Evaporation and Heat-flux Aggregation in Heterogeneous Boreal Landscapes

BY

TONY PERSSON
Dissertation presented at Uppsala University to be publicly examined in Hambergsalen, Geocentrum, Uppsala, Friday, June 4, 2004 at 10:00 for the degree of Doctor of Philosophy. The examination will be conducted in Swedish.

Abstract

The boreal forests represent 8% of all forested areas on the earth and have a significant role in the control of greenhouse gases and an impact on global climate change. The main objective of this thesis is to increase the understanding of how evaporation and heat-flux processes in the boreal forest zone are affecting the regional and global climate.

A meteorological mesoscale model with an advanced land-surface parameterization has been utilized to study aggregation of fluxes of water vapour and heat. The model has been compared against four other methods for flux estimation in a southern boreal landscape. The results show that the mesoscale model is successfully reproducing 24-hour averages of fractionally weighted mast measurements of sensible and latent heat flux.

The model was also evaluated against in-situ observations of surface fluxes and other meteorological variables. The results reveal that a correct initialization of soil moisture is crucial to simulate a realistic partitioning of the sensible and latent heat fluxes. Significant differences in surface fluxes and friction velocities between two apparently similar forest sites indicate the need for careful assessment of areal representativity when comparing mesoscale model results with in-situ observations.

A parameterization for the absorption of solar radiation of high-latitude sparse forests was implemented and tested in the model that significantly improved the simulation of high wintertime midday sensible heat fluxes. A scheme for heat storage in vegetation was also implemented which improved the results, but the scheme needs further evaluation for high latitude forests.

Two commonly used strategies for the description of land-surface heterogeneity, the effective parameter approach and the mosaic approach, were tested in the mesoscale model against airborne observations of sensible and latent heat fluxes. The results show that the mosaic approach produces better results especially when small lakes are present in model grid-squares.

Keywords: land-surface processes, heterogeneity, surface fluxes, soil-water content, high latitudes, snow, lakes, climate, mesoscale model, NOPEX, WINTEX

Tony Persson, Department of Earth Sciences, Villav. 16, Uppsala University, SE-75236 Uppsala, Sweden

© Tony Persson 2004

ISSN 1104-232X
ISBN 91-554-6001-1
urn:nbn:se:uu:diva-4326 (http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-4326)
List of papers

This thesis consist of a summary and of the following papers. In the summary the papers are referred to by their Roman numerals.


Comments:
In papers III and IV, I was responsible for the writing, model development, model simulations and analysis.

In paper I my contribution was that I, on a joint basis with D. Melas, carried out the simulations with the MIUU-model and the writing and analysis of the related parts. The first author is responsible for the overall analysis.

In Paper II my main contribution was that I wrote the major part of the text and that I contributed with the suggestion of the importance of heat storage in the vegetation. The first author carried out the implementation and the development of the new parameterizations in the MIUU-model and the analysis of the results and I contributed to both parts. I carried out the model simulations that the conclusions are based on jointly with the first author. In Paper II, authors three and four formulated the framework for the absorption of solar radiation in high-latitude forests at low solar angles.
## Contents

1 Introduction ..................................................................................................7

2 Materials and methods ...............................................................................10
  2.1 Experimental regions and observation data ......................................10
     2.1.1 Southern NOPEX region .......................................................10
     2.1.2 Northern NOPEX region .....................................................12
  2.2 Models ................................................................................................14
     2.2.1 Mesoscale model .....................................................................14
     2.2.2 Land-surface parameterization ...............................................16
        2.2.2.1 Short-wave and long-wave radiation ..........................17
        2.2.2.2 Stomatal resistance .........................................................17
        2.2.2.3 Absorption of direct solar radiation by the forest .......18
        2.2.2.4 Heat storage in vegetation ............................................20
     2.3 Representation of land-surface heterogeneity ..............................20
        2.3.1 The effective parameters approach ..................................21
        2.3.1 The mosaic approach .......................................................21

3 Results ........................................................................................................23
  3.1 Boreal-forest surface-flux estimates with mesoscale modeling ..........23
  3.2 A parameterization for a sparse northern forest .................................25
  3.3 Evaluation of mesoscale modeling of surface fluxes ...........................28
  3.4 Two strategies of land-surface heterogeneity representation .............30

4 Summary and conclusions .........................................................................35

5 Acknowledgements ....................................................................................38

6 Summary in Swedish ..................................................................................39

7 References ..................................................................................................43
1 Introduction

Simulation of complex climate systems has received an enormous attention over the last decades since concerns of a global warming were raised in the late 1970s. Central in the understanding of large-scale climate interactions is the use of General Circulation Models (GCMs) and much emphasis has been put on the improvement of these in order to produce reliable climate scenarios.

To understand the dynamics of a changing climate the hydrological cycle and other important parts of the climate system needs to be properly understood. Hydrology has developed from a field with a strong emphasis on engineering to establish itself as a discipline in science focusing on the understanding of physical, chemical and biological processes governing the occurrence and circulation of water on land surfaces of the earth. Evaporation is the least understood of the components in the hydrological cycle. Since most hydrological models has been to developed to simulate runoff, using rainfall data as input and streamflow data for calibration, evaporation has often been treated as a residual term. The need for a less static representation of hydrology in climate models has forced a change in the treatment of evaporation from simple empirically-based expressions to more detailed formulations. At high latitudes full or partial snow cover is a factor that is complicating the understanding of evaporation and this has induced the need for more reliable formulations. Evaporation and heat flux needs to be studied in different scales since most observations takes place in the local scale and climate models needs values representative for larger scales and to close this gap is a major challenge in climate research.

The land surface is a major element in the climate system since fluxes of heat and water vapour from the land surface determine the state of the overlying air column in terms of temperature, humidity, cloudiness and precipitation and will therefore have an impact on the incoming radiative fluxes that ultimately control the magnitude of a global change in climate.

The heterogeneity of the landscape presents a major obstacle since many land-surface processes are scale-dependent. A typical grid size of a GCM is $1^\circ \times 1^\circ$ (about 50 km x 100 km in the N-S and W-E directions, respectively, at 60°N) and a grid square might consist of many different types of vegetation and soils, water bodies of different sizes, complete or partial snow cover or snow on the ground but not on the vegetation. This means that some type of averaging of the land-surface parameters into effective values representa-
tive of the entire GCM grid square is necessary. If the area is very heterogeneous, the calculation of surface fluxes for separate sub-areas, a mosaic approach, might be required. To study subgrid exchange processes models of higher resolution is used, one-dimensional soil-vegetation-transfer-schemes (SVATs) for stand-alone studies, distributed hydrological models and three-dimensional mesoscale meteorological models with advanced land-surface parameterizations. Mesoscale models link their land-surface schemes to the planetary boundary layer which means that comparisons of model output with in-situ observations of surface fluxes and other variables such as air temperature and humidity makes sense, provided that the areal representativity of the observations are sufficient. Mesoscale models operate with grid resolutions of 2-20 km in the horizontal (for the meso-$\gamma$-scale) which makes the model results well suited for direct comparisons with airborne observations for studies of land-surface heterogeneity effects. This makes mesoscale models an effective tool for testing formulations of land-surface processes, for the exploration of aggregation methods and for comprehensive analysis of different types of observational data.

The need for data of high spatial and temporal resolution to test parameterizations and flux and parameter-aggregation strategies initiated a series of large scale climate experiments in the late 1980s. Measurements from in-situ and airborne platforms were performed in, e.g., HAPEX-MOBILHY (André et al., 1986) in a forested region in southern France, FIFE (Sellers et al., 1992) for a tallgrass prairie in Kansas, USA and EFEDA (Bolle et al., 1993) in a semi-arid area in central Spain. Further north, the boreal forest represents 8% of all forested land on the earth and is characterised by a heterogeneous landscape mosaic of forests, lakes and wetlands. At its southern border the boreal landscape is commonly interspersed with agricultural areas whereas at its northern border the forests become more sparse with a greater fraction of wetlands. The role of the boreal forest’s significance in the control of greenhouse gases and impact on global climate change have instigated large-scale experiments such as BOREAS (Sellers et al., 1997) in Canada and NOPEX (Halldin et al., 1998) in Sweden and Finland. Scenarios have stressed that changes in wintertime temperatures at high latitudes might have a large impact on climate change (Houghton, 1996) and therefore wintertime observation campaigns as WINTEX (Harding et al., 2001) has been performed.

