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MICROMETEOROLOGY OF FOREST SURFACE FLUXES

Tiina Markkanen

Division of Atmospheric Sciences
Department of Physical Sciences
Faculty of Science
University of Helsinki
Helsinki, Finland

ACADEMIC DISSERTATION

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Abstract

Atmospheric turbulence generated by friction between mean flow and underlying surface and by buoyancy is the most effective process carrying matter and kinetic energy between surfaces and the atmosphere. Transport by both turbulence and radiation inside a vegetation canopy is governed by properties of the vegetation, such as canopy architecture and optical properties of plant elements.

Balance of the most important greenhouse gas carbon dioxide (CO_2) between different land ecosystems and the atmosphere is still an open question. One approach to the problem is measuring the CO_2 flux in the atmospheric surface layer (ASL) above the canopy. At the timescales typical for measurements of net ecosystem carbon exchange (NEE) over a canopy, photosynthetically active radiation (PAR) is the main driving variable accounting for the variation of photosynthetic rate at plant surfaces. Under daytime atmospheric conditions, turbulence is usually efficient enough to carry the signal from the surfaces to the measurement height. Thus, the flux measured above the canopy is an integral in vertical of the exchange rates occurring inside the canopy and on the ground. Equally, the flux is an integral of fluxes in horizontal, although in horizontal the integration domain is not restricted by the forest floor and canopy top and not all the areas contribute equally to the result. The area having strongest influence on the measured flux depends on characteristics of the prevailing turbulence. Determining the area by modelling is called footprint analysis.

In this thesis, the influence of PAR on the CO_2 exchange of a Scots pine canopy was studied by using PAR distribution measurements to estimate canopy NEE. The estimates were compared with NEE values measured with the eddy covariance (EC) method. Furthermore, the EC measurements and a model for turbulence statistics were used to investigate the characteristics of turbulent flow inside and above a forest canopy and the results were further used in the flux footprint analysis. A stochastic Lagrangian flux footprint analysis was also used in an attempt to separate the influences of different forest types on the fluxes measured over a complex forest site. Finally, flux measurements were analysed to find out the annual CO_2 balance of a Scots pine forest.

Contents

List of publications

This thesis consists of an introductory review, followed by six research articles. Papers are reproduced with the kind permission of the journals concerned.

I Palva L., Markkanen T., Siivola E., Garam E., Linnavuo M., Nevas S., Manoochehri F., Palmroth S., Rajala K., Ruotoistenmäki H., Vuorivirta T., Seppälä I., Vesala T., Hari P. and Sepponen R. (2000) Tree scale distributed multipoint measuring system of photosynthetically active radiation. *Agricultural and Forest Meteorology* 106:71-80.

II Vesala T., Markkanen T., Palva L., Siivola E., Palmroth S. and Hari P. (2000) Effect of variations of PAR on CO_2 exchange estimation for Scots pine. *Agricultural and Forest Meteorology* 100:337-347.

III Rannik Ü., Markkanen T., Raittila J., Hari P. and Vesala T. (2003) Turbulence statistics inside and over forest: influence on footprint prediction. *Boundary-Layer Meteorology* 109:163-189.

IV Markkanen T., Rannik Ü., Marcolla B., Cescatti A. and Vesala T. (2003) Footprints and fetches for fluxes over forest canopies with varying structure and density. *Boundary-Layer Meteorology* 106:437-459.

V Rannik Ü., Aubinet M., Kurbanmuradov O., Sabelfeld K.K., Markkanen T. and Vesala T. (2000) Footprint analysis for measurements over a heterogeneous forest. *Boundary-Layer Meteorology* 97:137-166.

VI Markkanen T., Rannik Ü., Keronen P., Suni T. and Vesala T. (2001) Eddy covariance fluxes over a boreal Scots pine forest. *Boreal Environment Research* 6:65-78.

1 Introduction

Micrometeorology deals with the meteorological processes occurring in the lowest part of the atmosphere that is called the planetary boundary layer (PBL) or the atmospheric boundary layer (ABL). The properties of the PBL are strongly influenced by the properties of the underlying surface, such as the surface roughness and temperature. The signal of the surface-atmosphere interactions extends through the PBL within the timescale of a few hours to one day (Arya, 2001).

The extent of the PBL is very variable and in low and mid-latitudes usually has a distinctive daily cycle, the depth of the PBL being some tens to hundreds of metres in the night and reaching the maximum value of several hundreds of metres to a few kilometres in the afternoon. The range of the diurnal variation is at its largest over land surfaces during clear sky conditions due to effective surface heating during the day and cooling at night time (Arya, 2001). The heating of the ground surface also warms the air in contact with the surface generating upwelling structures of warm air which contribute positively to the intensity of turbulent mixing, a process responsible for the effectiveness of the transport of matter and energy, except for radiative energy. Cooling of the underlying surface, on the contrary, suppresses turbulent mixing leading to reduction of the PBL height. However, surface heating is not the only process affecting the intensity of the turbulence, as there is also mechanical mixing due to wind shear, the intensity of which depends on wind velocity and surface roughness. Thus, turbulent mixing, to some degree, usually exists within the PBL.

The planetary boundary layer is further divided into the outer layer and the surface layer (or the atmospheric surface layer, ASL) (Garratt, 1999). The former is also called the Ekman layer; in it the Coriolis force due to the rotation of the earth affects the motion of air. The latter is closest to the surface including also air in between the surface roughness elements, such as plants and buildings. Especially, which is important regarding this work, the ASL includes all the airspaces within plant canopies. In the ASL the effect of the Coriolis force can usually be neglected.

The upper boundary of the ASL is not well defined. According to one definition vertical turbulent fluxes are approximately constant throughout the ASL. Therefore, the layer is also called the constant flux layer. However, in the lowest part of the ASL, where the roughness elements are located, the gaseous or particulate matter of interest usually has both vertically and horizontally unevenly distributed sources and sinks within the canopy. Thus, the fluxes of these constituents within or under the canopy are not equal to the fluxes above. The distribution and structure of individual roughness elements have a strong influence on the flow characteristics within and just above the canopy. Consequently, the layer is called the roughness sublayer (RSL) (Kaimal and Finnigan, 1994). Above the RSL within the ASL, the vertical flux of momentum, sensible heat, water vapour, or any nonreactive scalar can be assumed to represent the exchange rate of a quantity per ground area between the underlying surfaces and the atmosphere. This fact has been widely adopted in empirical micrometeorology in efforts to find out the net exchange rate of a constituent between the atmosphere and different ecosystems.

During the last few decades, along with increasing awareness of the effects of greenhouse gases on climate (IPCC, 2001), increasing effort has been put into research concerning the exchange of these gases between the atmosphere and various ecosystems (Goulden *et al.*, 1996). Carbon dioxide (CO_2) is an important greenhouse gas that has considerable anthropogenic sources in addition to large natural sources and sinks in vegetation, soils and oceans. The balance between the natural source and sink terms is sensitive to several environmental variables both at global and local scales. The contribution of different ecosystem types on the global CO_2 balance has been studied using several methods, including process modelling, remote sensing, forest inventories, scaling up from local scale to global scale, and their combination. At ecosystem scale, the CO_2 balance has been widely investigated with a technique called eddy covariance (EC), which measures vertical fluxes at one point within the ASL with an averaging time of tens of minutes (Goulden *et al.*, 1996; Aubinet *et al.*, 2000; Baldocchi *et al.*, 2001). Besides CO_2, the fluxes of momentum, sensible heat and latent heat (water vapour) are routinely measured with the EC technique.

Scaling is the procedure to describe a process occurring at a certain temporal or spatial scale with knowledge of processes at another scale (Jarvis, 1995). When canopy scale gas exchange is of interest, a leaf is a reasonable scale unit from which to start the scaling-up procedure (Baldocchi, 1992). The driving variables of leaf-scale processes are solar and terrestrial radiation, temperature, humidity, wind velocity, and soil moisture, which are in turn determined by turbulent mixing, incoming and outgoing components of radiation at different wavelengths and the physiological status of the vegetation.

