
BEGIN
  sumx := sumx + x[jj];
  sumy := sumy + y[jj];
  sumxx := sumxx + x[jj]^2;
  sumyy := sumyy + y[jj]^2;
  sumxy := sumxy + x[jj]*y[jj];
END;
xbar := sumx/nobs;
ybar := sumy/nobs;
sx := sqrt((sumxx-nobs*sqr(xbar))/(nobs-1));
sy := sqrt((sumyy-nobs*sqr(ybar))/(nobs-1));
b1 := (sumxy-nobs*xbar*ybar)/(sumxx-nobs*xbar*xbar);
a1 := ybar - b1*xbar;
se := sqrt((sumyy-a1*sumy-b1*sumxy)/(nobs-2));
rsq := 100*sqr( (sumxynobs*xbar*ybar)/((nobs-1)*sx*sy));
END;
{-------------------------------------------------------------
  MAIN PROGRAM
  }
BEGIN
zeropitot;
write('enter reference Temperature (C) and Pressure(kPa): ');
readln(Tref,Pref);
c1rscr;
FOR jj := 1 to nobs DO
BEGIN
gotoxy(1,1);
write('set tunnel windspeed and press return: ');
readln(ch);
if ord(ch) in [1..255] then
BEGIN
  writeln('');
gotoxy(1,2);
  write('enter air temperature (C): ');
  readln(Ta);
  write(' kk U e1 e2 e3 U^0.45 e12 e22 e32 ');
  Tcor := 1 + 0.00225*(Ta-Tref);
  Ta := Ta + 273.1;
sample;
  if p0 <= 0.2 then u[jj] := 0.0;
  if p0 > 0.2 then u[jj] := sqrt(2*p0*ta*287/(Pref*1000));
v1[jj] := e1;
v2[jj] := e2;
v3[jj] := e3;
if u[jj] > 0.0 then a := exp(0.45*ln(u[jj]));
if u[jj] = 0.0 then a := 0.0;
b := sqr(v1[jj]);
c := sqr(v2[jj]);
\[ d := \text{sqr}(v3[jj]); \]
\[ \text{gotoxy}(1, jj+3); \]
\[ \text{write}( \text{jj}; 3, u[jj]; 7:3, e1; 8:4, e2; 8:4, e3; 8:4); \]
\[ \text{writeln}(a; 7:3, b; 7:3, c; 7:3, d; 7:3); \]
END; [if]
END;
\[ \text{gotoxy}(1, 20); \]
FOR \text{jj} := 1 \text{ to nobs DP}
BEGIN
  \text{if } u[jj] > 0.0 \text{ then } x[jj] := \exp(0.45*\ln(u[jj]));
  \text{if } u[jj] = 0.0 \text{ then } x[jj] := 0.0;
  y[jj] := \text{sqr}(v1[jj]);
END;
\text{regression;}
\text{writeln}(\text{constants } a1, b1, rsq, se : , a1; 7:3, b1; 7:3, rsq; 7:2, se; 7:3);
\text{FOR } \text{jj} := 1 \text{ to nobs DO}
BEGIN
  y[jj] := \text{sqr}(v2[jj]);
END;
\text{regression;}
\text{writeln};
\text{writeln}(\text{constants } a2, b2, rsq, se : , a1; 7:3, b1; 7:3, rsq; 7:2, se; 7:3);
\text{FOR } \text{jj} := 1 \text{ to nobs DO}
BEGIN
  y[jj] := \text{sqr}(v3[jj]);
END;
\text{regression;}
\text{writeln};
\text{writeln}(\text{constants } a3, b3, rsq, se : , a1; 7:3, b1; 7:3, rsq; 7:2, se; 7:3);
\text{END.}

\textbf{C2.2 3-WIRE PROGRAM TO COMPUTE STATISTICS FOR } u \text{ AND } w \text{ VELOCITIES}

\textbf{PROGRAM 3WIREQ1;}

\{to sample a 3-wire probe at 1000Hz and process in the std way\}

\textbf{CONST}
\[ k = 0.20; \]
\[ k2 = 0.04; \]
\[ k3 = 0.520833; \]
\[ \text{nobs} = 8192; \]

\textbf{VAR}
\text{ch: char;}
\text{sample1, sample2: array[1..8192] of integer;}
\text{sample3: array[1..8192] of integer;}
\text{unit1, unit2: text;}
\text{filnam: string[15];}
\text{a1, b1, a2, b2: real;}
\text{e1, r1, z1, u1, ulsum: real;}
\text{u1bar, ulsd, ulsk, ulkr: real;}
\text{e2, r2, z2, u2, u2sum: real;}
\text{u2bar, u2sd, u2sk, u2kr: real;}

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a3,b3,c3,z3,z4: real;
u1u2,ruw: real;
Ta,Tref,Tcor: real;
u1sq,u2sq: real;
ix,iz: integer;
i,j: integer;
measure: boolean;

FUNCTION ADSAMPLE (channel:INTEGER): INTEGER;
VAR
   ii: integer;
BEGIN
   PORT [$782] := (channel SHL 4) + 2;  
                  (channel selection and
               clear software-clock bit)
   PORT [$7821] := (channel SI-4) + 3;  
                  (channel selection and
               setting of software-clock bit)
   FOR ii:=1 TO 6 DO
      BEGIN
         (loop until END of conversion)
      END;
   ADSAMPLE :=((PORT[$781] AND $0F) SHL 8) + PORT[$780];
END;

PROCEDURE SAMPLE;
[ approx 1ms to measure each sample ]
BEGIN
   PORT[$783] := $92;  
                  [Initialization of A/D Board]
   PORT[$78B] := $9B;  
                  [Initialization ports A..C as inputs]
   FOR i := 1 to nobs DO
      BEGIN
         sample1[i] := adsample(1);
         sample2[i] := adsample(2);
         sample3[i] := adsample(3);
         FOR j := 1 to 278 DO
            BEGIN
               (loop 88x FOR 1000hz, 278x FOR 410 Hz)
               END;
      END;
   write('sample completed');
END;

PROCEDURE CONVERT;
[ approx 5.2ms (+2.6ms for writeln) for conversion of each sample ]
BEGIN
   u1bar := 0;
   u2bar := 0;
   u1sq := 0;
   u2sq := 0;
   u1sd := 0;
   u2sd := 0;
   u1u2 := 0;

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FOR I := 1 to nobs DO

BEGIN

e1 := 3.53033 + 1.24933*(sample1[i]/2048.0 - 1); \hfill \text{(x-wire voltage)}
e2 := 3.52427 + 1.26442*(sample2[i]/2048.0 - 1);
e3 := 3.52154 + 1.22438*(sample3[i]/2048.0 - 1);

e1 := Tcore1; \hfill \text{(temperature correction)}
e2 := Tcore2;
e3 := Tcor*e3;

z1 := exp(4.444440*ln((sqr(e1)-a1)/b1)); \hfill \text{(assume n=0.38, k=0.1)}
z2 := exp(4.444440*ln((sqr(e2)-a2)/b2));
z3 := exp(4.444440*ln((sqr(e3)-a3)/b3));
z4 := 2*z3 - (z1+z2);

u1 := sqrt( k3*(z4 + sqrt( sqr(z4) + sqrt( z2-z1) ) ));
u2 := k3*(z2-z1)/u1;

u1bar := u1bar + u1;
u2bar := u2bar + u2;

u1sq := u1sq + sqr(u1);
u2sq := u2sq + sqr(u2);
u1u2 := u1u2 + u1*u2;

END;

u1bar := u1bar/nobs; \hfill \text{(mean component velocity)}
u2bar := u2bar/nobs;
u1u2 := u1u2/nobs;
u1sd := sqrt( (u1sq - nobs*sqr(u1bar))/(nobs-1));
u2sd := sqrt( (u2sq - nobs*sqr(u2bar))/(nobs-1));
u1u2 := u1u2 - u1bar*u2bar;

write(ix:4,iz:4,u1bar:7:3,u2bar:7:3,u1u2:8:4,u1sd:7:3,u2sd:7:3);

END;

{-----------------------------------------------}
{ MAIN PROGRAM }
{-----------------------------------------------}

BEGIN

write('enter output filename: ');
readln(filnam);
assign(unit2,filnam);
rewrite(unit2);
write('enter al, bl: ');
readln(a1,b1);
write('enter a2, b2: ');
readln(a2,b2);
write('enter a3, b3: ');
readln(a3,b3);
write('enter reference temperature: ');
readln(Tref);
measure := true;
while measure DO
BEGIN

write('enter T (C): ');
readln(Ta);
Tcor := 1 + 0.00225*(Ta-Tref);
write('enter X,Z coordinates: ');
readln(ix,iz);


sample; \hspace*{1em} \textit{\{approx 1.0ms\}}
\begin{verbatim}
writeln(chr(7)); \hspace*{1em} \textit{\{approx 7.8ms\}}
write(chr(7));
\end{verbatim}
write(unit2,ix:4,iz:4);
write(unit2,u1bar:7:3,u2bar:7:3,u1u2:8:4);
writeln(unit2,u1sd:7:3,u2sd:7:3);
write('repeat sample (y/n)? ');
readln(ch);
if ord(ch) in [78,110] then measure := false;
END;
\begin{verbatim}
close(unit2);
END.
\end{verbatim}
APPENDIX C3.
Listing of Q1 file and GROUND subroutine for a PHOENICS model
of turbulent air flow through a forest of widely spaced trees.