The main objective of this thesis is to increase the understanding of how evaporation and heat-flux processes in the boreal forest zone are affecting the regional and global climate. This is done by:

- Evaluating the performance of mesoscale modeling as a tool for flux aggregation in a heterogeneous southern boreal forest region in comparison with other methods (Paper I).
• Implementing a parameterization for sparse canopies, typical for northern boreal forests, in a mesoscale model and evaluate it for winter conditions (Paper II).

• Using comprehensive in-situ data-sets from NOPEX to evaluate the performance of a commonly used land-surface parameterization in a mesoscale model under different conditions (Paper III).

• Exploring the performance of two conceptually different and commonly used strategies to represent land-surface heterogeneity in comparison with airborne observations (Paper IV).
2 Materials and methods

2.1 Experimental regions and observation data

2.1.1 Southern NOPEX region

The NOPEX region (Fig. 1) is situated in the southern part of the boreal forest zone and is the area of study in Papers I, III and IV. The central part of the region is located north-northwest of the city of Uppsala in central Sweden. The NOPEX area is hydrologically defined by three larger catchments confined in a rectangle of roughly 100 km x 80 km, but the mesoscale model domain is extended to cover an area of 140 km in the west-east direction and 120 km in the north-south direction. The topography is gentle with extreme values of 0 and 188 m above mean sea level. The landscape is very heterogeneous and dominated by forest (51 %) and agricultural fields (26 %). The agricultural areas are concentrated in the southern parts of the region and there is an increasing fraction of forests towards the north. The forest consists of spruce and pine, with a small fraction of deciduous trees (15 %), primarily in the south. Till is the dominant soil type in the northern and central parts of the region whereas finer grained soils as clay and sand becomes more frequent towards the south. Lakes and wet areas (bogs, mires) are important landscape elements. Areas with moraine and bogs get more and more predominant towards the north. Small lakes are scattered around the region and parts of the Dalälven river system and Lake Mälaren are located at the northern and southern borders of the model domain. Lake Tämnaren in the north is the largest lake in the region with a total area of 37 km², but with a mean depth of just 1.2 m.

The land cover classification for the central NOPEX region is derived from a Landsat TM scene from July 7, 1989 and consists of 16 classes, of which 7 classes are different types of forest and forested land. The topography used in the model is derived from the Swedish National Land Survey's 50 m horizontal resolution database.
The data used in Paper I and III are from three instrumented sites that were more or less continuously operational during two NOPEX concentrated field efforts (CFE’s). The first CFE was carried out from 27 May to 23 June, 1994, and the second CFE was carried out from 18 April to 14 July, 1995, and the sites that were used are the Tisby agricultural site and the Norunda and Siggefora forest sites. The Tisby agricultural site is located about 35 km west of Uppsala (Fig. 1). This site is typical for the area with alternating patches of forest and agricultural land. The area around Tisby is almost flat and the distance to the surrounding forest is 1.5 km in all directions except to the south, were the fetch is undisturbed for more than 10 km. The ground cover is barley and wheat. Continuous turbulence measurements of momentum and sensible heat were performed with Kaijo Denki sonic anemometers mounted at 6.8 m height on two masts positioned 130 m apart. The water content of the air was measured with an OPHIR optical hygrometer installed at 5.8 m height at one of the masts. In addition, measurements of standard meteorological variables, radiation and soil moisture were performed at the Tisby site.
The forest site with the most comprehensive measurement programme is the Norunda central tower site located 30 km north of Uppsala (Fig. 1). The area around the 102 m instrumented tower consists of a coniferous forests dominated by pine and spruce reaching maximum heights of 23 to 28 m, respectively. The forest around the tower is rather level and homogeneous with a maximum fetch of about 20 km towards southwest which is the prevailing wind direction (Lundin et al., 1999). Measurements of the fluctuating wind components were carried out with Solent three-axis ultrasonic anemometers mounted on 5 m booms at the 35, 70 and 100 m levels. Extensive observations of standard meteorological variables, radiation components, soil moisture and soil heat flux were performed.

The other forest site in the southern NOPEX region used in this thesis is the Siggefora forest site situated close to the center of the model domain 30 km NW of Uppsala (Fig. 1). A sonic anemometer system similar to that used at the Norunda site was mounted in mast at 32 m height above ground. The forest around the site consists of mature stands of pine and spruce. Standard meteorological variables were observed at the site.

In paper IV aircraft observations were utilized for the evaluation of the two different strategies for representing land-surface heterogeneity. During the two NOPEX CFE’s in 1994 and 1995 aircraft measurements of turbulent fluxes of momentum, heat and water vapour were performed. Standard meteorological variables as temperature, humidity, wind speed and wind direction were also observed together with other relevant parameters as the radiation components and surface temperature. The aircraft measurements used for comparison with the mesoscale model simulations in Paper IV are from turbulence flights flown at 100 m height AGL between Tisby and Lake Tämnaren where along the flight track in-situ observational sites with extensive instrumentation were located (Fig. 1). The measurements were averaged in 500 m blocks and a total of 2808 blocks were used for the testing of the two strategies of representing land-surface heterogeneity.

2.1.2 Northern NOPEX region

Between 12 March and 19 April, 1997, an experimental campaign took place in the northern and southern NOPEX regions. All references to WINTEX and the WINTEX region in this summary and in Paper II are referring to the northern NOPEX region and the part of the winter experimental campaign held there. The Sodankylä Meteorological Observatory (SMO) is located in a sub-arctic forest area in northern Finland (67°29’ N; 26°39’ E; 179 m above mean sea level; central Lapland) and operated by the Finnish Meteorological Institute. The terrain around SMO is moderately undulating with isolated hills reaching up to 500 m altitude (Fig. 2). The region surrounding SMO (100x100 km²) is dominated by coniferous forest (36 %) with pine as the most abundant species. Mixed/deciduous forest accounts for 13 % of the
land cover. Peatbogs that include open peatlands, and sparsely vegetated peatlands has a coverage of 23 %. Classified as “transitional woodland shrub” including conifer plantations and clear cuttings also covers 23 %. Lakes and rivers cover roughly 3 % of the region.

![Topographic map of the WINTEX region.](image)

**Figure 2.** Topographic map of the WINTEX region.

For the WINTEX campaign an 18 m high mast was erected in a sparse coniferous forest at SMO with a typical tree height of 7-9 m. During the studied period the trees were free from snow. Eddy-correlation measurements performed with Solent Research 3D sonic anemometers at a frequency of 10 Hz were used in this study. The measurements were performed in and above the sparse forest at heights 2, 6, 12 and 18 m. During the WINTEX campaign, radiosoundings were performed at SMO with three-hours interval. As part of the standard synoptic observation programme, hourly observations of cloud cover were carried out. Information of the vegetation cover was obtained from a digitized landuse map with a resolution of 1 km. The topographical information was derived from a Digital Elevation Model with a horizontal resolution of 1 km.
2.2 Models

2.2.1 Mesoscale model

The mesoscale model used in this thesis is the MIUU-model developed at the Meteorological Department at Uppsala University. The model is well documented in the literature (Enger, 1990; Tjernström, 1987) and only a brief summary will be presented in the following section.

A terrain influenced coordinate system is used to introduce the topography in the model. The new vertical coordinate, $\eta$, is defined as

$$\eta = \frac{z - z_g}{s - z_g}$$

where $s$ is the height of the model top, constant in this study; $z$ is the actual height above mean sea level (AMSL) and $z_g$ is the terrain height.

All model equations are transformed into the new coordinate system. The pressure terms in the transformed equations have been decomposed into two parts. The large-scale pressure force is expressed with the geostrophic wind, and the other two pressure terms in the equations represent the mesoscale forcing. Given the condition that the terrain slope is much less than 45°, the pressure field is determined according to Pielke and Martin (1981).