In timescales typical for most micrometeorological flux measurements, the CO_2 exchange rate of the ecosystem (the net ecosystem exchange, NEE) varies mainly according to the intensity of incoming photosynthetically active radiation (PAR). Typically, the photosynthetic response of green leaves is a nonlinear function of irradiance and saturates at high irradiances. In coniferous canopies an annual shoot comprising several needles is usually considered a basic photosynthesising unit. The shape of the response curve varies considerably according to the location of the shoot within the canopy. Because of the nonlinearity and the difference in light response curves of individual shoots, the scaling of the CO_2 exchange rate up to the scale of a tree or the ecosystem is not straightforward. It is important to assess our ability to understand and model the processes contributing to the CO_2 exchange at each temporal and spatial scale and to qualify and calibrate different measurement techniques.

Because of the random variation resulting from the statistical nature of the turbulence, from unideality of the measurement site or the measurement equipment and from patchy distribution of sources, it is difficult to predict the actual flux of the quantity of interest with any model. The sources and sinks at the surfaces in contact with the air and the measurements at a point in the ASL are connected with each other by a footprint function (Schmid, 1997). Reliable solution of a footprint function would be useful in quality assessment of the measured data to make sure that the flux originates from an area that is representative of the area of interest. Several models to solve the footprint function for different situations have been developed, of which the Lagrangian stochastic models are the physically most realistic for forests, provided that flow characteristics are described reliably.

In this study we assess the influence of PAR irradiance and turbulent flow characteristics and their spatial and temporal variation on forest surface fluxes. Throughout the work, CO_2 serves as an example gas because it is inert on the time scales under consideration, because its interaction with forest ecosystems is complicated although widely studied by modelling and measurements, and because it is of crucial importance both for plants and for the atmosphere.

The first aim of this study is to estimate the influence of the spatial and temporal changes of the PAR irradiance within and above a Scots pine canopy on the CO_2 exchange rate of the ecosystem (**Papers I** and **II**). The second aim is to evaluate Lagrangian stochastic footprint models by comparing the effect of measured and modelled turbulence statistics within the canopy on the footprints predicted (**Paper III**), by applying Lagrangian stochastic models to different canopy structures (**Paper IV**), and by making an attempt to explain the variations of measured CO_2 flux by the patchiness of the source term (**Paper V**). The final aim is to determine the long term balances of the CO_2 exchange of a Scots pine forest based on EC flux measurements above the canopy (**Paper VI**).

2 PAR and surface fluxes

When sunlight hits a surface it is reflected, absorbed or transmitted. The proportions of reflection, absorption and transmission vary according to the properties of the material and to the incidence angle and wavelength of incoming radiation (Monteith and Unsworth, 1990). The effects of solar radiation on plant life are various, including destruction of plant cells by high energetic ultra violet radiation and maintenance of processes, such as photosynthesis, that are essential to plant life.

Plants take in carbon dioxide by photosynthesis and release it by respiration. Photosynthesis takes place within cells containing chloroplasts (mesophyll tissue). In the process, certain molecules in the mesophyll cells get electronically excited by the solar radiative energy. The energy gained is further utilised in a chemical process that consumes CO_2 and water to produce carbohydrates and oxygen. Carbohydrates serve as a long-term storage of chemical energy in plant cells and oxygen is released from leaves to the atmosphere (Nobel, 1999). The light-absorbing reactions supplying energy for photosynthesis are sensitive to wavelengths approximately from 400 to 700 nm. Accordingly, the radiation within this wavelength range is called photosynthetically active radiation (PAR).

Under conditions when no other environmental factor (such as temperature or soil water content) restricts photosynthesis, the photosynthetic rate of a leaf is strongly dependent on irradiance on the leaf surface. The light response curve is nonlinear. Its shape is actually concave so that at low irradiances the photosynthetic rate is an approximately linear function of irradiance and at high intensities it saturates gradually towards a saturation point. At low irradiances, the ratio between CO_2 molecules bound and the incident PAR irradiance at the surface is called the apparent quantum yield. Because plants respond to the amount of quanta, quantum units ($\mathrm{molm^{-2}s^{-1}}$) are usually used to express the photosynthetic photon flux density (PPFD) on a leaf surface.

2.1 Radiative transfer in a plant canopy

Solar radiation above vegetation can be divided into two components: the direct radiation coming from the direction of the solar disc and the diffuse radiation coming from the blue sky. As solar radiation penetrates through a canopy it attenuates due to absorption and reflection by the plant elements along its path. The irradiance of direct radiation at a certain point within a canopy can be expressed in terms of the gap probability along its path (Nilson, 1971; Stenberg, 1998). That means that the intensity does not change, but the probability for the beam reaching the observation point diminishes. The irradiance of diffuse radiation reaching a certain point in a canopy is an integral of the gap probability with respect to the distribution of diffuse radiation of the sky. The total irradiance at some level (within the canopy) is the difference of the irradiance above the canopy and the radiation absorbed by the plant elements above.

Grouping of plant elements diminishes the fraction of leaf area in direct sun light in comparison with random distribution of the leaves. Leaves of the canopy are grouped at least in individual tree crowns and branches (Kuuluvainen and Pukkala, 1987). Needles of coniferous species are also grouped in shoots often in a very complex way. Grouping diminishes the absorption of radiation per unit leaf area by the canopy and increases penetration to the lower parts of the canopy, increasing the photosynthetic rate of the lower canopy (Stenberg, 1996).

Especially in the case of coniferous trees that have small needles instead of leaves there are also penumbral areas (Oker-Blom, 1985; Stenberg, 1995). These are areas where a needle shading another does not obscure the whole solar disc, allowing part of the direct radiation to the needle surface. The existence of penumbras complicates things further when estimating the irradiance of canopies and their photosynthetic rates. The importance of the phenomenon with respect to photosynthesis is that the penumbras make the irradiance distribution more even within the canopy, which increases the photosynthetic rate of the canopy (Stenberg, 1998).

2.2 CO_2 exchange rate of an ecosystem

To study the influence of radiation, a formulation has to be given to photosynthesis as a function of irradiance. The expression for shoot scale CO_2 exchange rate per unit leaf area used in **Paper II** of this work is as follows:

$$P = \frac{\alpha f(I)(g_s C + r)}{g_s + \alpha f(I)} - r, \tag{1}$$

where α is the carboxylation efficiency, g_s is conductance of CO_2, C is ambient CO_2 concentration, r is respiration rate and $f(I)$ is a hyperbolic function describing the PAR dependence, where I is PAR irradiance. The effect of r in the numerator of the first term is small and hence it can be ignored. $f(I)$ can be expressed as follows:

$$f(I) = \frac{I}{I + \gamma} \tag{2}$$

and the respiration rate:

$$r = r_0 Q_{10}^{\frac{T - T_0}{10}} \tag{3}$$

where Q_{10} represents the change in the respiration rate for a 10°C change in temperature, T is needle temperature and T_0 is a reference temperature at which the respiration rate is equal to r_0. In Equations 1, 2 and 3 α, γ and r_0 are empirical parameters that can be deduced from shoot scale measurements of CO_2.

Shoot scale measurements of transpiration are used in determination of conductance according to an optimum control model of gas exchange (Hari and Mäkelä, 2003). The model is based on the assumption that the opening of stomata is regulated so as to maximise the rate of photosynthesis depending on changing water availability.

When only the radiation dependence of photosynthesis is of interest, the CO_2 exchange rate is often given as follows (Valentini *et al.* (1996); Goulden *et al.* (1997); Hollinger *et al.* (1999) and **Paper VI**):

$$P = \frac{P_{max} I}{K + I} - r \tag{4}$$

where I denotes incident PAR, P_{max} is photosynthetic capacity, and K is half-saturation constant at which $P(I) = K/2$.

The instantaneous exchange rate of a whole canopy is the sum of the exchange rates of all the shoots within the canopy. It is not a straightforward task, however, to determine the whole-canopy photosynthesis, since the parameters in Equation 1 or 4 actually vary from shoot to shoot depending on the light and nutrient conditions under which the needles live. Furthermore, the intensity of incident light available depends on shading by the rest of the foliage and on the angle between the shoot and the direction of light propagation (Stenberg, 1998).

Finally, considering the CO_2 exchange rate of a whole ecosystem, ground vegetation and soil respiration r_s have to be taken into account. The photosynthetic rate of ground vegetation can be described with Equation 1 or 4. The parameters may differ considerably from those for trees. Soil CO_2 efflux depends on soil composition, temperature, and water content (Pumpanen, 2003). In the short term, the soil respiration rate is mainly dependent on soil temperature and can be described with an equation similar to Equation 3. Caution is necessary, however, in modelling extended time periods or temperature ranges because parameters r_0 and Q_{10} are functions of temperature and soil moisture content (Lloyd and Taylor, 1994).