C3.1 Q1 file:

TALK=T;RUN(1,1);VDU=3

GROUP 1. Run title and other preliminaries
** Declaration of variables
TEXT(R3H20, Cd=2.0, SWEES) 
REAL(UREF,ZEDO,HEIGHT,ROTAT,CD,C4E,SPACNG,SCALE,C1E,C2E,C3E)
INTEGER(FORTOP,FORLE,F0RTE)

** Turbulence constants
C1E=1.44; C2E=1.92; C4E=1.5

** Parameters for Equilibrium boundary layer
SCALE=1.0; ZEDO=0.0005*SCALE
UREF=5.5; HEIGHT=0.5*SCALE; ROTAT=(1.1E-2)/SCALE

** Parameters for forest model
FORTOP=10; FORLE=14; FORTE=30
CD=2.0; SPACNG=0.064/1.5
CD=2.0; SPACNG=0.096*
CD=2.0; SPACNG=0.128*2

GROUP 2. Transience; time-step specification
**
STEADY=T

**
GROUP 3. X-direction grid specification
**
GRDPWR(X,35,1000*0.2,1.2)
NX=55; XULAST=0.2*SCALE

*** X points upwind of forest
XFRAC(1)=4.596; XFRAC(2)=8.426; XFRAC(3)=11.618
XFRAC(4)=14.278; XFRAC(5)=16.495; XFRAC(6)=18.342
XFRAC(7)=19.881; XFRAC(8)=21.164; XFRAC(9)=22.233
XFRAC(10)=23.124; XFRAC(11)=23.866; XFRAC(12)=24.484
XFRAC(13)=25.000

*** X points within forest
XFRAC(14)=25.481; XFRAC(15)=26.058; XFRAC(16)=26.750
XFRAC(17)=27.581; XFRAC(18)=28.578; XFRAC(19)=29.774
XFRAC(20)=31.210; XFRAC(21)=32.933; XFRAC(22)=35.000
XFRAC(23)=37.067; XFRAC(24)=38.790; XFRAC(25)=40.226
XFRAC(26)=41.422; XFRAC(27)=42.419; XFRAC(28)=43.250
XFRAC(29)=43.942; XFRAC(30)=45.000

*** X points downwind of forest
XFRAC(31)=45.540; XFRAC(32)=46.189; XFRAC(33)=46.967
XFRAC(34)=47.900; XFRAC(35)=49.021; XFRAC(36)=50.365
XFRAC(37)=51.978; XFRAC(38)=53.914; XFRAC(39)=56.237
XFRAC(40)=59.025; XFRAC(41)=62.370; XFRAC(42)=66.384
XFRAC(43)=71.202; XFRAC(44)=76.982; XFRAC(45)=83.919
XFRAC(46)=92.243; XFRAC(47)=102.232; XFRAC(48)=114.218
XFRAC(49)=128.602; XFRAC(50)=145.863; XFRAC(51)=166.576
XFRAC(52)=191.431; XFRAC(53)=221.258; XFRAC(54)=257.050
XFRAC(55)=300.000
GROUP 4. Y-direction grid specification

NY=30; YVLAST=0.2*SCALE

*** Y grid points below the canopy
YFRAC(1) = 0.1; YFRAC(2) = 0.2
YFRAC(3) = 0.3; YFRAC(4) = 0.4
YFRAC(5) = 0.5; YFRAC(6) = 0.6
YFRAC(7) = 0.7; YFRAC(8) = 0.8
YFRAC(9) = 0.9; YFRAC(10) = 1.0

*** Y grid points above the canopy
YFRAC(11) = 1.1; YFRAC(12) = 1.2
YFRAC(13) = 1.3; YFRAC(14) = 1.4
YFRAC(15) = 1.5; YFRAC(16) = 1.62
YFRAC(17) = 1.76; YFRAC(18) = 1.94
YFRAC(19) = 2.14; YFRAC(20) = 2.39
YFRAC(21) = 2.69; YFRAC(22) = 3.05
YFRAC(23) = 3.48; YFRAC(24) = 4.00
YFRAC(25) = 4.62; YFRAC(26) = 5.36
YFRAC(27) = 6.25; YFRAC(28) = 7.32
YFRAC(29) = 8.60; YFRAC(30) = 10.14

GROUP 7. Variables stored, solved & named

C1 is used to store A, the area density
SOLUTN(P1,Y,Y,N,N,Y); SOLUTN(U1,Y,Y,N,N,Y)
SOLUTN(V1,Y,Y,N,N,Y); SOLUTN(KE,Y,Y,N,N,Y)
SOLUTN(EPl,Y,Y,N,N,Y)
NAME(17)=UV; SOLVE(U1,V1,KE,EP); STORE(UV,C1,ENUT,EL1)

GROUP 9. Properties of the medium (or media)

RHO1=1.2; ENUL=1.E-5; ENUT=GRND3; EL1=GRND4; KELIN=0

GROUP 11. Initialization of variable fields

INIADD = .F.
PATCH(IN,INIVAL,1,NX,1,NY,1,1,1,1,1)
COVAL(IN,P1,0.0,1.E-3); COVAL(IN,U1,0.0,GRND1)
COVAL(IN,KE,0.0,GRND1); COVAL(IN,EP,0.0,GRND1)
COVAL(IN,V1,0.0,0.0)

** Area density for use in GROUND

PATCH(A1,INIVAL,FORLE,FORTE,1,1,1,1,1,1,1,1)
COVAL(A1,C1,0.0,0.045/SPACNG)
PATCH(A2,INIVAL,FORLE,FORTE,2,2,1,1,1,1,1,1)
COVAL(A2,C1,0.0,0.025/SPACNG)
PATCH(A3,INIVAL,FORLE,FORTE,3,3,1,1,1,1,1,1,1)
COVAL(A3,C1,0.0,0.025/SPACNG)
PATCH(A4,INIVAL,FORLE,FORTE,4,4,1,1,1,1,1,1,1)
COVAL(A4,C1,0.0,0.169/SPACNG)
PATCH(A5,INIVAL,FORLE,FORTE,5,5,1,1,1,1,1,1,1,1)
COVAL(A5,C1,0.0,0.455/SPACNG)
PATCH(A6,INIVAL,FORLE,FORTE,6,6,1,1,1,1,1,1,1)
COVAL(A6,C1,0.0,0.380/SPACNG)
PATCH(A7,INIVAL,FORLE,FORTE,7,7,1,1,1,1,1,1,1,1)
COVAL(A7,C1,0.0,0.344/SPACNG)
PATCH(A8,INIVAL,FORLE,FORTE,8,8,1,1,1,1,1,1,1,1)
COVAL(A8,C1,0.0,0.281/SPACNG)
PATCH(A9,INIVAL,FORLE,FORTE,9,9,1,1,1,1,1,1,1,1)
COVAL(A9,C1,0.0,0.205/SPACNG)
PATCH(B1,INIVAL,FORLE,FORTE,10,10,1,1,1,1,1,1,1,1,1)
COVAL(B1,C1,0.0,0.120/SPACNG)