The turbulent exchange coefficients in this model are determined in terms of the turbulent kinetic energy, obtained from a prognostic equation. The turbulence closure is based on the approach developed by Yamada and Mellor (1975), the 'Level 2.5' model (distinguishing it from 'Level 3' which includes also a prognostic equation for potential temperature variance). The expressions for the turbulent exchange coefficients for momentum and heat are described by Enger (1990). The remaining turbulent moments are determined by diagnostic expressions. Details about the parameterization of the higher-order terms are found elsewhere (Andrén, 1990; Launder et al., 1975; Lumley, 1979; Mellor, 1973).

The advection scheme used in the model has been corrected for numerical diffusion and is of third order both in time and space. Zero gradient inflow - gradient outflow is used for the lateral boundary conditions (Tjernström et al., 1988). The gradient at the inflow boundary is equal to zero while air exiting the model is assumed to have the same value as found one grid point upstream. Due to the telescoping grid used in the model, the lateral boundaries are located far enough from the central parts of the domain to reduce the influence of the lateral boundary errors propagating into the area of interest. At four grid points at the lateral boundaries a “flow relaxation scheme” as applied in order to allow a temporal variation of the geostrophic wind. The scheme is successfully used in both atmosphere and ocean models (Davies, 1983; Engedahl, 1995).
The numerical simulations in Papers I-IV were performed for different domain sizes but common for all simulations is that in the horizontal a telescoping grid is employed, the grid distance being 1.5 km in the central parts of the model and expanding towards the lateral boundaries (Fig. 3). In order to properly resolve the sharp surface layer gradients of meteorological variables, the vertical grid levels are log linearly spaced, with mean and turbulent quantities vertically staggered. The vertical resolution at the lower boundary is chosen to be 2 m. The vertical coordinate contains 20 levels up to the model top which is set at 7000 m AMSL.

**Figure 3.** Simulated near-surface wind field in the WINTEX region at 0500 LST, 15 March, 1997. The arrows correspond to MIUZ-model grid points and the dotted lines represents the model topography.

In Paper I and II radiosonde data were used for initialization of the mesoscale model. In Papers III and IV input profiles of potential temperature and specific humidity were obtained from data extracted from the NCEP
Reanalysis project (Kalnay et al., 1996) at seven model levels (1000, 925, 850, 700, 600, 500 and 400 hPa, respectively) for a location at longitude 17°50’ E and latitude 60°00’ N. The input profiles and the geostrophic wind components are updated in the model with six-hour intervals at 00Z, 06Z, 12Z and 18Z. Since there are no 2 m or 10 m levels in the NCEP Reanalysis data set the surface values of air temperature, specific humidity, wind speed and wind direction used in the MIUU-model are derived from variables that exists in the mid-point of the lowest NCEP layer above the model terrain. The extrapolation from data that are obtained from well above the land-surface can have a large impact on the values of the surface variables and hence effect modeled surface-layer gradients. The NOPEX region is relatively flat and large horizontal differences in the extrapolated surface variables that are attributed to topographic inhomogeneities are likely to be small. However, the land cover in the NOPEX region is very inhomogeneous and there is no correction made at screen level for different land cover types.

At the onset of a model integration there is no topography in the model during 2 hours of integration. After this initial phase, the integration with the three-dimensional model with the terrain at its assigned height is performed. The model is run for 3 more hours before it is considered to be in quasi-equilibrium (dependent variables are changing only slowly in time). After this initialization period the real simulation starts at 0000 UTC. The time step used for the simulations performed in this thesis is 10 s.

Uncertainties in the simulation of radiative fluxes due to cloudiness are one of the main obstacles in correctly reproducing the daytime sensible and latent heat fluxes. In the MIUU-model version that was used in the present study the cloud liquid water content was assumed to be proportional to the cloud cover. Detected cloudiness was treated as a cloud that covers the entire model grid square and the thickness of the cloud was determined according to the cloud cover. No distinction between different cloud types was made which means that fractional cloudiness and overcast skies were treated in the same way.

2.2.2 Land-surface parameterization

The land-surface parameterization implemented in the MIUU-model is based on the scheme presented by Deardorff (1978). The scheme achieves a good balance between complexity and input data requirements and is the base for several land-surface schemes currently employed in meso- and largescale models, e.g. BATS (Dickinson et al., 1986), SiB (Sellers et al., 1986) and ISBA (Noilhan and Planton, 1989). The Deardorff-scheme carries prognostic equations for soil temperature and soil moisture and the vegetation is parameterized as a single canopy layer, which interacts both with the atmosphere and the underlying surface. The energy balance for the canopy layer is solved instantly as no heat storage is assumed in the vegetation (except for
parts of paper II, see section 2.2.2.4). In this thesis, modifications of the original Deardorff scheme are used and these are described and introduced in the following sections. In section 2.2.2.1 the parameterization of incoming short-wave radiation is described (Papers I, II, III and IV). In section 2.2.2.2 an alternative way of calculating the stomatal resistances is introduced (Papers III and IV). In section 2.2.2.3 a new parameterization for the absorption of direct solar radiation in sparse forest canopies is presented (Paper II) and in section 2.2.2.4 an expression of heat storage in vegetation is introduced (Paper II).

2.2.2.1 Short-wave and long-wave radiation

The radiation formulations are differing slightly from Deardorff's original scheme. The short-wave radiation reaching a surface in the MIUU-model, $S^\parallel$, is calculated as:

$$ S^\parallel = (t_r - a_q) S_0 $$  \hspace{1cm} (2)

where $t_r$ is the fractional transmissivity of short-wave irradiance at the ground that accounts for downward Rayleigh scattering and absorption of diffuse irradiance (Kondratyev, 1969); $a_q$ is the absorption of direct irradiance (McCumber, 1980) and $S_0$ is the direct downward solar irradiance reaching a horizontal surface of unit area at the top of the atmosphere. The fluxes of long-wave radiation are calculated using an emissivity model following Atwater (1974), Kuhn (1963) and Kondratyev (1969). The flux of downward long-wave radiation is obtained by integrating from the model top down to the top of the canopy layer.

2.2.2.2 Stomatal resistance

The most significant difference between the Deardorff (1978) scheme and the version used in the MIUU-model in Papers III and IV concerns the calculation of stomatal resistances, where the methods outlined by Jarvis (1976) have been implemented. The stomatal resistance is parameterized as:

$$ \frac{r_s}{LAI} = \frac{r_{s_{\text{min}}}}{F_1 F_2^{-1} F_3^{-1} F_4^{-1}} $$  \hspace{1cm} (3)

where $r_{s_{\text{min}}}$ is the minimum stomatal resistance (sm$^{-1}$) and $LAI$ is the leaf area index (m$^2$/m$^2$). The parameter $F_i$ describes the effect of photosynthetically active radiation:

$$ F_i = \frac{1 + f}{f + r_{s_{\text{min}}} / 5000} $$  \hspace{1cm} (4)

where

$$ f = \frac{1.1 R_G}{R_G L AI} $$  \hspace{1cm} (4b)
where $R_G$ is the global radiation (Wm$^{-2}$) and $R_{GL}$ is a species dependent limit value of global radiation set to 100 and 30 Wm$^{-2}$ for agricultural and forest vegetation, respectively (Jacquemin and Noilhan, 1990). Parameter $F_2$ in eq. (3) describes the dependence of soil-water content on the vegetation transpiration:

$$F_2 = \begin{cases} 
1 & w_2 > w_{fc} \\
\frac{w_2 - w_{wilt}}{w_{fc} - w_{wilt}} & w_{wilt} \leq w_2 \leq w_{fc} \\
0 & w_2 < w_{wilt}
\end{cases} \quad (5)$$

where $w_2$, $w_{wilt}$ and $w_{fc}$ is the soil water content (volume water/volume soil) in a 1 m deep bulk layer, at the wilting point and at the field capacity for the specific soil, respectively. The effect of vapour pressure deficit is parameterized as:

$$F_3 = 1 - \gamma \left[ e_s(T_a) - e_a \right] \quad (6)$$

where $\gamma$ is an empirical parameter; $e_s(T_a)$ is the saturated vapour pressure at temperature $T_a$ and $e_a$ is the actual vapour pressure. The temperature dependence of the stomatal resistance is given by:

$$F_4 = 1 - 0.0016(298 - T_a) \quad (7)$$

Details about the parameterization of the stomatal resistance can be found in Jacquemin and Noilhan (1990) and in Noilhan and Mahfouf (1996).