3 Turbulent flow

The following properties characterise turbulent flow (Arya, 2001): (1) Because of its deterministically chaotic nature turbulent flow cannot be predicted in detail. (2) Turbulent flow is three dimensional and rotational. (3) It is diffusive *i.e.* the flow tends to mix properties embedded in the fluid. Turbulent diffusion in the PBL is usually several orders of magnitude more effective than molecular diffusion. (4) The kinetic energy of turbulent flow dissipates into heat as a result of molecular viscosity. (5) Turbulent flow comprises a wide range of scales of motion. These scales of motion are called eddies - they are coherent patterns of velocity, vorticity, and pressure.

3.1 Flow in the atmospheric surface layer

Flow in the atmosphere is governed by the following equations: the conservation equation of mass, the conservation equation of thermal energy, the conservation equation of water vapour, the equation of state and the three conservation equations for momentum (Navier-Stokes equations) (Garratt, 1999). These equations determine the values of seven variables (along-mean wind, cross wind, and vertical components of wind speed u, v, w usually denoted as u_i, potential temperature Θ, air density ρ, pressure p and specific humidity q) at a point in space (x, y, z or simply x_i) at a certain time (t). Turbulent flow in the PBL cannot be described merely by its mean characteristics, for the fluctuation of the variables also has to be taken into account. According to Reynolds' decomposition, an instantaneous value can be written in two parts accounting for the mean value over a certain time period and fluctuation around the mean. For example, an instantaneous along-wind velocity is now written:

$$u = \overline{u} + u' \, . \tag{5}$$

When Reynolds' decomposed variables are used to solve the mean $\overline{u}$ and fluctuating u' parts of the governing equations, new terms arise in the mean equations (see *e.g.* Garratt, 1999) so that eventually the number of equations remains smaller than the number of variables. These terms comprising the covariances of fluctuations represent the turbulent fluxes so that for instance $\overline{u_i'q'}$ is the turbulent moisture flux and $\overline{u_i'u_j'}$ is the turbulent momentum flux, also called Reynolds' stress. When these terms (second order moments) are parameterised to close the set of governing equations the solution is called first-order closure. If, instead, equations are derived to solve second-order moments, second-order closure is required to close the set (Garratt, 1999).

First-order closure is often formulated analogous to molecular diffusion. For example, an equation for the moisture flux:

$$\overline{u_i'q'} = -K_q \frac{\partial \overline{q}}{\partial x_i}, \qquad (6)$$

where K_q is the turbulent diffusivity of water vapour in the air, implies a flux towards a lower concentration. This is, however, far too simple an expression for flows within and near above plant canopies, where counter-gradient fluxes are frequent (Wilson *et al.*, 1977).

To describe the budget of the momentum flux in the ASL, certain terms in the equations can be considered negligible (see *e.g.* Garratt, 1999; Stull, 1988, for detailed discussion). After considerable manipulation, the momentum equation comprises the (total) time derivative of the momentum flux and four terms feeding or suppressing the local momentum flux: shear production, buoyant production, turbulent transport, and pressure destruction (Kaimal and Finnigan, 1994).

Similarly, making use of the mean and the fluctuating velocity budget equations, an expression can be derived for the turbulent kinetic energy (TKE$= 1/2(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})$) and for the mean kinetic energy of the flow (MKE$= 1/2(\overline{u}^2 + \overline{v}^2 + \overline{w}^2)$). In the ASL, the TKE budget is a balance between the following terms: shear production, buoyant production, pressure transport, turbulent transport, and viscous dissipation (Kaimal and Finnigan, 1994).

3.2 Flow inside a canopy

Characteristics of turbulence inside a plant canopy differ considerable from those above because of drag forces imposed by the plant elements on the flow field (Kaimal and Finnigan, 1994). The drag forces are of two kinds: viscous drag caused by skin friction and form or pressure drag caused by individual plant elements with components perpendicular to mean flow. In addition to the momentum, also the exchange of scalar properties between the vegetation and the atmosphere occurs within the canopy and trunk space and on the ground. The plant elements generate turbulent wakes, the process providing the mean kinetic energy with a shortcut to be transformed into the TKE of the length scales of the waving elements. In addition, large-scale turbulent motions are transformed into smaller-scale motions instead of merely being cascaded at a constant rate through the inertial subrange of the TKE spectrum (Wilson *et al.*, 1977; Raupach and Thom, 1981). Most plants tend to wave in the wind, converting MKE into TKE with a frequency typical of each plant under each wind condition. This phenomenon is important, however, only in the case of coherently waving cereal canopies (see Finnigan, 2000, and the references therein).

Horizontal averaging of the time-averaged momentum equation and of the conservation equation of a scalar s over an area large enough to overcome the influence of individual canopy elements gives rise to new terms in the equations. This is due to the non-commutativity of horizontal averaging and spatial differentiation (Wilson *et al.*, 1977). The terms in the momentum equation correspond to the form drag and viscous drag per unit mass of air. In the conservation equation for a scalar s one term which arises is the emission rate of the scalar per unit mass of air. In addition, a term representing any net movement of stress, called the 'dispersive' flux, arises because of the spatial correlation between local variations of stress and mean velocity (Finnigan, 2000).

Several models have been developed to provide a one-dimensional description of the flow field inside a horizontally homogeneous canopy under neutral, steady state conditions (Wilson *et al.*, 1977; Meyers and Paw U, 1986; Massman and Weil, 1999). According to observations the mean velocity profile inside a forest under neutral stratification, instead of being logarithmic (as above the RSL) is rather exponential, decaying gradually towards the ground because of plant elements serving as sinks for momentum (Kaimal and Finnigan, 1994). In **Papers III** and **IV**, a function given by Albini (1981) was used to predict mean velocity profile as a function of the foliage drag coefficient ($C_d(z)$), leaf area density ($a(z)$) and the foliage shelter factor for momentum ($P_m(z)$), each of which are functions of height. To be precise, C_d and P_m are functions of wind speed and leaf area density, which in turn are functions of height (Marcolla *et al.*, 2003). Despite the fact that C_d and P_m may have a considerable effect on values of displacement height and roughness length (Massman, 1997), they were kept constant in **Papers III** and **IV**, their values being difficult to determine and distinguish from each other.

In **Paper III**, the measured average wind speed profile under near-neutral stratification was compared with that predicted by the model by Albini (1981) (see Chapter 6 for the description of the measurements) (Fig. 1). Above the canopy, the model predicted a little higher mean wind velocity than the average of observation under near neutral stratification. In the upper part of the canopy, the model prediction showed values considerably lower than the observations. The selected set of parameters for the canopy leaf area density can partly account for the difference. According to **Paper IV**, lowering the peak of the leaf area distribution would modify the wind profile so that it shows a better correspondence with the measured values. However, the observations contradict other studies that report in dense canopies uniform values of wind speed or even second maximum in wind speed profiles has been observed (Finnigan, 2000). The reason for this is unclear; the profile in Figure 1 can be biased due to few observation levels within the canopy.

When the momentum equation in the canopy is averaged over an area of suitable size (see Raupach and Thom (1981) Eq. 5 or Finnigan (2000) Eq. 2.7) and then combined with an expression for drag force by a single element ((Raupach and Thom, 1981) Eq. 12), the momentum equation can be presented as a function of the foliage drag coefficient, the leaf area density, and the foliage shelter factor for momentum (Raupach and Thom, 1981; Massman, 1997). Further combining this with the equation for mean wind speed and assuming constant flux above the canopy, the set of equations can be closed by parameterising the surface drag coefficient (Massman, 1997). Assuming that displacement height d is the effective level of mean drag by canopy elements (see Massman, 1997, and the references therein) an equation for d can be derived. Furthermore, a solution for the roughness length z_0 can be found by assuming a logarithmic wind profile above the RSL (Massman, 1997).

The velocity variances ($\sigma_u = (\overline{u'^2})^{1/2}, \sigma_v = (\overline{v'^2})^{1/2}$ and $\sigma_w = (\overline{w'^2})^{1/2}$) are approximately constant throughout the ASL under neutral stratification but decrease rapidly below the canopy (see *e.g.* Raupach (1989) for a review on the variances from several measurement campaigns). A model by Massman and Weil (1999), based on the second-order closure equations developed by Wilson *et al.* (1977) was used in **Papers III** and **IV** to predict the profiles of variances. Comparison with various measurements (see *e.g.* Raupach and Thom, 1981) reveals that the behaviour of the variances is similar to that of the mean wind speed - instead of having uniform values in the lowest parts of the canopy, all the variances decrease continuously down to the forest floor.