GROUP 13. Boundary conditions and special sources

** Linearized source terms for KE and EP from GREX1

300
PATCH(KESOURCE,PHASEM,1,NX,2,NY,1,1,LSTEP)
COVAL(KESOURCE,KE,GRND4,GRND4); COVAL(KESOURCE,EP,GRND4,GRND4)

** Inlet Boundary: Equilibrium boundary layer

-----------------------------
PATCH(IN1,WEST,1,1,1,1,1,1); COVAL(IN1,P1,FIXFLU,3.0000)
COVAL(IN1,U1,ONLYMS,2.5000); COVAL(IN1,V1,ONLYMS,0.000)
COVAL(IN1,KE,ONLYMS,0.4261); COVAL(IN1,EP,ONLYMS,10.0100)
PATCH(IN2,WEST,1,1,2,1,1,1); COVAL(IN2,P1,FIXFLU,4.0728)
COVAL(IN2,U1,ONLYMS,3.3940); COVAL(IN2,V1,ONLYMS,0.000)
COVAL(IN2,KE,ONLYMS,0.4265); COVAL(IN2,EP,ONLYMS,3.9410)
PATCH(IN3,WEST,1,1,3,1,1,1); COVAL(IN3,P1,FIXFLU,4.5768)
COVAL(IN3,U1,ONLYMS,3.8140); COVAL(IN3,V1,ONLYMS,0.000)
COVAL(IN3,KE,ONLYMS,0.3830); COVAL(IN3,EP,ONLYMS,2.1460)
PATCH(IN4,WEST,1,1,4,1,1,1); COVAL(IN4,P1,FIXFLU,4.9272)
COVAL(IN4,U1,ONLYMS,4.1060); COVAL(IN4,V1,ONLYMS,0.000)
COVAL(IN4,KE,ONLYMS,0.3636); COVAL(IN4,EP,ONLYMS,1.4320)
PATCH(IN5,WEST,1,1,5,1,1,1); COVAL(IN5,P1,FIXFLU,5.1912)
COVAL(IN5,U1,ONLYMS,4.3260); COVAL(IN5,V1,ONLYMS,0.000)
COVAL(IN5,KE,ONLYMS,0.3518); COVAL(IN5,EP,ONLYMS,1.0620)
PATCH(IN6,WEST,1,1,6,1,1,1); COVAL(IN6,P1,FIXFLU,5.4036)
COVAL(IN6,U1,ONLYMS,4.5030); COVAL(IN6,V1,ONLYMS,0.000)
COVAL(IN6,KE,ONLYMS,0.3432); COVAL(IN6,EP,ONLYMS,0.8399)
PATCH(IN7,WEST,1,1,7,1,1,1); COVAL(IN7,P1,FIXFLU,5.5800)
COVAL(IN7,U1,ONLYMS,4.6500); COVAL(IN7,V1,ONLYMS,0.000)
COVAL(IN7,KE,ONLYMS,0.3364); COVAL(IN7,EP,ONLYMS,0.6921)
PATCH(IN8,WEST,1,1,8,1,1,1); COVAL(IN8,P1,FIXFLU,5.7312)
COVAL(IN8,U1,ONLYMS,4.7760); COVAL(IN8,V1,ONLYMS,0.000)
COVAL(IN8,KE,ONLYMS,0.3305); COVAL(IN8,EP,ONLYMS,0.5872)
PATCH(IN9,WEST,1,1,9,1,1,1); COVAL(IN9,P1,FIXFLU,5.8644)
COVAL(IN9,U1,ONLYMS,4.8870); COVAL(IN9,V1,ONLYMS,0.000)
COVAL(IN9,KE,ONLYMS,0.3253); COVAL(IN9,EP,ONLYMS,0.5088)
PATCH(IN10,WEST,1,1,10,1,1,1); COVAL(IN10,P1,FIXFLU,5.9832)
COVAL(IN10,U1,ONLYMS,4.9860); COVAL(IN10,V1,ONLYMS,0.000)
COVAL(IN10,KE,ONLYMS,0.3205); COVAL(IN10,EP,ONLYMS,0.4482)
PATCH(IN11,WEST,1,1,11,1,1,1); COVAL(IN11,P1,FIXFLU,6.0900)
COVAL(IN11,U1,ONLYMS,5.0750); COVAL(IN11,V1,ONLYMS,0.000)
COVAL(IN11,KE,ONLYMS,0.3160); COVAL(IN11,EP,ONLYMS,0.3998)
PATCH(IN12,WEST,1,1,12,1,1,1); COVAL(IN12,P1,FIXFLU,6.1872)
COVAL(IN12,U1,ONLYMS,5.1560); COVAL(IN12,V1,ONLYMS,0.000)
COVAL(IN12,KE,ONLYMS,0.3116); COVAL(IN12,EP,ONLYMS,0.3604)
PATCH(IN13,WEST,1,1,13,1,1,1); COVAL(IN13,P1,FIXFLU,6.2772)
COVAL(IN13,U1,ONLYMS,5.2310); COVAL(IN13,V1,ONLYMS,0.000)
COVAL(IN13,KE,ONLYMS,0.3075); COVAL(IN13,EP,ONLYMS,0.3275)
PATCH(IN14,WEST,1,1,14,1,1,1); COVAL(IN14,P1,FIXFLU,6.3600)
COVAL(IN14,U1,ONLYMS,5.3000); COVAL(IN14,V1,ONLYMS,0.000)
COVAL(IN14,KE,ONLYMS,0.3034); COVAL(IN14,EP,ONLYMS,0.2998)
PATCH(IN15,WEST,1,1,15,1,1,1); COVAL(IN15,P1,FIXFLU,6.4380)
COVAL(IN15,U1,ONLYMS,5.3650); COVAL(IN15,V1,ONLYMS,0.000)
COVAL(IN15,KE,ONLYMS,0.2995); COVAL(IN15,EP,ONLYMS,0.2760)
PATCH(IN16,WEST,1,1,16,1,1,1); COVAL(IN16,P1,FIXFLU,6.5172)
COVAL(IN16,U1,ONLYMS,5.4310); COVAL(IN16,V1,ONLYMS,0.000)
COVAL(IN16,KE,ONLYMS,0.2953); COVAL(IN16,EP,ONLYMS,0.2535)
PATCH(IN17,WEST,1,1,17,1,1,1); COVAL(IN17,P1,FIXFLU,6.6048)
COVAL(IN17,U1,ONLYMS,5.5040); COVAL(IN17,V1,ONLYMS,0.000)
COVAL(IN17,KE,ONLYMS,0.2904); COVAL(IN17,EP,ONLYMS,0.2307)
PATCH(IN18,WEST,1,1,18,1,1,1); COVAL(IN18,P1,FIXFLU,6.7044)
COVAL(IN18,U1,ONLYMS,5.5870); COVAL(IN18,V1,ONLYMS,0.000)
COVAL(IN18,KE,ONLYMS,0.2846); COVAL(IN18,EP,ONLYMS,0.2072)