### 2.2.2.3 Absorption of direct solar radiation by the forest

A sparse high-latitude forest is a very effective absorber of short-wave radiation. Under low solar angle conditions, a large portion of the direct solar radiation is absorbed by the canopy which is apparently covering the ground. In order to describe the effect of low solar angles which leads to an apparent high vegetation cover for direct solar radiation Gryning et al. (2001) introduce a shading factor $f_{sh}$. The shading factor is generally a function of the vegetation fraction $\sigma_f$ and the solar angle $\alpha$. A simple expression for $f_{sh}$ is derived in Gryning et al. (2001) and tested in Paper II:

$$f_{sh} = \sigma_f \left( 1 + \frac{4h}{\pi d \tan(\alpha)} \right) \quad \alpha \geq \alpha_c \quad (8)$$
where $h$ is the height of the trees and $d$ is the crown diameter. The critical solar angle, $\alpha_c$, below which the ground is fully shaded, i.e. $f_{sh}=1$, can be estimated with the expression:

$$\tan(\alpha_c) = \frac{4h}{\pi d} \left( \frac{\sigma_f}{1 - \sigma_f} \right)$$  \hspace{1cm} (9)

Gryning et al. (2001) also introduce a transmittancy factor, $\tau$, describing the fact that the sparse vegetation is not opaque for solar radiation. If the canopy is entirely transparent, $\tau$ will be equal to unity and if the canopy is opaque, $\tau$ will be equal to zero.

With the implementation of a shading factor and a transmittancy factor the gain of short-wave radiation for the snow cover and the vegetation canopy will be expressed differently from that proposed by Deardorff (1978). Gryning et al. (2001) divide the short-wave radiation received by the canopy into three terms. The first refers to the diffuse solar radiation which is treated as in Deardorff (1978). The second term refers to the direct solar radiation received by the canopy and the third term describes the reflected short-wave radiation received by the canopy from the snow cover. The following equation is introduced:

$$S_c^G = \sigma_f D + f_{sh} (1 - \tau) I \sin \alpha + \sigma_f a_g (1 - \tau) S_s^G$$  \hspace{1cm} (10)

in which $D$ is the diffuse component of the incoming short-wave radiation, $I$ is the incoming solar radiation at the top of the vegetation across a plane perpendicular to the solar beam and $a_g$ is the snow surface albedo. The short-wave radiation received by the snow cover is expressed as:

$$S_s^G = (1 - \sigma_f) D + f_{sh} \tau I \sin \alpha + (1 - f_{sh}) I \sin \alpha$$  \hspace{1cm} (11)

The implementation of a shading factor and a transmittancy factor will thus modify the partitioning of direct short-wave radiation between the snow surface and the vegetation and have a different impact on the snow surface and foliage temperatures as compared with Deardorff’s scheme. Throughout the day, the shading will then effect the partial contributions to the total sensible heat flux to the atmosphere from the snow surface and the vegetation, see Paper II for details on how the sensible and latent heat fluxes are summarized in a MIUU-grid square. The maximum value of the shading factor $f_{sh}$ is unity and its minimum value is equal to the shielding factor $\sigma_f$. The shading factor for the studied case is equal to one for the entire day. The transmittancy factor is generally a function of the solar angle and extensive data are required for the empirical determination. As a first approximation a constant value, $\tau=0.3$, is used in Paper II.
2.2.2.4 Heat storage in vegetation

The model by Deardorff (1978) assumes no heat storage in the vegetation and the energy balance of the vegetation is solved instantly. This concept is valid in soil-vegetation systems where the ground is the major storage for heat due to its large heat capacity.

When a snow-cover with a very low heat capacity is present the ground is no longer dominant and the vegetation becomes the system’s major heat source and sink. Studies have shown that the time constant for heating of trunks of trees can be up to several hours (Monteith, 1981).

In paper II an objective hysteresis model is implemented in the mesoscale model to predict the heat storage by the vegetation (Grimmond et al., 1991):

$$\Delta H_{sf} = a_1 Q^* + a_2 \left[ \frac{\partial Q^*}{\partial t} \right] + a_3$$

where $Q^*$ is the net all-wave radiation flux density, $a_1$, $a_2$ and $a_3$ are dimensionless coefficients with the values $a_1 = 0.11$, $a_2 = 0.11 h$ and $a_3 = -12.3 \text{ Wm}^{-2}$ for mixed forest (McCaughey, 1985).

2.3 Representation of land-surface heterogeneity

The surface fluxes of sensible and latent heat, which provide the coupling between the atmosphere and the land surface, depend not only on the atmospheric conditions but also strongly on the surface characteristics. To examine the effects of different approaches of representing land-surface heterogeneity in a mesoscale model grid square the performance of the effective parameter approach and the mosaic approach were evaluated against airborne measurements of sensible and latent heat flux (Paper IV). The two approaches are commonly used but differ significantly in concept.

2.3.1 The effective parameter approach

The effective parameter approach can be considered a parameter aggregation method assuming horizontally well mixed surface elements that interacts with the atmosphere through an intermediate layer of air with its temperature and humidity influenced by the respective land surface types, whether it is several types of vegetation or vegetation and bare ground together in a model grid square. The effective parameter should thus account for non-linearity’s that might be the result of the spatial heterogeneity of the land surface. The effective parameter approach uses averages of the land surface parameters albedo, emissivity, minimum stomatal resistance, LAI and surface roughness based on the fraction of the land surface they occupy in a model grid square. Since not all land-surface interactions are linear methods...
to form effective values of certain vegetation and land surface parameters as minimum stomatal resistance (Blyth et al., 1993) and roughness length (Mason, 1988) have been proposed in literature.

For the effective parameter approach the calculation of the sensible heat flux is straightforward with the summation of the fluxes from the vegetated part of the model grid square covering a fraction \( \sigma_f \) and the non-vegetated part, covering a fraction \( 1 - \sigma_f \). The total sensible heat flux from a MIUU grid square to the atmosphere with the effective parameter approach is given by:

\[
H_{EP} = (1 - \sigma_f) H_{sg} + \sigma_f (H_{sgf} + H_{sf})
\]  

(13)

where indexes \( sg \), \( sgf \) and \( sf \) denotes the sensible heat flux from bare ground, from ground beneath vegetation and from vegetation, respectively. The total latent heat flux using the effective parameter approach from a grid square to the atmosphere is formulated in a similar way:

\[
E_{EP} = (1 - \sigma_f) E_{sg} + \sigma_f (E_{sgf} + E_{sf})
\]  

(14)

The use of the fractional vegetation cover \( \sigma_f \) and separate energy balance calculations for the ground and canopy imply that the Deardorff scheme as implemented in the MIUU-model comply with the mixture strategy as defined by Koster & Suarez (1993) but still the important difference is that the vegetation parameters used are effective parameters, hence the use throughout this paper of the effective parameter approach.