The correlation between the vertical and along-mean wind components of turbulent flow defined as

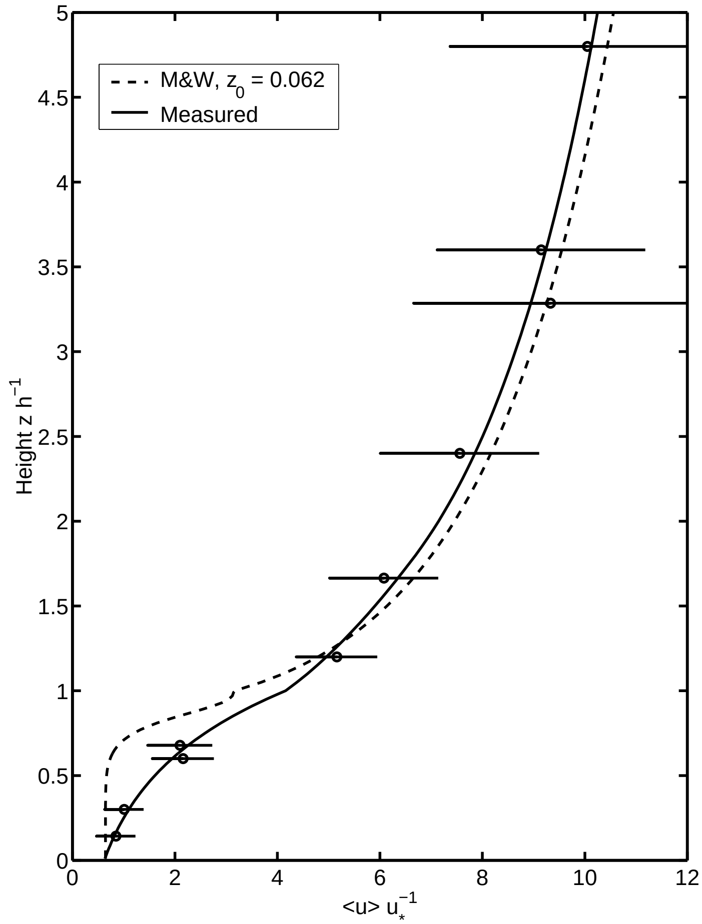

Figure 1: Mean velocity profile under near neutral conditions (See also **Paper III**). Circles represents mean observations at each measurement height and error bars indicate standard deviation. The solid line is a fit to the observed values. Normalised displacement height is $d = 0.78h$, where h is canopy height. The dashed line is the mean velocity predicted with the model by (Massman and Weil, 1999). Normalised roughness length is $z_0 = 0.07h$ and $0.062h$ for the measurements and the model, respectively. Height of the RSL is $Z_* = h + d$.

$$r_{uw} = \frac{\overline{u'w'}}{\sigma_u \sigma_w} \tag{7}$$

can be interpreted as the efficiency of momentum transport (Finnigan, 2000). According to observations, it has a constant value of around -0.3 within the ASL above the RSL, it has larger negative values at the upper part of the canopy and it decreases close to zero near the ground. This is also the case with the observations in **Paper III**, implying that the downward momentum transport is relatively more efficient in upper parts of the canopy than higher up in the ASL. The model by Massman and Weil (1999) does not predict the maximum in efficiency inside the canopy.

Higher-order statistics, including skewness (Sk) and kurtosis (K), are measures of intermittency in the flow (Kaimal and Finnigan, 1994). Above the RSL, skewness and kurtosis have Gaussian values of 0 and 3, respectively. Inside the RSL, however, they typically deviate from Gaussian values: skewness of along-wind velocity component reaches a value of $\mathrm{Sk}_u = 1$ inside the canopy, whereas Sk_w changes over the same distance to a negative value of approximately -0.6. The combination of positive skewness of along-wind and negative skewness of cross-wind components implies that the turbulence is dominated by intermittent downwind moving gusts (Kaimal and Finnigan, 1994). Our observations are similar with the earlier ones, although highly scattered.

4 Footprints

Footprint analysis is an important tool to estimate the spatial context of flux measurements. If flux measurements were performed over a horizontally homogeneous canopy that extended to infinity in horizontal directions and had the same vertical source/sink distribution everywhere, the measured flux at any two points in the RSL would be identical. Furthermore, the flux measured over the canopy would be equal to the integral of the exchange rates at plant surfaces in a vertical column of the canopy. However, no natural canopy is that ideal but rather consists of areas of different source/sink strengths. Especially in the case of large inhomogeneities it is important to distinguish which areas actually contribute to the flux measured at a certain point to properly interpret the results.

The area contributing a certain fraction to the measured flux is called the footprint or the source area of the measurement (Schmid, 1997). Besides the obvious influence of the wind direction, other characteristics of the prevailing flow, such as wind speed and intensity of turbulence, also have an influence on the extent and the location of the source area. Observation height, the roughness length of the canopy and the structure of the canopy are geometrical constraints that are representative for a certain measurement set up and do not change between subsequent measurements.

For a given geometry and meteorological situation the footprint function (Leclerc and Thurtell, 1990; Schuepp *et al.*, 1990), also called a source weight function (Schmid, 1994, 1997), connects the actual sources on the surfaces (source strength distribution) to the measurements at the observation point. Expression for a measured value (η) at the point ($\mathbf{r}$) is as follows:

$$\eta(\mathbf{r}) = \int_R Q_\eta(\mathbf{r} + \mathbf{r}') f(\mathbf{r}, \mathbf{r}') d\mathbf{r}' \tag{8}$$

where $Q_\eta(\mathbf{r} + \mathbf{r}')$ is the source (or sink) strength distribution and $f(\mathbf{r}, \mathbf{r}')$ is the footprint function, and R stands for integration domain. However, the distribution cannot usually be known a priori and thus, relative source weights, are considered instead of a source strength distribution (Schmid, 1997).

From now on a wider term 'footprint' will be used instead of 'footprint function' and the work on determining the footprint functions will be called footprint analysis. Several methods have been used in determining the footprints of concentrations and fluxes in different situations, including analytical models using analytical solutions to the advection-diffusion equation, Lagrangian stochastic models, large eddy simulations and models based on K-theory (Vesala *et al.*, 2004). The different methods, except for those based on K-theory (Sogachev *et al.*, 2004), have been reviewed by Schmid (2002) and Wilson *et al.* (1996). The different kinds of models were originally used for the ASL conditions only, because velocity, time and length scales are heterogeneous inside the RSL and the canopy, unlike elsewhere in the ASL. However, the Lagrangian stochastic approach can be applied to more complicated flows as well, because the structure of turbulent flow is external to the model itself (Schmid, 2002).

In this work we mainly concentrate on Lagrangian stochastic models. The analytical models of Horst and Weil (1992) and Schuepp *et al.* (1990) were used for comparison among different models in **Paper V**. One of the differences that reveals the superiority of Lagrangian models in the case of forest canopies over the analytical models is the inclusion of the along-mean wind diffusion. Especially at low observation levels relative to the canopy height the contribution of down-wind sources may be considerable but is totally neglected by analytical ASL models.

4.1 Lagrangian stochastic footprint models

In Lagrangian stochastic modelling, a large number of passive tracers is released from the source and followed until their influence on the footprint probability density function (pdf) can be considered unimportant. The time evolution of a tracer position ($\mathbf{X}(t)$) or its trajectory is given as follows:

$$d\mathbf{X}(t) = \mathbf{U}(t)dt \tag{9}$$

$$d\mathbf{u}(t) = \mathbf{a}(t, \mathbf{X}(t), \mathbf{u}(t))dt + \mathbf{b}(t, \mathbf{X}(t))d\mathbf{B}(t), \tag{10}$$

where capital **U** refers to total velocity and **u** to the fluctuating wind components. They differ from each other only for the along-mean wind component, which is the sum of average Eulerian velocity and the along-mean wind fluctuation. Equation 10 is the Langevin equation that describes the Lagrangian velocity of a first-order Markov process. The first term at the right hand side determines correlated part depending on turbulent velocity and the second term determines the uncorrelated random contribution of the acceleration of velocity components. The functions a_i are required to satisfy the well mixed conditions of Gaussian turbulence by Thomson (1987). The requirement does not determine uniquely a model for turbulent diffusion in more than one dimension. The $B_i(t)$ (components of $\mathbf{B}(t)$) are the increments of a three-dimensional Wiener process with independent components, they have a zero mean and a variance of dt (Reynolds, 1998). See Thomson (1987) or Reynolds (1998) for requirements for the terms b_i. The simplest choice is $b_i = \sqrt{C_0 \epsilon}$, where C_0 is the Kolmogorov constant and ϵ is the dissipation rate of TKE.