301
PATCH(IN19, WEST, 1, 1, 19, 19, 1, 1, 1, 1); COVAL(IN19, P1, FIXFLU, 6.8124)
COVAL(IN19, U1, ONLYMS, 5.6770); COVAL(IN19, V1, ONLYMS, 0.000)
COVAL(IN19, KE, ONLYMS, 0.2778); COVAL(IN19, EP, ONLYMS, 0.1843)
PATCH(IN20, WEST, 1, 1, 20, 20, 1, 1, 1, 1); COVAL(IN20, P1, FIXFLU, 6.9288)
COVAL(IN20, U1, ONLYMS, 5.7740); COVAL(IN20, V1, ONLYMS, 0.000)
COVAL(IN20, KE, ONLYMS, 0.2700); COVAL(IN20, EP, ONLYMS, 0.1621)
PATCH(IN21, WEST, 1, 1, 21, 21, 1, 1, 1, 1); COVAL(IN21, P1, FIXFLU, 7.0560)
COVAL(IN21, U1, ONLYMS, 5.8800); COVAL(IN21, V1, ONLYMS, 0.000)
COVAL(IN21, KE, ONLYMS, 0.2606); COVAL(IN21, EP, ONLYMS, 0.1403)
PATCH(IN22, WEST, 1, 1, 22, 22, 1, 1, 1, 1); COVAL(IN22, P1, FIXFLU, 7.1928)
COVAL(IN22, U1, ONLYMS, 5.9940); COVAL(IN22, V1, ONLYMS, 0.000)
COVAL(IN22, KE, ONLYMS, 0.2496); COVAL(IN22, EP, ONLYMS, 0.1196)
PATCH(IN23, WEST, 1, 1, 23, 23, 1, 1, 1, 1); COVAL(IN23, P1, FIXFLU, 7.3392)
COVAL(IN23, U1, ONLYMS, 6.1160); COVAL(IN23, V1, ONLYMS, 0.000)
COVAL(IN23, KE, ONLYMS, 0.2367); COVAL(IN23, EP, ONLYMS, 0.1003)
PATCH(IN24, WEST, 1, 1, 24, 24, 1, 1, 1, 1); COVAL(IN24, P1, FIXFLU, 7.4916)
COVAL(IN24, U1, ONLYMS, 6.2430); COVAL(IN24, V1, ONLYMS, 0.000)
COVAL(IN24, KE, ONLYMS, 0.2216); COVAL(IN24, EP, ONLYMS, 0.0822)
PATCH(IN25, WEST, 1, 1, 25, 25, 1, 1, 1, 1); COVAL(IN25, P1, FIXFLU, 7.6512)
COVAL(IN25, U1, ONLYMS, 6.3760); COVAL(IN25, V1, ONLYMS, 0.000)
COVAL(IN25, KE, ONLYMS, 0.2041); COVAL(IN25, EP, ONLYMS, 0.0657)
PATCH(IN26, WEST, 1, 1, 26, 26, 1, 1, 1, 1); COVAL(IN26, P1, FIXFLU, 7.8132)
COVAL(IN26, U1, ONLYMS, 6.5110); COVAL(IN26, V1, ONLYMS, 0.000)
COVAL(IN26, KE, ONLYMS, 0.1842); COVAL(IN26, EP, ONLYMS, 0.0508)
PATCH(IN27, WEST, 1, 1, 27, 27, 1, 1, 1, 1); COVAL(IN27, P1, FIXFLU, 7.9728)
COVAL(IN27, U1, ONLYMS, 6.6440); COVAL(IN27, V1, ONLYMS, 0.000)
COVAL(IN27, KE, ONLYMS, 0.1622); COVAL(IN27, EP, ONLYMS, 0.0376)
PATCH(IN28, WEST, 1, 1, 28, 28, 1, 1, 1, 1); COVAL(IN28, P1, FIXFLU, 8.1216)
COVAL(IN28, U1, ONLYMS, 6.7680); COVAL(IN28, V1, ONLYMS, 0.000)
COVAL(IN28, KE, ONLYMS, 0.1394); COVAL(IN28, EP, ONLYMS, 0.0265)
PATCH(IN29, WEST, 1, 1, 29, 29, 1, 1, 1, 1); COVAL(IN29, P1, FIXFLU, 8.2452)
COVAL(IN29, U1, ONLYMS, 6.8710); COVAL(IN29, V1, ONLYMS, 0.000)
COVAL(IN29, KE, ONLYMS, 0.1191); COVAL(IN29, EP, ONLYMS, 0.0183)
PATCH(IN30, WEST, 1, 1, 30, 30, 1, 1, 1, 1); COVAL(IN30, P1, FIXFLU, 8.3220)
COVAL(IN30, U1, ONLYMS, 6.9350); COVAL(IN30, V1, ONLYMS, 0.000)
COVAL(IN30, KE, ONLYMS, 0.1068); COVAL(IN30, EP, ONLYMS, 0.0139)

** South Wall Boundary from GROUND

**

PATCH(GROUND, SOUTH, 1, NX, 1, 1, 1, 1, LSSTEP)
COVAL(GROUND, U1, GRND, 0.00); COVAL(GROUND, EP, GRND, GRND)
PATCH(GROKE, PHASEM, 1, NX, 1, 1, 1, LSSTEP)
COVAL(GROKE, KE, GRND9, GRND9)

**

** 2D FOREST momentum sink from GROUND

**

** rate of loss of SKE to WKE == dissipation ... U.KE

PATCH(FORSKE, PHASEM, FORLE, FORTE, 1, FORTOP, 1, 1, 1, 1)
COVAL(FORSKE, U1, FIXFLU, GRND7); COVAL(FORSKE, V1, FIXFLU, GRND7)
COVAL(FORSKE, KE, GRND7, 0.0); COVAL(FORSKE, EP, GRND7, 0.0)
PATCH(FORMKE, PHASEM, FORLE, FORTE, 1, FORTOP, 1, 1, 1, 1)
COVAL(FORMKE, KE, FIXFLU, GRND8); COVAL(FORMKE, EP, FIXFLU, GRND8)

**

** FREEN boundary

**

PATCH(FREEN, NORTH, 1, NX, NY, NY, 1, 1, 1, LSSTEP)
COVAL(FREEN, U1, ONLYMS, SAME); COVAL(FREEN, V1, ONLYMS, SAME)
COVAL(FREEN, KE, ONLYMS, SAME); COVAL(FREEN, EP, ONLYMS, SAME)

**
** OUTLET boundary

** PATCH(OUTLET,EAST,NX,NX,1, NY,1,1,LSTEP)

** COVAL(OUTLET,P1,FIXVAL,0.0)

** GROUP 15. Termination of sweeps

** RESREF(P1)=1e-4; RESREF(U1)=1e-4; RESREF(V1)=1e-4
RESREF(KE)=1e-4; RESREF(EP)=1e-4; LSWEEP=100

** GROUP 17. Under-relaxation devices

** FALSDT = xmin/umax ( approx= 0.025/3 say)
RELAX(P1,LNR=0.7)
RELAX(U1,FALSDT,SCALE*0.2); RELAX(V1,FALSDT,SCALE*0.2)
RELAX(KE,FALSDT,SCALE*0.2); RELAX(EP,FALSDT,SCALE*0.2)

** GROUP 18. Limits on variables or increments to them

** VARMIN(KE)=1.E-10; VARMIN(EP)=1.E-10

** GROUP 19. Data communicated by satellite to GROUND

** USEGRX=F; USEGRD=T
GENK=T; DUDY=T; DUDX=T; DVDY=T; DVDX=T
RSG6=1.0; RSG7=3.0; RSG8=3.0
RSG16=C1E; RSG17=C2E; RSG18=C3E; RSG21=C4E
RSG15=ROTAT; RSG27=HEIGHT; RSG28=UREF
RSG29=ZED0; RSG30=0.5*CD

** GROUP 20. Preliminary print-out

** ECHO=F

** GROUP 22. Spot-value print-out

** IYMON=F; IXMON=(FORLE+FORTE)/2

** GROUP 23. Field print-out and plot control

** OUTPUT(P1,Y,N,N,Y,Y,Y); OUTPUT(EP,Y,N,N,Y,Y,Y)
OUTPUT(ENUT,N,N,N,N,N,N); OUTPUT(EL1,N,N,N,N,N,N)
OUTPUT(C1,N,N,N,N,N,N); OUTPUT(UV,N,N,N,N,N,N)