2.3.1 The mosaic approach

The mosaic approach circumvents the need for averaging of land-surface parameters by coupling independently each landuse tile in a model grid square to the atmosphere of the model, and the tiles affect each other only through the atmosphere. The mosaic approach thus can be considered a flux aggregation method as the energy balance is calculated for each landuse class/tile and the surface heat and water fluxes from each tile are summarized according to the fraction of land they occupy into grid square flux values. One advantage of the mosaic approach is during strongly varying conditions in a model grid square, when there is non-linearity between surface heat fluxes and vertical mean profiles. For instance, the vertical gradient of potential temperature can be positive on average over a large area, while local fluxes can be in the opposite direction due to a local negative gradient of temperature, e.g. with the presence of lakes or with partial snow cover.
For the mosaic approach the total sensible heat flux becomes:

\[ H_{MO} = \sum_i f_i \left[ (1 - \sigma_f) H_{sg_i} + \sigma_f (H_{sg_i} + H_{sf}) \right] \]  \hspace{1cm} (15)

in which \( f_i \) is the fractional cover of land surface type \( i \). Each tile or vegetation class in a model grid square will have its unique surface and canopy temperatures for the calculation of the fractional sensible heat flux. The total latent heat flux from a model grid square is given by:

\[ E_{MO} = \sum_i f_i \left[ (1 - \sigma_f) E_{sg_i} + \sigma_f (E_{sg_i} + E_{sf}) \right] \]  \hspace{1cm} (16)

and analogous to the calculation of sensible heat flux, each tile within a model grid square will have its unique specific humidity at the ground and a saturated specific humidity at the unique canopy temperature.
3 Results

3.1 Boreal-forest surface-flux estimates with mesoscale modeling

In Paper I five methods for the estimation of regional sensible and latent heat flux in the NOPEX southern boreal forest region are compared:

1. Direct aggregation – mixed layer evolution method
2. Weighted averages of
   a) aircraft measurements in the boundary layer
   b) mast measurements,
3. Numerical models
   a) ECOMAG – a distributed hydrological model
   b) MIUU – a mesoscale meteorological model

Only the results from the comparison of the MIUU-model with the direct mast and aircraft measurements are discussed since no independent comparison between the MIUU-model and the mixed-layer evolution method or the ECOMAG model, respectively, has been performed in this thesis. Of the eight days of CFE1 in 1994 and CFE2 in 1995 for which the MIUU-model was used for surface flux comparisons the mesoscale model was successfully reproducing the 24-hour sensible heat fluxes compared with the direct mast method (Fig. 4a). When the sensible heat fluxes have low absolute values the model simulations were in very good agreement with the mast measurements. A tendency to underestimate the sensible heat fluxes was evident when the absolute values were higher. For 2-hour flight periods the MIUU-model also produced good results compared to the mast measurements, although the variability is much higher. An important reason for the discrepancies between the MIUU-model and the direct mast observations are differences in net radiation. The MIUU-model uses prescribed cloudiness from observations performed in Norunda and Marsta and the cloud cover is not always homogeneous within the model domain, for instance there was a significant difference in cloud cover on June 13, 1994, between the Siggefora and Norunda sites. Intermittent clouds reduce the incoming shortwave radiation component instantly and have a greater impact on the net radiation and hence the surface fluxes during daytime than during the night when the incoming short-wave radiation is zero and the surface fluxes are low.
The MIUU-model estimates of latent heat flux were very close to the direct mast method for the 24-hour periods (Fig. 4b). In fact, the average difference between the mesoscale model and the mast measurements was just 3 Wm$^{-2}$. This result indicates that the mesoscale model well mimic the diurnal variation of the sensible heat fluxes. For the 2-hour flight period comparisons the MIUU-model simulated lower latent heat fluxes, except for two days, May 3 and 4, 1995 (see Table 6 in Paper I). This is somewhat interesting since observations from only two sites were used for the direct mast method during these two days. In Paper III it is shown that the other forest site, in Siggefora, exhibits generally much lower latent heat fluxes than the Norunda site suggesting that there are significant differences between the forests which might have implications for the aggregation of fluxes using weighted averages based solely on landuse. This is further indicated by the fact that the model produces the most overestimated sensible heat fluxes for May 3 and 4, 1995.

For one day, 13 June, 1994, the MIUU-model overestimates the 2-hour latent heat flux with 86 Wm$^{-2}$ which is difficult to explain with differences in cloudiness over the domain since the 2-hour sensible heat flux is well estimated compared with the direct mast method. It was initially suggested that difficulties with the initialization of the soil moisture content in the mesoscale model was the reason for the overestimated latent heat flux, but since most of the other days are reasonably well simulated and no significant change in soil moisture occurred to the next day, June 14, 1994, which is also well simulated in both 24-hour and 2-hour periods the reason for the overestimation might be found in the formulation of stomatal resistances. In
Paper I the stomatal resistances in MIUU’s land surface scheme are only dependent on the solar radiation and soil moisture content. For papers III and IV a canopy resistance formulation after Jarvis (1976) was introduced in which the effect of vapour pressure deficit and ambient temperature on stomatal control is included which might have improved the simulations of latent heat flux in Paper I, especially at noon during clear and sunny days when vapour pressure deficits are usually high.

The MIUU-model overestimates the aircraft observed sensible heat fluxes as do the direct mast aggregation method. One reason for this overestimation that is discussed in Paper I is that the constant flux layer is not reaching up to 100 m (the height of the aircraft measurements) for sensible heat flux, which is also indicated by mast measurements from different heights in the Norunda forest, where the sensible heat flux is decreasing with height with 0.3 % per meter around noon.

The MIUU-model generally simulates the 2-hour aircraft measurements of latent heat flux quite well with the overestimation by the model being about 25 Wm⁻². The results from CFE1 in 1994 are somewhat contradictory since the MIUU-model is simulating the highest latent heat flux on the day with the lowest 2-hour flight period estimate and vice versa the MIUU-model simulates the lowest 2-hour latent heat flux on the day with the highest 2-hour aircraft observations of latent heat flux. But as was the case with the 2-hour direct mast comparison the inhomogeneities in the cloud cover can play an important role for comparisons in such short time intervals, which is also shown in Paper IV. The aircraft-model comparisons for CFE2 in 1995 shows much better agreement.

In general, the results from the comparison of direct mast measurements and the MIUU-model suggest that the mesoscale model is producing reliable spatial surface flux estimates. However, the comparison with the MIUU-model also indicated that individual differences between sites that are pooled as forest sites and agricultural sites for the direct mast estimates can be of significant importance when the weighting is only based on land-use fraction. A more detailed characterisation of different types of forest and agricultural land that is possible with a mesoscale model might be useful in the analysis in regional surface flux estimates from in-situ observations.

3.2 A parameterization for a sparse northern forest

The MIUU-model was used to study the diurnal variation of surface fluxes and boundary-layer structure during four consecutive days during the WIN-TEX in Sodankylä, March 15 to 18, 1997. The existing land-surface parameterization was found to underestimate the high values of sensible heat flux that was observed at midday and afternoon hours. Consequently, all other boundary layer parameters that are related to the prevailing stability condi-
tions (temperature, wind speed, friction velocity, and to a less extent wind direction) are affected accordingly. In order to remove this discrepancy, two simple modifications were implemented in the model: 

1) A shading factor together with a transmittancy factor to compensate for the apparent high vegetation cover due to low solar angles (Gryning et al., 2001),

2) A simple expression for heat storage in the canopy to compensate for the asymmetry in the simulated daytime sensible heat fluxes and temperatures (Grimmond et. al, 1991).

![Figure 5](image_url)

**Figure 5.** The variation of latent and sensible heat flux at the Sodankylä site during the period 15-18 March, 1997. Circles: Observations at 12 m AGL (latent heat flux at 18 m AGL); Dashed line: Control simulation; Dotted line: Simulation results with the MIUU model implementing a shading factor; Full line: Simulation results with the MIUU model implementing a shading factor and heat storage in vegetation.

During the entire four-day period, the latent heat flux exhibits a very small variation, being close to zero during nighttime and reaching a maximum of 20-30 Wm$^{-2}$ in the afternoon hours (Fig. 5a). During the last two days (17-18 March) the observations indicate a sharp maximum of ~50 Wm$^{-2}$ in morning hours. The relatively small values of latent heat fluxes are attributed to the low temperatures and the associated closing of the stomatas. The simulation results of the three model runs are almost identical, being in close
agreement with the observations, except for the morning maximum which is not reproduced by the model.