For footprint analysis, we use a three-dimensional model by Thomson (1987) in **Papers III** and **IV** and a three-dimensional model by Kurbanmuradov and Sabelfeld (2000) in **Paper V**. Both models fulfill the requirement of well mixed conditions. See **Paper V** for a comparison of the two models. In the soil-vegetation-atmosphere transport (SVAT) model used in **Paper IV** to predict the source sink distribution of the ecosystem, we use a one-dimensional model by Thomson (1987). The performance of the SVAT model will not be further discussed in this text.

4.2 Source area in a forest

Applying footprint models to forest canopy conditions is problematic owing to characteristics of the flow, such as the large vertical gradients of turbulence statistics, the non-Gaussian nature of the turbulence, large dissipation rates, and intermittency. **Papers III, IV** and **V** consider the sensitivity of footprint predictions to different flow characteristics. Some of the results are discussed below.

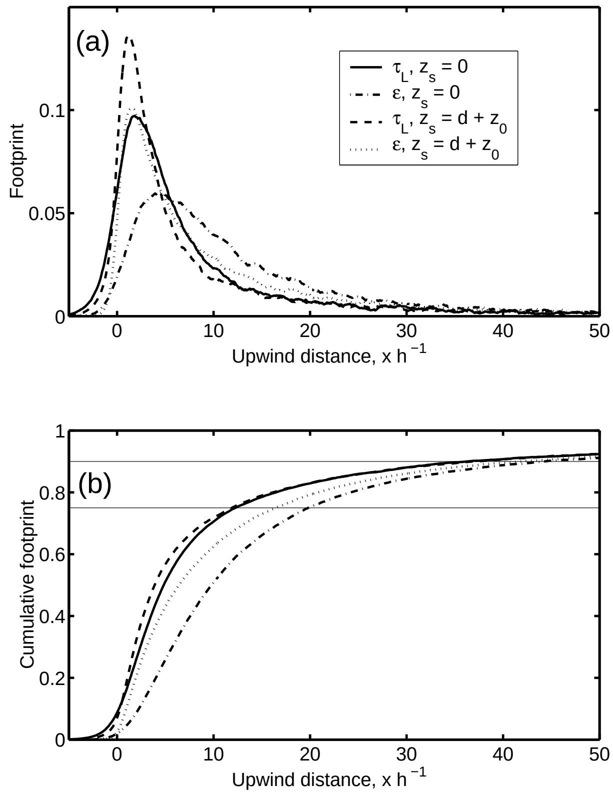

Figure 2: (a) Cross-wind-integrated footprints predicted with Massman and Weil (1999) flow statistics as functions of normalised distance. Different cases stand for: source heights ($z_s = 0$ *i.e.* on the ground or $z_s = d + z_0$) and two different parameterisations of $C_0\epsilon$ (via the Lagrangian time scale τ_L or ϵ according to Massman and Weil (1999)). (b) Cumulative footprints. The horizontal lines denote the 75% and 90% values. The footprint extensions are calculated with a Lagrangian trajectory model by Thomson (1987). Observation level is $z/h = 1.5$. For more details on the simulations see **Paper III**.

Source height has a strong influence on the extent of a footprint (Fig 2). The location of the peak value of the crosswind-integrated footprint is further upwind in cases where the sources are on the ground than in cases where they are upper in the canopy. In particular, the relative importance of the upwind sources is more pronounced, increasing the distances of cumulative footprints of certain percents considerably. When the constant Lagrangian time scale τ_L is used to determine $C_0\epsilon$ within the canopy instead of using the ϵ profile given by Massman and Weil (1999) the influence of source height is much weaker.

In **Paper IV** we studied the effect of the vertical source distribution with the conclusion that if the sinks in the canopy (positive source term) are smaller than the sources on the ground (negative source term), the integral footprint may predict unphysical negative footprint values near the measurement point that lead to long-fetch requirements. In the opposite case (sinks in the canopy larger than sources on the ground), the cumulative footprint exceeds unity at a very short distance owing to surface emissions passing the observation level from below within the distance considered. The representative location of the source term should be considered separately in each case. In the case of whole ecosystem CO_2 exchange, the conservative way to include all parts of the ecosystem in the analysis is to release the tracers from the ground.

In **Paper IV** we used the flow statistics by Massman and Weil (1999) to study the influence of canopy architecture on footprint predictions. The 75% cumulative footprint values depend both on the shape of the leaf area distribution and on the total leaf area at the lowest observation levels (Fig. 3). At higher observation levels, the influence of leaf area decreases but the influence of the shape of the distribution remains strong.

In **Paper III** we studied the influence of atmospheric stability on footprint predictions. According to the observations, in the stable case the upwind extent of the footprints grows considerably large. In the unstable case the footprint is more concentrated near the observation point than in the neutral case. The scaling parameters of stability relevant for the RSL are still an open question.

5 Measurement sites

The experiments in this study were carried out at two measurement sites, Hyytiälä in southern Finland and Vielsalm in Belgium. The two sites provide challenges for micrometeorological measurements, both being to a certain extent heterogeneous by species, plant age, or topography. Both were original sites of the Euroflux and Carboeuroflux programs for forest ecosystem CO_2 flux measurements (Valentini, 2003)

The measurements in **Papers I, II, III** and **VI** were carried out in Hyytiälä (61° 51´N lat., 24° 17´E long.) at a field station designed for measuring forest ecosystem-atmosphere relations (SMEAR II) (Vesala *et al.*, 1998). Gas fluxes and concentrations were measured in a 72-m tall tower located in a Scots pine (*Pinus sylvestris* L.) dominated stand. At the time of the measurements the stand was homogeneous by species for about 200 m in all directions from the measurement tower, containing only 1% of

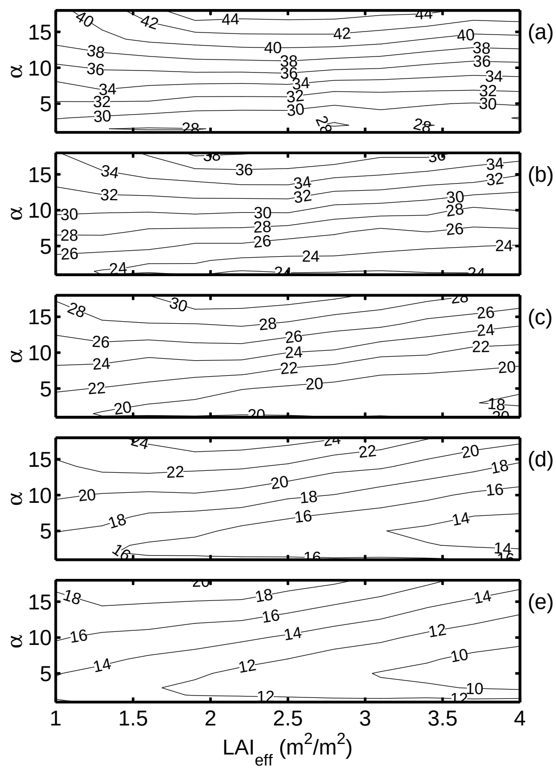

Figure 3: The normalised distance (in terms of xh^{-1}, where h is canopy height) of 75% cumulative pdf as a function of effective leaf area (LAI_e) and a parameter (α) controlling foliage leaf area distribution for five observation heights: (a) $2h$, (b) $1.8h$, (c) $1.6h$, (d) $1.4h$ and (e) $1.2h$. The footprint extensions are calculated with a Lagrangian trajectory model with sources on the ground. See also **Paper IV**.

species other than Scots pine. The site was sown in 1962 after a prescribed burning. In 1999, the dominant tree height of the stand was 13 m, the tree density was 2100-2500 stems per hectare and the stem volume was 119 m^3 h^{-1} (Ilvesniemi and Liu, 2001). The PAR distribution measurements in **Papers I** and **II** and the EC measurements within the canopy in **Paper III** both with movable measurement set-ups were carried out in close vicinity of the tower. Further than 200 m from the tower, there are areas of Scots pine of variable age as well as Norway spruce (*Picea abies* (L.) Karsten) and downy birch (*Betula pubescens* Ehrh.).