** GROUP 24. Dumps for restarts

** RESTR(P1,V1,U1,KE,EP,ENUT)
STOP
C3.2  GROUND subroutine

C******************GROUND
C$DIR**GROUND
C FILE NAME GROUND.FTN ------------------------------- 23-AUG 1990
SUBROUTINE GROUND
C (C) COPYRIGHT 1984, LAST REVISION 1986.
C CONCENTRATION HEAT AND MOMENTUM LTD. ALL RIGHTS RESERVED.
INCLUDE'SATEAR'
INCLUDE'GRDLOC'
INCLUDE'GRDEAR'
LOGICAL STORE,SOLVE,PRINT
COMMON/TURB/CMU,CD,CMUCD,C1E,C2E,AK,EWAL
INTEGER HIGH,OLD,AUX,SOUTH,NORTH,EAST,WEST
CHARACTER NP''2,NPA''3,NPAT''4
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX USER SECTION STARTS:
C
C 1 User here sets SATLIT-to-GROUND COMMONS exactly as in SATLIT
COMMON/LSG/DUDX,DVDX,DWDX,DUDY,DVDY,DWDY,DUDZ,DVDZ,DWDZ,GENK,
  ILSG1,LSG2,LSG3,LSG4,LSG5,LSG6,LSG7,LSG8,LSG9,LSG10
LOGICAL  DUDX,DVDX,DWDX,DUDY,DVDY,DWDY,DUDZ,DVDZ,DWDZ,GENK,
  ILSG1,LSG2,LSG3,LSG4,LSG5,LSG6,LSG7,LSG8,LSG9,LSG10
COMMON/ISG/IZW1,ISG1,ISG2,ISG3,ISG4,ISG5,ISG6,ISG7,ISG8,ISG9,
  IISG10,IISG11,IISG12,IISG13,IISG14,IISG15,IISG16,IISG17,IISG18,KELIN
COMMON/RSG/TEMP0,PRESS0,ENUL0A,ENULB,ENULC,ENUTA,ENUTB,ENUTC,
  1CFIPA,CFIPB,CFIPC,CFIPD,CMDTA,CMDTB,CMDT,CMTD,WALLA,WALLB,
  ITMPI1,TMP1B,TMP1C,RHO1A,RHO1B,RHO1C,PRLH1A,PRLH1B,PRLH1C,
  1PRLC1A,PRLC1B,PRLC1C,PRLC3A,PRLC3B,PRLC3C,EL1A,EL1B,EL1C,
  1CINH1A,CINH1B,CINH1C,PHNH1A,PHNH1B,PHNH1C,
  1PRLC2A,PRLC2B,PRLC2C,PRLC4A,PRLC4B,PRLC4C,EL2A,EL2B,EL2C,
  1CINH2A,CINH2B,CINH2C,PHNH2A,PHNH2B,PHNH2C,
  IAZW1,BZW1,CZW1,DZW1,RSG1,RSG2,RSG3,RSG4,RSG5,RSG6,RSG7,RSG8,
  1RSG9,RSG10,RSG11,RSG12,RSG13,RSG14,RSG15,RSG16,RSG17,RSG18,
  1RSG19,RSG20,RSG21,RSG22,RSG23,RSG24,RSG25,RSG26,RSG27,RSG28,
  1RSG29,RSG30
COMMON/CSG/CSG1,CSG2,CSG3,CSG4,CSG5,CSG6,CSG7,CSG8,CSG9,CSG10
CHARACTER*4  CSG1,CSG2,CSG3,CSG4,CSG5,CSG6,CSG7,CSG8,CSG9,
  1CSG10
C
C 2 User dimensions own arrays here, for example:
C DIMENSION UUH(10,10),UU0C(10,10),UUUX(10,10),UUUXZ(10)
  DIMENSION GCI(100,100),GYG(100,100),GLEN1(100,100),
  G.XG(100,100),GDUX(100,100),GU1(100,100),GU1D(100,100),
  G.P1(100,100),GP1D(100,100),GKE(100,100),GKE1D(100,100),
  G.GEP(100,100),G.EPID(100,100),UI1SRCE(100,100)
C
C 3 User places his data statements here, for example:
C DATA NXDIM,NYDIM/10,10/
  CHARACTER*40 LINE
  INTEGER UV, IJU, VV
  DATA NXDIM,NYDIM/100,100/
  DATA UV,UU,UV/VV/17,18,19/
C
C User should not change next eleven lines.
LOW(I)=NPHI+I
HIGH(I)=2*NPHI+I

304
OLD(I)=3*NPHI+I
IN(I)=4*NPHI+I
INXYZ(IJ)=-KF(4*NPHJ+I)-(J-1)*NX*NY
STORE(I)=MOD(ISLN(I),2).EQ.0
SOLVE(I)=MOD(IPRN(I),2).EQ.0
PRINT(I)=MOD(IPRN(D,2).EQ.0
SOUTH(I)=-(KF(I)-1)
NORTH(I)=-(KF(I)+1)
EAST(I)=-(KF(I)+NY)
WEST(I)=-(KF(I)-NY)

The next function permits reference to the field variables
at any slab IZDASH. This can only be used when the field
variables are stored in main memory, i.e., not stored on disc.
INDPHI(I,IZDASH)=KF(I+(IzIZDASH*4cy(io w
( ))
IF(IGR.EQ.19) GO TO 19
IF(IGR.EQ.13) GO TO 13
GO TO (1,2,2,2,2,2,2,9,2,11,2,13,2,2,2,2,2,19,2,2,
12,2,2),IGR
C The next function permits reference to the field variables
C at any slab IZDASH. This can only be used when the field
C variables are stored in main memory, i.e., not stored on disc.
C
C--- GROUP 1. Run title and other preliminaries
C
1 GO TO (1001,1002),ISC

C * CALL MAKE(EARTH-variable index) if EASP1, EASP2,...
C ...EASP10 are needed as working-space stores for slabwise
C quantities. Examples are as follows.
1001 CONTINUE
CALL MAKE(YG2D)
CALL MAKE(XG2D)
CALL MAKE(EASP1)
CALL MAKE(EASP2)
CALL MAKE(EASP3)
CALL MAKE(EASP4)
CALL MAKE(EASP5)
CALL MAKE(EASP6)
CALL MAKE(EASP7)
CALL MAKE(EASP8)
CALL MAKE(EASP9)
CALL MAKE(EASP10)

turbulence constants
CALL SUB4R(CMU,0.5478,CD,0.1643,CMUCD,0.09,C1E,RSG16)
CALL SUB4R(C2E,RSG17,C3E,RSG18,AK,0.435,EWAL,9.0)
C CALL SUB4R(CMU,0.5478,CD,0.1643,CMUCD,0.09,C1E,1.44)
C CALL SUB3R(C2E,1.92,AK,0.435,EWAL,9.0)
RETURN

1002 CONTINUE
RETURN

C--- GROUP 9. Properties of the medium (or media)
C
C The sections in this group are arranged sequentially in their
C order of calling from EARTH. Thus, as can be seen from below,
C the temperature sections (10 and 11) precede the density
C sections (1 and 3); so, density formulae can refer to
C temperature stores already set.
9 GO TO (91,91,91,95,91,91,91,91,91,902,91),ISC
C
305
CONTINUE
RETURN

*A. SECTION 12*

For EL1.EQ.GRND: phase-1 length scale Index AUX(LENI) 
IF(EL1.EQ.GRND) THEN

Mixing length derived from height above ground and, within the 
canopy, the local area density (Li et al (1990))

CALL SUB3(IFORLE,ISG1,IFORTE,ISG2,IFORTOP,ISG5)
CALL SUB2(IFORUP,ISG3,IFORDN,ISG4)
CALL SUB3R(ROTAT,RSG15,HEIGHT,RSG27,UREF,RSG28)
CALL SUB2R(ZED,RSG29,FORHT,RSG9)

CALL WRIT2R('HEIGHT ',HEIGHT,'ZED ',ZED)

USTAR=(AK*WREF)/(ALOG(HEIGHTIzED+l.0))

Then the boundary layer depth DELBL is estimated:

DELBL=USTAR/(6.0*ROTAT)
DL1=DELBL
DL2=DELBL

IF(NX.EQ.1.AND.(IFORTOP.GT.0)) GOTO 9023

Length scale upwind; Blackader, d for open terrain
D1=5*ZED
DO 9021 IY=1,NY
   DO 9021 IX=I,IFORUP
   GZ = GYG(IY,IX)-D1
   9021 GLEN1(IY,IX) = AK*GZ/(1+AK*GZ/DL1)
IF((NX.EQ.1).AND.(IFORTOP.EQ.0)) GOTO 9028
IF(IFORTOP.EQ.0) GOTO 9028

Length scale downwind; Blackader, d for open terrain
DO 9022 IY=1,NY
   DO 9022 IX=IFORDN,NX
   GZ = GYG(IY,IX)-D1
   9022 GLENI (IY,IX) = AK*GZ/(1+AK*GZ/DL1)

Length scale above forest; Blackader, d for forest
C9023 GH = (GYG(IFORTOP,IFORLE)+GYG(IFORTOP+1,IFORLE))/2

Length scale within forest; Li et al, (1990)
GLH= GLEN1(IFORTOP+1,IFORLE)
DO 9025 IY=1,IFORTOP
   DO 9025 IX=IFORLE,IFORTE
   GZ = GYG(IY,IX)-D2
   9025 GLEN1(IY,IX) = GLH*GYG(IY,IX)/(1+0.4*GCI(Y,IX))/CIH
C CALL WRIT1R('GLH ')
IF(NX.EQ.1) GOTO 9028