In contrast to the latent heat fluxes, the sensible heat fluxes show a remarkable diurnal variation (Fig. 5b). At night, the sensible heat fluxes at the Sodankylä site have small-to-moderate negative values. Approximately two hours after sunrise, the sensible heat flux becomes positive and, subsequently, steadily increases reaching approximately ~100 Wm\(^{-2}\) at midday. Most of the days the sensible heat flux shows a “tail” of relatively high values into the late afternoon. This feature is more pronounced during the 15\(^{th}\) of March which was a clear day. During the same day, the sensible heat flux exhibits a sharp maximum at ~15.00 LST. The original energy balance scheme implemented in the MIUU model is unable to reproduce the magnitude of the observed sensible fluxes, especially at midday. The underestimation of the observed maximum is 30-40 Wm\(^{-2}\). The implementation of the shading factor in the surface energy balance improves the agreement of the simulation results with the observations (Figs. 5a-b). The maximum fluxes are still underestimated but only by ~10 Wm\(^{-2}\). The inclusion of the objective heat storage scheme explains parts of the diurnal variation of the sensible heat fluxes, but there are still some discrepancies. This addresses the need to evaluate the coefficients \(a_1\) to \(a_3\) used in eq. (12) for a sparse sub-arctic forest.

Figure 6. The variation of temperature at Sodankylä site during the period March 15-18, 1997. Triangles: SYNOP measurements; Dashed line: Control simulation; Dotted line: Simulation results with the MIUU model implementing a shading factor; Full line: Simulation results with the MIUU model implementing a shading factor and heat storage in vegetation.
The near surface temperature exhibits a remarkable diurnal variation, the daily range being ~20 °C (Fig. 6). As expected, the results of the control run underestimate the maximum temperature values observed during afternoon hours. The implementation of the shading factor improves the agreement between model simulations and observations but the observed maximum temperatures are still underestimated by a few °C. Finally, the impact of the heat storage is significant and it improves the ability of the model to reproduce the observed diurnal variation of temperatures. This is a step in the right direction but the observations indicate a stronger effect.

It is found that the inclusion of the shading factor and the transmittancy factor in the surface energy balance scheme produces sensible heat fluxes during daytime which are in good agreement with the observed ones. The impact of the expression for the heat storage in vegetation in the results is smaller and it indicates the need to evaluate the coefficients used for a sparse high latitude forest.

3.3 Evaluation of mesoscale modeling of surface fluxes

In most studies regarding mesoscale model evaluations that have been performed the boundary layer wind field has been the primary subject for the evaluation (Hanna, 1994). Most of the few studies that have involved a comprehensive analysis of the statistical component of a model evaluation involving other boundary layer parameters as air temperature and surface fluxes have had an emphasis on flow field and air pollution applications (e.g. Steyn and McKendry, 1988).

The objective of paper III was to evaluate the performance of a three-dimensional numerical mesoscale model for a range of atmospheric conditions in a heterogeneous southern boreal forest region for spring to summer conditions. The evaluation is focusing on the model’s ability to reproduce the sensible and latent heat fluxes at three different surface sites representing the two major land cover types in the region, forest and agricultural land. In addition, the friction velocity, air temperature and specific humidity are evaluated. The radiative flux components and the model energy budget are evaluated for one of the forest sites. The evaluation is done by using a range of statistical measures. Twenty-four days in June 1994 and May and June 1995 are simulated and evaluated against observations from the southern NOPEX region. Six four-day periods were used, 11-14 June and 18-21 June, 1994 and 1-4 May, 5-8 May, 17-20 June and 23-26 June, 1995, respectively.

It was found that a reasonably correct initialization of soil water content is crucial for the partitioning of the surface fluxes for the forests. A simple sensitivity test together with an analysis of the soil moisture observations indicated that the low observed soil water content for the forest in Norunda was not representative as initial values. This is largely due to a very high
sensitivity of deep soil water content on the vegetation parameterization in the land-surface scheme. A significant increase of the initial deep soil water improved the simulation results particularly for the latent heat flux at the forest sites (Figs. 7a-b).

**Figure 7.** Sensible heat flux (a); latent heat flux (b) at the Norunda site with observed (dotted line) and high (solid line) deep initial soil moisture for the period June 11-14, 1994. The circles represent the observations.

The MIUU-model is able to satisfactorily reproduce the mean sensible and latent heat fluxes for all three sites. Particularly good results were found for the Norunda forest site for which the model was able to well reproduce both the mean quantities and the diurnal courses. Significant differences in turbulent fluxes and friction velocities between the two forest sites in Norunda and Siggefora was found, which is partly due to differences in roughness characteristics and partly due to the fact that observations were performed at different heights. The observations at 70 m in the Norunda forest appear to be more representative for grid-square comparisons (Figs. 8a-b).

**Figure 8.** Norunda forest site: Observed (circles) and simulated (solid line) average friction velocity at 70 m AGL in Norunda (a); at 30 m AGL in Siggefora (b). The vertical bars represents the standard deviation of the observations.
The mean wind speed is satisfactory simulated at all three sites with deviations from the observations of less than 0.6 m s\(^{-1}\). The variability of the observed wind speed is much larger than the variability of the simulations at all three sites. The diurnal amplitude at the agricultural Tisby site is much lower than the observed due to high sensitivity to large-scale forcing data which is not as apparent at the forest sites because of higher observation levels. The overestimated friction velocity at the Tisby agricultural site further indicate that the observations represent local conditions that the MIUU-model was unable to properly resolve at the chosen resolution.

Evaluation of the radiation components at the Norunda forest site showed that the model overestimated the net radiation largely due to uncertainties in the simulation of the incoming shortwave radiation due to cloudiness. However, the observed energy budget was not closed and the resulting difference was larger than the difference between the observed and the simulated net radiation.

3.4 Two strategies of land-surface heterogeneity representation

In Paper IV a comparison of two different approaches, the effective parameter approach and the mosaic approach, for the description of land surface heterogeneity and the calculation of surface fluxes were tested in the MIUU-model and evaluated against aircraft measurements of sensible and latent heat fluxes performed along a flight track in a boreal landscape consisting of agricultural areas, forests and lakes (Fig. 9).

For the southernmost part of the flight track Tisby-Lake Tämnaren which is dominated by agricultural land both approaches (Fig. 9) behave similarly with the mosaic approach giving slightly higher sensible heat flux than compared to the effective parameter approach (Fig. 10a). An interesting feature is exhibited at ~18 km into the flight track. The aircraft observed sensible heat flux decreases to about 100 Wm\(^{-2}\) and the mosaic approach is well able to capture the decrease while the effective parameter approach simulates an increase in the sensible heat flux. The explanation is that there is a small lake located in the grid square mostly dominated by forest (Fig. 9). Normally during daytime in the summer the lakes in the NOPEX region are colder than the air above and therefore negative sensible heat fluxes are dominating which is shown by a decrease in the averaged aircraft observed sensible heat flux. The effective parameter approach only simulates lakes if more than 50% of the grid cell is covered by lake as realistic effective parameters cannot be obtained for grid squares consisting of both lakes and land surfaces since the averaging of parameters like \(r_{\text{sw}}\) and \(LAI\) will lose their meaning. There-
fore a grid square using the effective parameter approach must consist entirely of land/vegetation or water. The mosaic approach which calculates separate energy budgets for each land-use type in a grid square is able to circumvent this problem when grid squares consist of both land surfaces and lakes.

**Figure 9.** The flight track for the airborne observations between Tisby and Lake Tämnaren. Dark areas are lakes, grey areas are forests and bright areas are agricultural land. The distance between Tisby and Lake Tämnaren is ~50 km.

Between 20 and 40 km the flight track is dominated by forest and none of the two approaches perform particularly well in this section as the variability of the observed sensible heat flux is large due to the high roughness of the forest that creates intense turbulence. At 43 km a small peak in the observed sensible heat flux is observed due to an increase in the fraction of forest which both approaches capture with no significant differences between them. Between 43 and 46 km the observed sensible heat flux is rapidly decreasing due to the influence of Lake Tämnaren. Again, the advantage of the
mosaic approach is demonstrated when a fraction of lake is present in a model grid square as the effective parameter approach is overestimating the sensible heat flux. Lake Tämnaren is located at 50 km and both approaches are well capturing the aircraft observed sensible heat flux which is close to zero. Since Lake Tämnaren is covering 100 % the particular grid square at 50 km the effective parameter approach also calculates realistic sensible heat fluxes.