The leaf area index of Scots pine reaches its maximum by the end of June each year. In Hyytiälä within 200 m around the tower the average total surface area of needles was around 7 m^2 m^{-2} during the time of our measurements. By winter, the needle area diminishes by approximately one fourth.

The micrometeorological data in **Paper V** were measured in Vielsalm at a site that consisted of patches of Douglas fir (*Pseudotsuga menziesii* Mirbel) and beech (*Fagus sylvatica* L.) within the nearest 400 m around the measurement tower. The surroundings include also patches of grassland. At the time of the measurements, the average tree height around the tower was 35 m.

At the Vielsalm site, the leaf area index in the beach patches varies according to the season, naturally being zero during the pre-leaf springtime (**Paper V**). The total leaf area of the spruce stand was 10 m^2 m^{-2} during the time of the measurements.

6 Measurement set-ups

6.1 Radiation measurements

Measurements of radiation in the Hyytiälä Scots pine forest were carried out with a movable measurement system consisting of a 6- to 12-m tall, adjustable mast, of cross booms attached to the mast, 2, 4 or 5 m in length, and of 168 PAR sensors attached to the cross booms and connected to seven measuring units in groups of 24 sensors. The construction makes it possible to distribute the measurement sensors within the canopy space.

The sensors were silicon photodiodes with IR filters. The spectral responses of the sensors were compared against a reference detector MRI-9402 (Manoochehri *et al.*, 1999). Relative spectral responses exceeded 0.2 within the wavelength range of 340-680 nm and peaked at 580 nm. The angular cosine responses of the sensors were found to be 90% or more for incident angles under 50°, diminishing gradually to 50% at an incident angle of 80°. The active area of this sensor type was only 1.6 mm^2, which makes them especially suitable for measurements in a coniferous canopy where shading objects are narrow.

In 1997 (**Paper II**) and 1998 (**Paper I**) the light distribution measurement system was located in two different places among the trees. Of the five cross booms attached to the pole the longest ones reached the crowns of the nearby trees making the light environments of the sensors similar to that experienced by shoots growing inside a crown. The time resolution of the measurements varied from 6 to 10 s and the distances between adjacent sensors varied from 1 to 10 cm.

6.2 The eddy covariance method

The eddy covariance (EC) method is based on the average of the product of instantaneous vertical velocity and a scalar quantity (Kaimal and Finnigan, 1994; Aubinet *et al.*, 2000). The vertical flux of a quantity (s) is given by

$$F = \overline{w's'} \tag{11}$$

where the primes denote fluctuation from mean values and the overbar represents the mean over the period under consideration. Flux of any scalar quantity that can be measured with a high enough frequency, can be determined with the method (Aubinet *et al.*, 2000).

The energy spectrum in the ASL has an area of very small energies at time scales of the order of hours. Because of this gap in the energy spectrum an averaging time of half an hour has usually been used for measurements of CO_2 and water vapour fluxes (Aubinet *et al.*, 2000). Half an hour is a short enough period to exclude the influence of large-scale changes in the PBL such as the daily cycle controlled by radiation balance or changes due to synoptic weather system. On the other hand, half an hour includes the largest eddies transporting matter and energy between the surfaces and the measurement point as can be deduced from the spectrum. Reliable measurements require stationary flow conditions(Foken and Wichura, 1996). Of all the environmental variables having an effect on source strengths of an ecosystem, the largest relative influence is that of short-wave radiation on the CO_2 exchange rate of photosynthesising plants.

The EC technique has certain drawbacks that make it susceptible to errors particularly in the case of long-term balances. First of all, because of the random nature of turbulent transport, each half-hourly measurement exhibits random variation of about 10% (Rannik *et al.*, 2004). Secondly, the instrumentation and data manipulation cause systematic errors, the importance of which may vary according to flow conditions. Finally, the patchiness and complicated topography of measurement sites give rise to errors because of variations in source strengths according to the source area (Wilson *et al.*, 2002; Aubinet *et al.*, 2000).

6.3 Eddy covariance measurements

Both in Hyytiälä and in Vielsalm, the flux measurement systems comprised a Solent ultrasonic anemometer (Solent Research R3, Gill, U.K.) to measure the three wind speed components and sonic temperature, and a LiCor closed-path infrared gas analyser (Li 6262, LiCor, USA), which measured water and CO_2 concentrations. For details and requirements for a measurement set-up for EC measurements see Aubinet *et al.* (2000)

In Vielsalm, the flux measurements were performed in a tower at the height of 40 m, that is, about 5 m above the canopy top. Other data needed for the analysis in **Paper V**, such as PAR, were measured in the same tower (see Aubinet *et al.*, 2001, for a detailed description of the site).

In Hyytiälä, the EC set-up is located in the 72-m tall tower at 23 m above the ground, which is approximately 10 m above the top of the canopy. Continuous measurements (used in **Papers II, III** and **VI**) at this height started in April 1996. In February 1998, measurements also started at 46 m. In summer 2000, an experiment was performed with a sonic anemometer inside and below the Scots pine canopy. The sonic anemometer was installed at the heights of 2 m and 9.5 m for periods of 5 and 6 days, respectively, in a tower 20 m apart from the 72-m tall tower. These measurements together with the continuous measurements at the heights of 23 and 46 m were used to study the profiles of wind statistics in **Paper III**.

6.4 Shoot-scale gas exchange measurements

In Hyytiälä, several cylindrical trap-type cuvettes were used to measure the gas exchange rates of living shoots. The cuvettes, each enclosing one Scots pine shoot, were alternately closed for 70 s. During this period the CO_2 and water vapour concentrations were recorded every 5 s. The rest of the time the cuvette was open, keeping the conditions inside the cuvette close to those in the ambient air. A fan mixed the air inside the cuvette and air temperature and irradiance on the upper surface of the cuvette were measured. For more details about the measurement set-up and the determination of the exchange rate from the measurements see **Paper II** of this thesis and papers by Aalto (1998) and Hari *et al.* (1999). The surface area of shoots were estimated by measuring the length, width and thickness of individual needles and transforming these dimension in total area after one or two summers of measurements.

6.5 Other micrometeorological measurements

In Hyytiälä, the profiles of CO_2 concentration, water vapour concentration, sensible heat and wind speed and direction were measured in and above the forest canopy in the 72-m tall tower at six levels, 4.2, 8.4, 16.8, 33.6, 50.4 and 67.2 m. Wind speed was also measured with cup anemometers at these levels. The wind measurements were recorded every three minutes and averaged over 30-min periods for the analysis in **Paper III**. Net radiation sensor and sensors for reflected global radiation and PAR were located at the top of the 72-m tall tower and other radiation measurements including global and PAR were performed in another tower well above the canopy top at 16 m. For more details of the measurements see (Vesala *et al.*, 1998) and the description of materials and methods in each experimental paper (**I, II, III, V** and **VI**) of this thesis.

7 CO_2 flux in a forest canopy

In this section the different counterparts of NEE are discussed to the extent they are considered in the research articles on which the thesis is based.

7.1 PAR irradiance in a Scots pine canopy

We selected two measurement levels at 8.6 and 6.6 m within the canopy for detailed examination of PAR irradiance distribution (**Paper I**). Both measurement levels comprised 48 sensors. The distances between adjacent sensors varied from about 1 to 10 cm (See **Paper I** Fig. 3. for details). Instantaneous point by point measurements on a sunny day (26 June) revealed differences of up to 30 times in magnitude between the sensors in the shade and in the sun. In addition to the two extremes, intermediate values existed indicating the effect of penumbra inside the canopy. The fraction of penumbra was more pronounced at 6.6 m than at 8.6 m (Fig. 4). The shapes of the frequency distributions were quite similar among the ten-minute measurement periods which implies similarity in shading conditions throughout the day. The distributions were negatively skewed at 6.6 m and bimodal at 8.6 m.