Linear (horizontal) interpolation upwind of forest edge
DO 9026 IY=1,NY
   DO 9026 IX=IFORUP+1,IFORLE-1
   9026 GLEN1(IY,IX) = (GXG(IY,IX)-GXG(IY,IFORUP))/(GXG(IY,IFORLE)-
* GXG(IY,IFORUP))*(GLEN1(IY,IFORLE)-GLEN1(IY,IFORUP))+
GLEN1(IY,IFORUP)

C Linear (horizontal) interpolation downwind of forest edge
DO 9027 IY=1,NY
DO 9027 IX=IFORTE+1,IFORDN-1
9027 GLEN1(IY,IX) = (GXG(IY,IX)-GXG(IY,IFORTE))/(GXG(IY,IFORDN)-
* GXG(IY,IFORTE))*GLEN1(IY,IFORDN)-GLEN1(IY,IFORTE)+
* GLEN1(IY,IFORTE)

9028 CONTINUE
C CALL PRNYX('GLEN',GLEN1,NYDIM,NXDIM)
CALL SETYX(AUX(LENI),GLEN1,NYDIM,NXDIM)
C CALL PRN('GRNDEL1 ',AUX(LENI))
ENDIF
C--- Mixing length derived from the turbulent kinetic energy
C and its rate of dissipation...
IF(EL1.EQ.GRND4) CALL FN22(KE,1.E-10)
IF(EL1.EQ.GRND4) CALL FN22(EP,1.E-10)
C.... FN31(Y,X1,X2,A,B1,B2) Y = A * (X1**B1) * (X2**B2)
IF(EL1.EQ.GRND4) CALL FN31(AUX(LENI),KE,EP,CD,1.5,-1.0)
RETURN
95 CONTINUE
C * ----------- GROUP 9 SECTION 5 ---------------------------
C----------Prandtl mixing-length formula...
IF(ENUT.EQ.GRND2) CALL FN31(AUX(VIST),AUX(LENI),EASP1,1.0
1,2,0,5)
C---------- Prandtl-Kolmogorov formula...
IF(ENUT.EQ.GRND3) CALL FN22(KE,1.E-10)
IF(ENUT.EQ.GRND3) CALL FN31(AUX(VIST),KE,AUX(LENI),CMU,
10.5,1.0)
RETURN
C*****************************************************************
C
C--- GROUP 11. Initialization of variable or porosity fields
C
C
11 CONTINUE
GO TO(111,112,113),ISC
111 CONTINUE
C---------GROUP 11 SECTION 1 --------------------value = GRND
C Profile data calculated from 1-d model
OPEN(UNIT=31,FILE='I DUIN.DAT',TYPE='OLD',READONLY)
DO 1103 IY=1,NY
READ(31,* ) II,GUID(IY,I),GKE1D(IY,1),GEP1D(IY,1)
GP1D(IY,1)=RHO1*GUID(IY,1)
DO 1102 IX=IXF,IXL
GUI(IY,IX)=GUID(IY,1)
GKE(IY,IX)=GKE1D(IY,1)
1102 GEP(IY,IX)=GEP1D(IY,1)
1103 CONTINUE
CLOSE(31)
CALL ONLYIF(U1,U1,'ALL')
CALL SETYX(VAL,GUI,NYDIM,NXDIM)
CALL ONLYIF(KE,KE,'ALL')
CALL SETYX(VAL,GKE,NYDIM,NXDIM)
CALL ONLYIF(EP,EP,'ALL')
CALL SETYX(VAL,GEP,NYDIM,NXDIM)
Log-law representation of initial conditions.

First USTAR is estimated from the reference velocity UREF at the reference HEIGHT:

\[
USTAR = \frac{(AK_1 UREF)}{(ALG(HEIGHT/ZED+1.0))}
\]

Then the boundary layer depth DELBL is estimated:

\[
DELBL = \frac{USTAR}{(6.0 \times ROTAT)}
\]

and finally a more accurate USTAR is calculated:

\[
USTAR = \frac{(AK_1 UREF)}{(ALG(HEIGHT/ZED+1.0)+5.75*HEIGHT/DELBL)}
\]

EASP6 is set to the distance from the cell node to the y=0 plane

\[
EASP6 = \text{set distance from cell node to the y=0 plane}
\]

CALL FN0(EASP6,YG2D)

The initial velocities are set to

\[
U1 = USTAR \times \{LN(Y/ZED+1.0)+5.75*Y/DELBL\}/AK
\]

CALL ONLYIF(U1,U1,'ALL')

CALL FN2(VAL,EASP6,1.0,1.0,ZED)

NOTE FN43(Y,X,A,B) CALCULATES Y=LN(A+X+B) NOT Y=LN(A*X+B)

CALL FN43(VAL,VAL,0.0,0.0)

CALL FN34(VAL,EASP6,5.75,DELBL)

CALL FN25(VAL,USTAR/AK)

The initial KE values are set to

\[
KE = USTAR^2 \times \{LN(Y/DELBL)^2/\sqrt{CMUCD}\}
\]

CALL ONLYIF(KE,KE,'ALL')

CALL FN2(VAL,EASP6,1.0,-1.0,DELBL)

CALL FN3(VAL,VAL,0.0,0.0,USTAR*USTAR/\sqrt{CMUCD})

CALL FN22(VAL,1.E-8)

The initial EP values are set to

\[
EP = CD \times KE^{1.5} \times (1+5.75*Y/DELBL)/(AK_1 (Y+ZED)/(1-Y/DELBL))
\]

CALL ONLYIF(EP,EP,'ALL')

CALL FN2(VAL,EASP6,AK*ZED,AK)

CALL FN46(VAL,EASP6,1.0,-1.0,DELBL)

CALL FN28(VAL,VAL,CD)

CALL FN46(VAL,EASP6,1.0,5.75,DELBL)

CALL FN22(KE,1.E-8)

RETURN

HIR & JFD 2 Sept 86. Prevent negative k values...

CALL FN22(VAL,1.E-8)

The initial EP values are set to

\[
EP = CD \times KE^{1.5} \times (1+5.75*Y/DELBL)/(AK_1 (Y+ZED)/(1-Y/DELBL))
\]

CALL ONLYIF(EP,EP,'ALL')

CALL FN2(VAL,EASP6,AK*ZED,AK)

CALL FN46(VAL,EASP6,1.0,-1.0,DELBL)

CALL FN28(VAL,VAL,CD)

CALL FN46(VAL,EASP6,1.0,5.75,DELBL)

CALL FN22(KE,1.E-8)

CALL FN37(VAL,KE,1.5)

RETURN
* CALL SETYX(VAL,ARRAY,NYDIM,NXDIM) when value information is contained in the user-dimensioned (i.e., external) GROUND array ARRAY.

GO TO (130,131,131,131,134,131,131,137,131,139,131,11311,1312,131,131,1315,131,131,1318,1319,1320,13 1),ISC
131 CONTINUE
RETURN

130 CONTINUE
C----------GROUP 13 SECTION 1 ----------- coefficient = GRND
ZED=RSG26
C For ground patches the roughness length is held in RSG29
IF(NPATCH(1:3),EQ,'GRO')ZED=RSG29
C The skin-friction factor for smooth horizontal walls
C is deduced from the log law
C s=AK*CMUCD**0.25*KE**0.5/vel/ln(1.01+EWAL*dist*CMUCD**0.25*KE**0.5/ENUL)
C and for rough walls with roughness length ZED is deduced from
C the log law,
C s=AK*CMUCD**0.25*KE**0.5/vel/ln(dist/ZED+1.0)
C EASP8 stores the distance from the node to the south or north wall
CALL ONLYIF(1,100,'ALL')
CALL FN0(EASP8,YG2D)
C EASPIO stores CMUCD**0.25*KE**0.5
CALL FN22(KE,1.E-8)
CALL FN8(EASPIO,KE,CMUCD**0.25,0.0,0.5,0.0)
CALL ONLYIF(U1,V1,'ALL')
IF(ZED.GT.0)GO TO 1303
CALL FN1(CO,1.01)
CALL FN53(CO,EASPIO,EASP8,EWAL/ENUL)
C NOTE FN43(Y,X,A,B) CALCULATES Y=LN(A+X+B) NOT Y=LN(A*X+B)
CALL FN43(CO,CO,0.0,0.0)
GO TO 1304
1303 CALL FN2(CO,EASP8,1.0,1.0/ZED)
C Finally for velocities CO is set to s*vel
1304 CALL FN15(CO,EASPIO,CO,0.0,AK)
C Wall function for EP
CALL ONLYIF(EP,EP,'ALL')
CALL FN28(CO,PATGEO,10*FIXVAL)
RETURN