Figure 10. Ensemble averages of sensible heat flux (a); latent heat flux (b) along the flight track Tisby- Lake Tämnaren at sections corresponding to MIUU-model grid-points. Observations (circles); Simulations using the Mosaic approach (solid line); Simulations using the Effective parameter approach (dashed line). The vertical bars represent the standard deviation of the observations.

The pattern of the observed latent heat flux very much resembles that of the sensible heat flux except that the range between grid squares is somewhat smaller (Fig. 10b). On the other hand the variability is pronounced at every grid square whereas for the sensible heat flux the variability was lower for areas with a larger fraction of agricultural land. The effect of the lake at ~18 km into the flight track is well simulated with the mosaic approach while the effective parameter approach is not able to capture the decrease in latent heat flux. It is interesting that the occurrence of lakes gives lower latent heat fluxes than the surrounding land surfaces, but this is probably due to the influence of the four days in early May, 1995, when lake temperatures in the NOPEX region are usually much lower during day-time than the temperature of the surrounding land-surfaces.

Between 20 and 40 km the effective parameter approach calculates higher latent heat fluxes than the mosaic approach. As this difference was not evident for the sensible heat flux in the same section of the flight track this sug-
gests that even small fractions of other landuse types than the dominating forest will affect the latent heat flux more than the sensible heat flux.

![Figure 11. Simulated surface temperature using the effective parameter approach compared with aircraft surface temperature.](image)

The variation of the surface temperature using the effective parameter approach compared with the aircraft measured surface temperature is large (Fig. 11). Since the mosaic approach calculates separate energy budgets for each land-use class, with its unique surface temperature, within a model grid square it is impossible to compare simulations with the airborne observations in an objective way.

Closer to Lake Tämnaren the mosaic approach performs much better as it can handle the fraction of lake in the grid square while the effective parameter approach overestimates the latent heat flux. However, both approaches underestimate the latent heat flux significantly for the lake itself. This suggests that the effects of lakes when performing flux and parameter aggregation exercises need further investigation. Especially as lake temperature is usually set to a constant value in a mesoscale model. This can be important for very shallow lakes, as Lake Tämnaren, when a higher diurnal variation of the lake temperature might be expected than compared with a deeper lake.

In general, both methods simulate the general behavior of the variations of the surface fluxes along the flight track Tisby-Lake Tämnaren in the NOPEX region reasonably well but overestimates the fluxes significantly, in particular the sensible heat flux (Figs. 9a-b). In Paper I it was shown that aircraft observed average sensible heat fluxes in the NOPEX region were
underestimated with 49% compared to aggregated mast measurements while the latent heat fluxes were less underestimated. That result partially complies with the results of Paper IV where the sensible heat flux is overestimated by the MIUU-model for both approaches with 39% and the latent heat flux was overestimated with 32% with the effective parameter approach and 25% using the mosaic approach. It appears also from a statistical point-of-view that the mosaic approach better explains the observed latent heat fluxes along the flight track.
4 Summary and conclusions

Evaporation and heat fluxes in the boreal forest zone were studied using a meteorological mesoscale model with an advanced land-surface parameterization.

The MIUU-model was compared with three methods for flux estimation utilizing observed data and a distributed hydrological model, the latter only for evaporation comparisons. The MIUU-model produced good results for both sensible and especially for the latent heat flux when compared with 24-hour fractionally weighted mast measurements. Higher variability was evident when 2-hour midday averages were compared, mainly due to variability in the cloud cover. This means that regional evaporation and heat fluxes from a very heterogeneous boreal forest area can be deduced from mesoscale modeling with reasonable accuracy on a diurnal basis. For comparisons at hourly time intervals the correct simulation or prescription of the cloud cover is very important.

To further investigate the implications of comparing mesoscale model results with tower measurements, 24 days with observed sensible and latent heat fluxes and other meteorological variables for one agricultural site and two forest sites were evaluated. The results revealed that a correct initialization of soil-water content is crucial for the correct partitioning of the sensible and latent heat flux. By removing the control on stomatal resistance of the deep soil-water content in the land-surface scheme the results improved considerably. This complies with other studies in the same region suggesting that soil-water content does not appear to be a limiting factor for evapotranspiration from the forest during the simulated periods even though observations exhibit low soil-water contents. Since soil-water content is highly variable even at small scales and difficult to estimate at larger scales this result might serve as guidance when initialising large-scale models in boreal forest areas during spring to early summer conditions. By initializing the deep soil-water content above the field capacity of the respective soil type a reasonable partitioning of the sensible and latent heat fluxes can be obtained.

The 24-day comparison revealed significant differences between the directly comparable variables, sensible and latent heat flux, and friction velocity between two apparently similar forest sites. Differences in surface roughness partly explain the differences but the different observation heights might also be of importance since the areal representativity is different. The diurnal variation of the examined variables was best captured by the MIUU-
model at the site with the highest observation level indicating that the areal representativity of the observation site in Norunda is sufficient for comparisons with mesoscale model results. The differences between the forest sites might also have an implication when performing regional aggregation of surface fluxes based on in-situ observations and the fractional coverage of respective vegetation type. A more detailed characterisation of different types of forest and agricultural land that is possible with a mesoscale model might assist in the analysis of regional surface flux estimates from in-situ observations.

Although the MIUU-model produced good estimates of regional sensible and latent heat flux, the NOPEX area is very large and the impact of smaller-scale variability on flux estimation is difficult to interpret. For the evaluation of the MIUU-model against tower measurements the model utilizes effective parameters to describe the land-surface heterogeneity which makes sense as the measurements were performed at locations with relatively homogeneous vegetation cover. But, as was indicated when comparing the model results against tower measurements, the areal representativity might sometimes be questioned for mesoscale model comparisons, particularly for the agricultural site. However, the only technique to experimentally assess the spatial variation in surface fluxes is airborne observations. Despite being systematically underestimated compared to the other flux estimation methods that were tested for the NOPEX area the airborne observations of turbulent surface fluxes can assist in testing model approaches to describe the heterogeneity of a landscape. Two commonly used strategies, the effective parameter approach and the mosaic approach, were tested in the MIUU-model against aircraft observed sensible and latent heat fluxes. For the simulation of the sensible heat fluxes along the flight track differences between the effective parameter and mosaic approaches were generally small in terms of absolute values, but the mosaic approach performs much better when a grid square is occupied by a fraction of lake. For the simulation of latent heat flux along the same flight track much larger differences between the two approaches were found. Apart from simulating the average latent heat flux with closer agreement to the observations the mosaic approach simulated grid squares with a fraction of lake with better performance. The mosaic approach also simulated lower latent heat fluxes over flight track sections dominated by forests than the effective parameter approach which might indicate that non-linearity’s between surface characteristics and turbulent surface fluxes are more pronounced for latent heat flux. The effects of lakes when performing flux and parameter aggregation exercises need further investigation.