Correlation coefficients between any two sensors at 6.6 and 8.6 m calculated for periods of three hours had a wide range even at the shortest distances of around 1 cm (See **Paper I** Fig. 9.). The averages of the correlations decreased monotonically along with

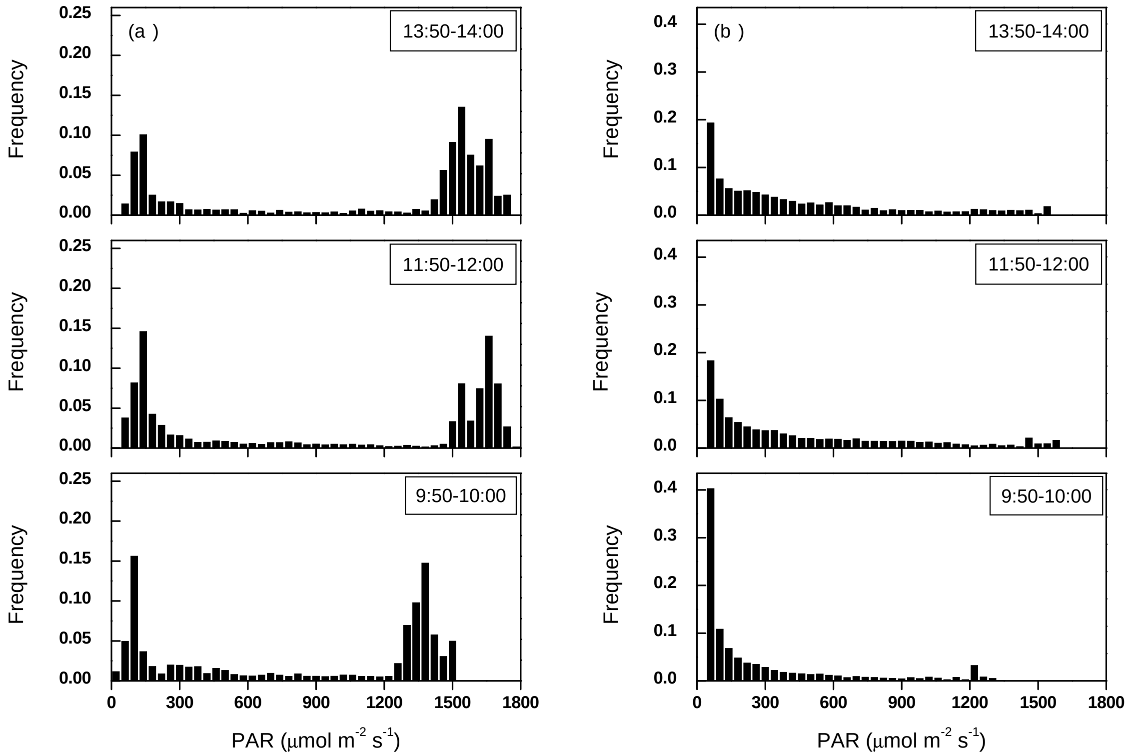

Figure 4: Frequency distributions of instantaneous PAR measurements within the Scots pine canopy at (a) 8.6 m and (b) 6.6 m during sunny periods on 26 June 1998.

increasing distances reaching zero correlation at the distances of 60 and 150 cm at 6.6 and 8.6 m, respectively. Deeper inside the canopy (at 6.6 m), both the resolution and the horizontal dimension of the measurement set-up were. At 8.6 m, however, correlation coefficients less than zero implied that higher resolution would have been needed to measure the smallest scales of light variation.

7.2 PAR distribution measurements in estimating NEE

Because of the nonlinear dependency of photosynthetic rate on incident PAR (Eq. 1), the averaging of radiation measurements over time or space is expected to overestimate the CO_2 exchange rates of the canopy in comparison with exchange rates calculated with non-averaged irradiances. We tested the effect of temporal averaging over 2-min and over 30-min periods and spatial averaging over each measurement level on the half hourly CO_2 exchange rates in **Paper II**. During clear sky conditions, the highest overestimation of half hourly canopy exchange rate occurred with spatial averaging (Fig. 5).

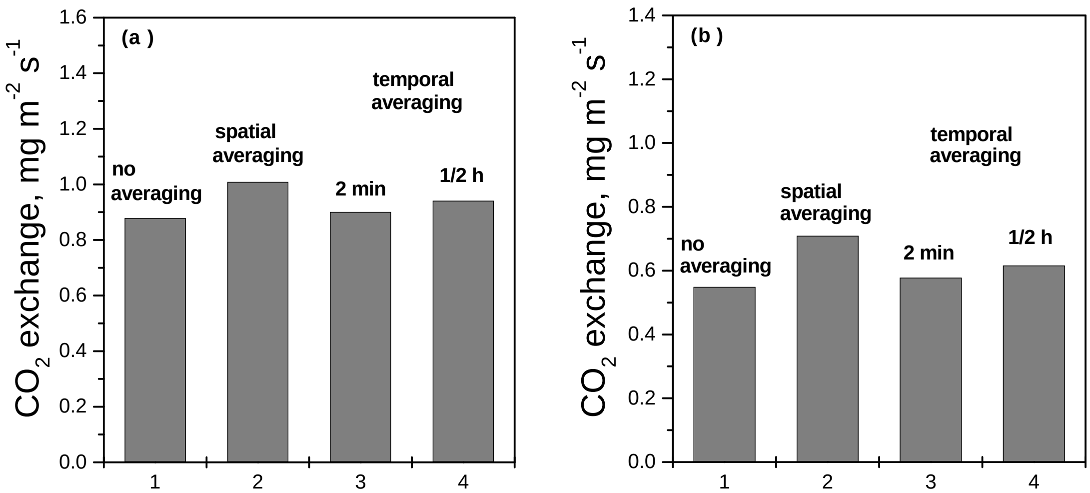

Figure 5: The influence of different averaging schemes on the 30-min canopy CO_2 exchange under clear sky conditions. The four cases refer to calculations making use of (1) all the sensors, (2) averaging over each horizontal sensor array, (3) 2-min averaging and (4) 30-min averaging. (a): little shading by the foliage. (b): Significant shading by the foliage.

The exchange rates calculated with 2-min averages did not differ considerably from reference values. On the contrary, for partly cloudy conditions 30-min temporal averaging produced the highest overestimation in the case of little shading, whereas the other two averaging schemes did not differ much from the reference. During partly cloudy and significant shading conditions all the averaging schemes led up to relatively good estimates of CO_2 exchange rates.

We also studied the influence of smaller total number of sensors on estimates by calculating canopy CO_2 exchange rates with ten sensors. We selected all the two sensor pairs from each of the five measurement levels. The range of estimates was largest in the case of significant shading by foliage under clear sky conditions (See **Paper II** Fig. 4.). In that case the largest values were almost two times and the smallest values were less than half of the estimates using all the sensors.

We estimated the CO_2 exchange rate of whole ecosystem using instantaneous PAR irradiance distribution measurements in Equation 1. Estimated exchange rates per leaf area for each horizontal sensor array represented a foliage layer of certain thickness and they were multiplied by the LAI of the respective foliage layer (**Paper II**). Whole ecosystem exchange rate was sum of these layers and soil respiration rate. The calculated whole ecosystem CO_2 exchange rates agreed well with those measured with EC (**Paper II** Fig. 5.).

7.3 Estimating NEE in a forest

The spring-time NEE measured above the canopy at the patchy Vielsalm site showed variability according to wind direction under high radiation conditions (PAR> 1000μmol m^2 s^{-1})(**Paper V**). Because the beech did not photosynthesise at this time of the year, the total flux was assumed to consist of fluxes from the Douglas fir canopy F_{DC}, from the Douglas fir forest floor F_{DF} and from the beech forest floor F_{BF}. To estimate the flux of the Douglas fir canopy (F_{DC}), the relative contributions of each of the three source/sink term to flux measurements were predicted using a Lagrangian stochastic model by Kurbanmuradov and Sabelfeld (2000).

Instead of an approximately constant F_{DC} as was expected, the prediction indicated clear wind speed dependence in addition to considerable scatter because of the errors related to the flux measurement itself and the statistical estimators of footprints. The result suggests that above a complex canopy, footprint predictions are uncertain. The reliability of footprint predictions should be further improved by evaluating the models by intercomparison among different models and by tracer experiments (Foken and Leclerc, 2004; Finn *et al.*, 1996; Leclerc *et al.*, 2003).

Even if a site is heterogeneous, surface flux measurements within the RSL may still be representative of the surrounding landscape if possible sources of biases are thoroughly analysed and unrepresentative measurements removed or corrected. In determining long-term balances of a quantity one also has to take into account missing data arising from instrument failure or maintenance. **Paper VI** reports NEE values and latent and sensible heat fluxes for 44 months in Hyytiälä. To calculate annual balances for three calendar years, the fetch of the EC system was restricted by only accepting periods with strong enough mixing into the analysis. The square root of vertical momentum flux $u_* = \sqrt{|\overline{u'w'}|}$ called the friction velocity was used as a measure of mixing conditions (**Paper VI**). Certain mean wind directions were also excluded in cases of low stability when the fetch was long.