134 CONTINUE
C----------GROUP 13 SECTION 5 ----------- coefficient = GRND4
C----------Coefficient part of linearized kinetic-energy source
IF(KELIN.NE.0) GO TO 1341
CALL ONLYIF(KE,KE,'ALL')
CALL FN31(CO,AUX(VIST),AUX(LEN1),CD/CMU,1.0,-2.0)
C----------Coefficient part of linearized dissipation-of-turbulent-kinetic-energy source...
CALL ONLYIF(EP,EP,'ALL')
CALL FN31(CO,AUX(VIST),AUX(LEN1),(C2E*CD/CMU),1.0,-2.0)
RETURN
1341 IF(KELIN.NE.1) GO TO 1342
CALL ONLYIF(KE,KE,'ALL')
CALL FN56(CO,AUX(VIST),EASP1,KE,0.5)
CALL FN54(CO,KE,AUX(VIST),C2E*CMUCD)
CALL SET(EASP7,CO)
CALL ONLYIF(EP,EP,'ALL')
CALL FN28(CO,AUX(VIST),(2.*C2E-1.)*CMUCD)
CALL FN26(CO,KE)
RETURN
1342 IF(KELIN.NE.2) RETURN
CALL ONLYIF(KE,KE,'ALL')
CALL FN15(CO,KE,AUX(VIST),0.,CMUCD)
CALL ONLYIF(EP,EP,'ALL')
CALL FN15(CO,KE,AUX(VIST),0.,C2E*CMUCD)
RETURN
137 CONTINUE

C----------GROUP 13 SECTION 8 ------------ coefficient = GRND7

c dissipation of SKE to WKE (and eventually to heat)
CALL ONLYIF(KE,KE,'FORSKE')
c dissipation term = -1/2.Cd.a.IULKE times RSG7 (3)
CALL FN0(CO,U1)
CALL FN40(CO)
CALL FN26(CO,C1)
CALL FN25(CO,RSG7*RSG30)
CALL ONLYIF(EP,EP,'FORSKE')
c dissipation term = -1/2.Cd.a.IULKE times RSG8 (3)
CALL FN0(CO,U1)
CALL FN40(CO)
CALL FN26(CO,C1)
CALL FN25(CO,RSG8*RSG30)
RETURN

139 CONTINUE

C----------GROUP 13 SECTION 10 ------------ coefficient = GRND9
CALL ONLYIF(KE,KE,'ALL')
C For a near wall cell the linearised KE source has a Coefficient of
C CO=(CMUCD)**0.75*KE*0.5*LF(2d)/(2*D*AK)
C where for smooth walls
C LF(dist)=LN(1.01+EWAL*clist*CMUCD*0.25*J(J**0.5*ENL))
C and for rough walls
C LF(dist)=LN(dist/ZED+1.0)
C EASP8 stores the distance from the cell node to the north or south walls
CALL FN0(EASP8,YG2D)
ZED=RSG26
C For ground walls the roughness length is held in RSG29
IF(NPATCH(1:3).EQ.'GRO')ZED=RSG29
C EASP10 stores CMUCD**0.25*KE**0.5
CALL FN22(KE,1.E-8)
CALL FN8(EASP10,KE,CMUCD*.25,0.00500)
IF (ZED.NE.0.0) GO TO 1393
C Calculate LF(2*d) for smooth walls
CALL FN1(CO,1.01)
CALL FN53(CO,EASP8,EASP10,2.0*EWAL/ENUL)
C NOTE FN43(Y,X,A,B) calculates Y=ALOG(A+X+B)
CALL FN43(CO,CO,0.0,0.0)
GO TO 1394
1393 CONTINUE
C Calculate LF(2*d) for rough walls
CALL FN2(CO,EASP8,1.0,2.0/ZED)
C NOTE FN43(Y,X,A,B) Calculates Y=ALOG(A+X+B)
CALL FN43(CO,CO,0.0,0.0)
C Multiply LF(dist) by CMUCD**0.75*KE*0.5/(2*AK*dist)
1394 CONTINUE
CALL FN31(CO,CO,KE,CMUCD**0.75/(2*AK),1.0,0.5)
CALL FN27(CO,EASP8)

310
RETURN

1311 CONTINUE
C--------GROUP 13 SECTION 12 ------------------------ value = GRND
C The near horizontal wall value of EP is set to
C (CMUCD)**0.75*KE**1.5/(AK*dist+AK*ZED)
CALL ONLYIF(EP,EP,'ALL')
CALL FN4(VAL,EASP10,0.0,0.0,0.0,1.0/AK)
ZED=RSG26
IF(NPATCH(1:3).EQ.'GRO')ZED=RSG29
CALL FN2(EASP8,EASP8,ZED,1.0)
CALL FN27(VAL,EASP8)
RETURN

1312 CONTINUE
C--------GROUP 13 SECTION 13 ------------------------ value = GRND1
IF(NPATCH.NE.'1DINLET') GOTO 13121
CALL ONLYIF(PI ,PI ,'ALL')
CALL SETYX(EASP5,GP1D,NYDIM,NXDIM)
CALL FN0(VAL,EASP5)
CALL WRIT40('IDINLET FOR P1... OK')
CALL PRNYX('GP1D ',GP1D,NYDIM,NXDIM)
CALL ONLYIF(U1 ,U1 ,'ALL')
CALL SETYX(EASP5,GUI D,NYDIM,NXDIM)
CALL FN0(VAL,EASP5)
CALL ONLYIF(KE,KE,'ALL')
CALL SETYX(EASP5,GKEID,NYDIM,NXDIM)
CALL FN0(VAL,EASP5)
CALL ONLYIF(EP,EP,'ALL')
CALL SETYX(EASP5,GEP1D,NYDIM,NXDIM)
CALL FN0(VAL,EASP5)
RETURN
C Log-law representation of the inlet conditions.
C First USTAR is estimated from the reference velocity URef at the
C reference HEIGHT:
13121 CALL ONLYIF(1,100,'ALL')
CALL SUB4R(ROTAT,RSG15,HEIGHT,RSG27,UREF,RSG28ZEDSG29)
USTAR=(AK*UREF)/(ALOG(HEIGHTIZED+1.0))
C Then the boundary layer depth DELBL is estimated:
DELBL=USTAR/(6.0*ROTAT)
C and finally a more accurate USTAR is calculated:
USTAR=(AK*UREF)/(ALOG(HEIGHTIZED+1.0)+5.75*HEIGHT/DELBL)
C EASP6 is set to the distance from the cell node to the y=0 plane
CALL FN0(EASP6,YG2D)
C The initial velocities are set to
C U1=USTAR*(LN(YJZED+1.0)+5.75*YIDELBL)/AK
13122 CONTINUE
CALL ONLYIF(U1,U1,'ALL')
CALL FN2(VAL,EASP6,1.0,1.0/ZED)
C NOTE FN43=ALOG(A+Y+B) NOT ALOG(A*Y+B) AS STATED IN MANUAL
CALL FN43(VAL,VAL,0.0,0.0)
CALL FN34(VAL,EASP6,5.75/DELBL)
CALL FN25(VAL,USTARJAK)
C The pressure inlet condition is given by the mass flow rate
C and hence equal to U1*Density.
CALL ONLYIF(P1,P1,'ALL')
CALL FN2(VAL,EASP6,1.0,1.0/ZED)
C NOTE FN43=ALOG(A+Y+B) NOT ALOG(A*Y+B) AS STATED IN MANUAL
CALL FN43(VAL,VAL,0.0,0.0)
CALL FN34(VAL,EASP6,5.75/DELBL)
CALL FN25(VAL, USTAR*RHO1/AK)
C The inlet KE values are set to
C KE = USTAR**2*(1-Y/DELBL)**2/SQRT(CMUCD)
CALL ONLYIF(KE, KE,'ALL')
CALL FN2(VAL, EASP6, 1.0, -1.0/DELBL)
CALL FN3(VAL, VAL, 0.0, 0.0, USTAR*USTAR/SQRT(CMUCD))
C+++ HIR & JFD 2 Sept 86. Prevent negative k values...
CALL FN22(VAL, 1.E-8)
C The inlet EP values are set to
C EP = CD*KE**1.5*(1+5.75*YfDELBL)/(AK*(Y+ZED)*(1+yfDELBL))
CALL ONLYIF(EP, EP,'ALL')
CALL FN2(VAL, EASP6, AK*ZED, AK)
CALL FN46(VAL, EASP6, 1.0, -1.0/DELBL)
CALL FN28(VAL, VAL, CD)
CALL FN46(VAL, EASP6, 1.0, 5.75/DELBL)
CALL FN22(K, 1.E-8)
CALL FN37(VAL, KE, 1.5)
RETURN
1315 CONTINUE
C----------GROUP 13 SECTION 16 ---------------------- value = GRND4
IF(KELIN, NE, 0.) GO TO 13151
C---------- Value part of linearized kinetic-energy source...
CALL ONLYIF(KE, KE,'ALL')
CALL FN31(VAL, EASP1, AUX(LEN1), CMU/CD, 1.0, 2.0)
C---------- Value part of linearized dissipation-of-turbulent-k
C energy source...
CALL ONLYIF(EP, EP,'ALL')
CALL FN21(VAL, AUX(VIST), EASP1, 0.0, C1E/C2E)
RETURN
13151 IF(KELIN, NE, 1.) GO TO 13152
CALL ONLYIF(KE, KE,'ALL')
CALL FN56(VAL, KE, KE, AUX(VIST), (C2E-1.0)*CMUCD)
CALL FN53(VAL, AUX(VIST), EASP1, 1.5)
CALL FN27(VAL, EASP7)
CALL ONLYIF(EP, EP,'ALL')
CALL FN21(VAL, EASP1, AUX(VIST), 0.0, C1E/(2.*C2E-1.))
CALL FN34(VAL, EP, (C2E-1.)/(2.*C2E-1.))
RETURN
13152 IF(KELIN, NE, 2.) RETURN
CALL ONLYIF(KE, KE,'ALL')
CALL FN15(VAL, EASP1, KE, 0.1, /CMUCD)
CALL FN37(VAL, AUX(VIST), 2.0)
CALL ONLYIF(EP, EP,'ALL')
CALL FN21(VAL, AUX(VIST), EASP1, 0.0, C1E/C2E)
RETURN
1318 CONTINUE
C----------GROUP 13 SECTION 19 ---------------------- value = GRND7
C momentum sink term = -1/2Cd.a.IUII.S, CO=fixflu
CALL ONLYIF(U1, U1,'FORSKE')
CALL FN0(VAL, V1)
CALL FN50(VAL, 2)
CALL FN49(VAL, U1)
CALL FN30(VAL)
CALL FN26(VAL, U1)
CALL FN40(VAL)
CALL FN25(VAL, 1.0*RSG6)
C IF(SOLVE(KE)) CALL FN34(VAL, KE, -1.0)
CALL FN26(VAL, C1)
CALL FN25(VAL, RSG30)
C momentum sink term = -1/2Cd.a.V1.S, CO=fixflu
CALL ONLYIF(V1,V1,'FORSKE')
CALL FN0(VAL,V1)
CALL FN50(VAL2)
CALL FN49(VAL,U1)
CALL FN30(VAL)
CALL FN26(VAL,V1)
CALL FN40(VAL)
CALL FN25(VAL,-1.0*RSG6)
CALL FN26(VAL,C1)
CALL FN25(VAL,RSG30)
RETURN

1319 CONTINUE
C-----------GROUP 13 SECTION 20 ------------------ value = GRND8
C production of SKE, generation of KE and EP
C production of KE = ... + 1/2Cd.a.U^3
CALL ONLYIF(KE,KE,'FORMKE')
CALL FN0(VAL,U1)
CALL FN40(VAL)
CALL FN51(VAL,3.0)
CALL FN25(VAL,RSG30)
CALL FN26(VAL,C1)

C production of EP = ... + 2.EP/KE.1/2Cd.a.UA3
CALL ONLYIF(EP,EP,'FORMKE')
CALL FN31(VAL,AUX(VIST),AUX(LEN1),RSG21*CD/CMU,1.,2.)
CALL FN37(VAL,U1,3.0)
CALL FN40(VAL)
CALL FN26(VAL,C1)
CALL FN25(VAL,RSG30)
CALL ONLYIF(EP,EP,'XEPSRCE')
CALL FN56(VAL,EASPI,EASPI,KE,C3E)

C sweeps/bursts model, Li et al, 1985
CALL ONLYIF(U1,U1,'SWEEP')
IF(IFORTOP.EQ.0) GOTO 13193
CALL GETYX(U1,GUI,NYDIM,NXDIM)
CALL SUB3R(A,RSG1,B,RSG2,AR,RSG3)
C \t GH = (GYG(IYL+1,IX)+GYG(IYL,IX))/2
GH = RSG9
DO 13192 IY=IYF,IYL
   DO 13192 IX=IXF,TXL
      CUR = (GU1(IYL+1,IX)+GU1(IYL,IX))/2
      CU = GU1(IY,IX)
      GZ = GYG(IY,IX)
   13192 USRCE(IY,IX) = A/(1+B*AR)*(GUR*GU)*GZ/CH
C \t CALL PRNYX('UISRCE ',UISRCE,NYDIM,NXDIM)
CALL SETYX(VAL,USRCE,NYDIM,NXDIM)
13193 RETURN

1320 CONTINUE
C-----------GROUP 13 SECTION 21 ------------------ value = GRND9
C Value for North or South wall KE source.
CALL ONLYIF(KE,KE,'ALL')
ZED=RSG26
C For ground walls the roughness length is held in RSG29
IF(NPATCH(1:3),EQ.'GRO')ZED=RSG29
C For a near wall cell the linearised KE source has a VALUE of
C VAL=(vel*AK/(CMUCD**0.25*LF(dist)))**2
IF (ZED,NE.0.0) GO TO 13201
C Calculate LF(dist) for smooth walls
CALL FN1(VAL,1.01)
CALL FN53(VAL,EASP8,EASP10,EWAL/ENUL)

C       NOTE FN43(Y,X,A,B) calculates Y=ALOG(A+X+B)
CALL FN43(VAL,VAL,0.0,0.0)
GO TO 13202

13201 CONTINUE
C   Calculate LF(dist) for rough walls
CALL FN2(VAL,EASP8,1.0,1.0/ZED)
C       NOTE FN43(Y,X,A,B) Calculates Y=ALOG(A+X+B)
CALL FN43(VAL,VAL,0.0,0.0)

13202 CONTINUE

C Calculate LF(dist) for rough walls
CALL FN2(VAL,EASP8,1.0,1.0/ZED)
C       NOTE FN43(Y,X,A,B) Calculates Y=ALOG(A+X+B)
CALL FN43(VAL,VAL,0.0,0.0)

CALL FN51(VAL,-2.0)
C   EASP9 is used for storing the square of the velocity across the wall
CALL FN3(EASP9,U1,0.0,0.0,0.0)
C   Finally VAL is set to the desired function
CALL FN21(VAL,VAL,EASP9,0.0,AK*AK/CMUCD**0.5)
RETURN

C*********************************************************************************************
C
C--- GROUP 19. Special calls to GROUND from EARTH
C
19 GO TO (191,191,191,194,191,196,191,191),ISC
191 CONTINUE
RETURN

194 CONTINUE
C * ---------GROUP 19 SECTION 4 ---- START OF ITERATION.
CALL FNGENK(EASP1,1)
CALL GETYX(C1,G1,NYDIM,NXDIM)
CALL GETYX(Y2D,GY,NDIM,NXDIM)
CALL GETYX(X2D,GX,NDIM,NXDIM)
RETURN

196 CONTINUE
C * ---------GROUP 19 SECTION 6 ---- FINISH OF IZ SLAB.
C calculate Reynolds stress
IF(ISWEEP.EQ.LSWEEP) THEN
CALL FNDUDY(EASP2,U1)
CALL FNDUDX(EASP3,U1)
CALL FNDVDY(EASP4,V1)
CALL FNDVDX(EASP5,V1)
ELSE
ENDIF
RETURN
END