The missing and unrepresentative data had to be replaced by fitted relationships between driving variables and fluxes. For instance, summer daytime NEE values of acceptable quality were divided into classes according to air temperature (Fig. 6).

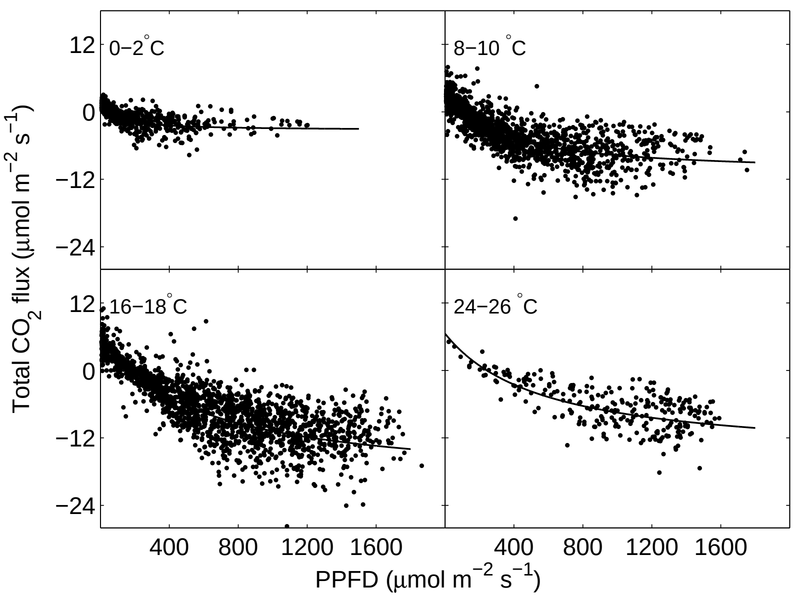

Figure 6: Examples of CO_2 flux as a function of photosynthetic photon flux density (PPFD) above the canopy classified according to air temperature.

Equation 4 was fitted into each class and these regressions were used to estimate the missing data. In some temperature classes the scatter of the measurements was so high that using the regressions uncertain. The scatter is partly due to varying soil water conditions. In the final analysis, the summer (or growing season) was divided into two parts to cover the most important changes in the state of the ecosystem. The annual NEE balance varied from -190 g m^{-2} to -260 g m^{-2} during the three years (**Paper VI**). Further analysis on a longer data series by Suni *et al.* (2003) showed a range from -168 g m^{-2} to -245 g m^{-2} during four years. The variation could not be accounted for by annual average temperatures or estimated growing season lengths (**Paper VI**).

8 Review of papers

Papers I and **II** introduce a multisensor PAR irradiance measurement system that facilitates measurement of variations in irradiance in space and time within a vegetation. **Papers III, IV** and **V** deal with the problem of relating measured surface fluxes to the actual ones. **Paper VI** presents NEE measurements of several years in a forest canopy.

Paper I is mainly technical by nature, describing the characteristics and performance of radiation sensors and presenting measurements of their spectral and angular responses and their calibration. Furthermore, it describes a set-up for measuring light environment within a Scots pine canopy and, finally, presents an analysis of the effects of varying sensor amounts and averaging times on the estimates of light penetration through the canopy.

In **Paper II** PAR distributions measured at five heights within the canopy space are used to estimate the effect of variations of irradiance on half-hourly whole-canopy photosynthesis. The estimates are scaled up using a shoot-scale photosynthetic light response curve and vertical LAI distribution. Furthermore, the soil-temperature-dependent ecosystem respiration is subtracted from whole-canopy photosynthesis and the resulting half-hourly estimates for net ecosystem exchange are compared with NEEs measured with the eddy covariance method.

Paper III examines wind statistics within and above a Scots pine canopy. It compares profiles of wind statistics with those predicted by a second-order closure model. Further, it provides an analysis of the influence of wind statistics on footprint predictions from a Lagrangian stochastic model.

Paper IV provides dimensions of source areas in along-wind direction for scalar fluxes observed over tall vegetation. Source contributions are calculated for fluxes under neutral atmospheric stratification over forest with different leaf area densities and distributions using a Lagrangian stochastic trajectory model. An analytical a one- and a half-order closure model is used to predict the vertical profiles of mean wind velocity, wind velocity statistics, Lagrangian time-scale, and dissipation rate.

Paper V makes use of a stochastic trajectory model to predict the CO_2 exchange rate of a Douglas fir stand from eddy covariance flux measurements above a mixed Douglas fir - beech forest during the pre-leaf period of beech in spring. The predicted values are compared to the half-hourly net exchange values measured by the eddy covariance system. The paper also compares different stochastic and analytical models and sensitivity tests on certain model parameters.

Paper VI reports the results of NEE measurements at the SMEAR II station in Hyytiälä, southern Finland, made with the eddy covariance method during the years 1996-1999. The paper considers the quality of half-hourly measurements, half-hourly values of NEE and latent and sensible heat fluxes. Treatment of the periods with unreliable data or measurement breaks is considered from the point of view of estimating long-term CO_2 balance. Finally, annual balances of NEE are estimated using three different gap filling methods.

9 Conclusions

Inside canopies, both cloudiness and the structure of the canopy have an influence on the light distribution. Averaging irradiance in space and time leads to overestimation of actual surface fluxes by models, because of nonlinear dependence of photosynthesis on light. In the present study physiological differences between shoots growing in the upper and lower parts - *i.e.* between shoots acclimated to high irradiance and those acclimated to low irradiance values - were not taken into account. Furthermore, no actual irradiance at the shoot surfaces was considered. However, by using instantaneous PAR irradiance measurement with 161 sensors distributed within a canopy half-hourly NEE can be predicted with a reasonable accuracy. Of different averaging schemes of PAR irradiance the highest overestimation of half hourly canopy exchange rate occurred with spatial averaging during clear sky conditions. For partly cloudy conditions 30-minute temporal averaging produced the highest overestimation in the case of little shading.

There are some features that transmission of radiation and air flow through a canopy have in common. For instance, waving of the plant elements that arise in the equation of momentum after proper averaging over space, also has an effect on the radiation environment of the plant elements. The detailed description of a forest canopy was not considered in relation to the flow within a canopy. In that context averaging is a standard procedure. Comparison of measured wind statistics with predictions of the model by Massman and Weil (1999) revealed differences both in the profile of mean wind speed and in the profiles of second moments of wind statistics. Inside the canopy the model predicted lower mean wind velocity and higher second moments of wind statistics than the observations. Also momentum flux and and correlation between vertical and along-wind fluctuating wind components differed between the observations and the model.

Footprint models used to connect the sources of a quantity to the point measurements within the ASL are sensitive to the characteristics of the flow and the location of the source term. The location of the peak value of the crosswind-integrated footprint is further upwind in cases where the sources are on the ground than in cases where they are upper in the canopy. However, when the constant Lagrangian time scale τ_L is used to determine the term $C_0\epsilon$ in the random component of the velocity increment instead of using the ϵ profile given by Massman and Weil (1999) the influence of source height on the position of the peak and on the cumulative footprint function is much weaker. The representative location of the source term should be considered for each case separately. In the case of whole ecosystem CO_2 exchange the conservative choice including all parts of the ecosystem into the analysis is to release the tracers from the ground. Under the stable stratification the upwind extent of the footprints grows considerably large. In the unstable case the footprint is more concentrated near the observation point than in the neutral case. Both the shape of the leaf area distribution and the total leaf area has influence on the footprint dimensions at low observation levels. At high above the canopy, the influence of leaf area decreases but the influence of the shape of the distribution remains strong up to observation height of two times canopy height. Above a heterogeneous forest the footprint estimates are biased because of a lack of information on flow statistics. Thus, one should be cautious when trying to use a footprint model to calculate the flux contribution of a certain area of a horizontally heterogeneous ecosystem. Even if a site is heterogeneous, surface flux measurements within the RSL may still be representative of the surrounding landscape. Eddy covariance flux measurements of three years in Hyytiälä showed the variation of annual NEE balance from -190 g m^{-2} to -260 g m^{-2}.

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