The northern boreal forest zone differs very much from the southern parts both with respect to the forests which are usually sparser but also in climatology as the mean temperatures are lower and the winters are longer. A sparse high-latitude forest is a very effective absorber of short-wave radiation. Under low solar angle conditions, a large portion of the direct solar
radiation is absorbed by the canopy which is apparently covering the ground. This has implications for especially the daytime sensible heat fluxes. A parameterization for the absorption of solar radiation of high-latitude sparse forests was implemented and tested in the MIUU-model that significantly improved the simulation of high wintertime midday sensible heat fluxes. A scheme for heat storage in vegetation was also implemented which improved the results but needs to be further evaluated for high latitude forests.
5 Acknowledgements

I would like to express my gratitude to my supervisors Sven Halldin and Dimitris Melas for their great help and support all along the way. Thanks to Tomas Nord for great computer assistance. Thanks to all my good friends and colleagues who always makes life easier. I would like to express my deepest gratitude to my mother Märta, she is wonderful, always looking after me when I’m at “home”. Thanks to my brothers, Jan and Johny, and their families for being there during trying times. My greatest supporter was my father John, who sadly passed away in November 2003. This one is for you!
Ett ämne som diskuterats flitigt under de senaste decennierna är huruvida vi har en global uppvärmning som inte kan hänföras till naturliga variationer av klimatet. Hypotesen är att utsläpp av växthusgaser, i huvudsak koldioxid, förstärker växthuseffekten. För prognoser av det framtida klimatet används globala cirkulationsmodeller (General Circulation Models, GCM). Dessa modeller används för att uppskatta effekterna på vår omgivning av exempelvis en fördubbling av nuvarande koldioxidutsläpp. Dock är osäkerheterna stora och mycken möda har lagts på att försöka förbättra dessa modeller för att göra tillförlitligare klimatscenarier.


Landytan är en central komponent i klimatsystemet eftersom utbytet av värme och vattenånga, i form av sensibelt och latent värmeflöde vid denna, påverkar förhållandena i den överliggande luftpelaren med avseende på temperatur, luftfuktighet, molnighet och nederbörd. Dessa påverkar i sin tur de inkommande strålningkomponenternas storlek som i slutändan bestämmer omfattningen av en global klimatuppvärmning.

Ett stort problem är beskrivningen av landytans variabilitet och de effekter den ger upphov till i skalar mindre än storleken av en GCM-ruta (normalt 1°x1°, dvs i Mellansverige ca. 50 km x 100 km i nord-sydlig respektive västöstlig riktning). Landytan i en modellruta kan innehålla många olika vegetations- och marktyper, små och stora sjöar eller våtmarker, och den kan vara fullständigt eller delvis täckt av snö samt att marken kan vara snötäckt men
inte vegetationen, vilket är särskilt vanligt på senvintern och våren. Detta betyder att någon sorts medelvärdesbildning av de parametrar som beskriver jordytans beskaffenhet i en storskalig modells rutnät måste göras och dessa kallas effektiva parametrar. Ibland är förhållandena så heterogena att beräkningen av sensibla och latent värmeflöden måste utföras separat för olika homogena delområden i modellrutan med den så kallade mosaikmetoden.

Ett sätt att studera effekter av landytans heterogenitet är att använda modeller med högre tid- och rumsupplösning. Mark-vegetation-atmosfärsscheman (SVAT) används i lokalskalan eller är integrerade i meteorologiska mesoskalemodeller. De sistnämnda kopplar landytparameteriseringen till det atmosfäriska gränsskiktet vilket betyder att modellresultat kan jämföras med markmätningar av sensibelt och latent värmeflöde, temperatur och luftfuktighet på ett meningsfullt sätt förutsatt att markmätningarna är representativa för ett tillräckligt stort område. Mesoskalemodeller körs med modellupplösningar på 2-20 km i horisontalled (i meso-γ-skalan) vilket gör att modellresultat med fördel kan jämföras med flygbumna mätningar för studier av effekter av landytans heterogenitet. Detta sammantaget gör att mesoskalemodellering är ett effektivt verktyg för tester av formuleringar av olika utbytetsprocesser, undersökningar av aggregeringsmetoder och för heltäckande analyser av många olika typer av mätningar.

Ett stort hinder i utvecklandet av GCM och andra typer av storskaliga modeller har varit bristen på högkvalitativa data för att testa modellformuleringar och aggregeringsmetoder. Från senare delen av 1980-talet och framåt har storskaliga klimatexperiment med omfattande mark- och luftburna mätningar utförts. HAPEX-MOBILHY (André m.fl., 1986) i en skogsregion i södra Frankrike, FIFE (Sellers m.fl., 1992) för ett prärieområde i Kansas, USA och EFEDA (Bolle m.fl., 1993) för ett torrt område i centrala Spanien. I Skandinavien, Ryssland och Kanada, så har vi barrskogsbältet som representerar 8 % av jordens skogsområden. Den karakteriseras av ett heterogent lapptäcke av skogar, sjöar och våtmarker. I den södra delen av barrskogsbältet är områden med jordbruksmark vanliga och i dess norra deler så är skogen ofta gles och våtmarker mer frekvent förekommande. Den boreala skogens betydelse för kontroll av växthusgaser och dess betydelse för globala klimatförändringar har initierat storskaliga klimatexperiment som BOREAS (Sellers m.fl., 1997) i Kanada och NOPEX (Halldin m.fl., 1998) i Sverige och Finland. Undersökningsområdet för klimatprojektet NOPEX (A Northern Hemisphere Climate Processes Land Surface Experiment) är beläget i Uppland som ligger i den södra delen av den boreala skogszonen. Mätningar skedde kontinuerligt och under intensiva mätkampanjer som utfördes under sommaren 1994 och vår-vintern 1995. En vinterkampanj, kallad WINTEX, utfördes i mars-april 1997 och då utökades NOPEX/WINTEX med Sodankyläområdet beläget i norra Finland. Detta gjordes på grund av att ett område som uppmärksammat på senare är att effekten på klimatet beroende på temperturändringar vintertid på norra halvklotet antas vara stor och
därmed även behovet av att simulera dessa på ett realistiskt. Sodankylä är beläget i den norra delen av barrskogsbelt är gles barrskog och våtmarker dominerar till skillnad mot den södra delen av barrskogsbelt där skogen är tätare och gradvis mer uppbladad med åkermark.

Syftet med denna avhandling är att öka förståelsen för hur avdunstning och värmeflöden i den boreala skogszon påverkar klimatet regionalt och globalt. Detta har åstadkommits genom att:

- Utvärdera hur mesoskalemodellering fungerar som verktyg jämfört med andra metoder verktyg för aggregering av flöden av vatten och värme i en heterogen skogsregion i den södra delen av den boreala skogszonen.
- Införa en parameterisering för glesa skogsbestånd, typiska för den norra boreala skogszonen, i en mesoskalemodell och utvärdera denna för vinterförhållanden.
- Använda omfattande observationer från markmätningar utförda inom NOPEX för att utvärdera hur en vanligt förkommande landyteparameterisering i en mesoskalemodell fungerar under olika förhållanden.
- Undersöka hur två begreppsmässigt olika strategier för att beskriva landytans heterogenitet fungerar i jämförelse med flugburna mätningar.

Resultaten visar att mesoskalemodellen reproducerar 24-timmarsmedelvärdet angående av sensibla och latent värme-flöden från areellt viktade mätnings- ställen och att modellen visar en bra överensstämmelse. Den jämförelse med flygmätningar visar större skillnad mellan modell och mätningar främst beroende på att molntäcket varierar över undersökningsområdet, något som modellen inte tar hänsyn till.

Modellen utvärderades även för 24 dagar med detaljerade mätningar från två skogsmätstationer och för en flugtäckning belägen i ett område med jordbruksmark. Utvärderingen visar att ett korrekt initialisation av markvatteninhaltet är avgörande för fördelningen av den tillgängliga energin i sensibelt och latent värme-flöde. Utvärderingen vidimerar resultat från andra studier i regionen som visar att markvatteninhaltet inte förändras på grund av skog och södra skogsmätningar. Utvärderingen visar också att skogsmått med till synes likadana egenskaper uppvisar stora skillnader i avdunstning och värme-flöde samt i friktionshastighet vilket påvisar nödvändigheten av en noggrann bedömning av den areella representativiteten när man jämför resultat från mesoskalemodellen med markbaserade mätningar.

En parameterisering av absorption av solstrålning i glesa skogsbestånd på höga breddgrader infördes och testades i modellen. Däremot markant förbättrade simuleringen av de höga sensibla värme-flöden som observerats vid middags- tid under vintern. Ett uttryck för att beskriva varmolning i vegetationen infördes också vilket förbättrade resultaten, men uttrycket behöver vidare utvärdering för skogsbestånd på höga breddgrader.
Två ofta använda strategier för att beskriva markytans heterogenitet, effektiva parametermetoden och mosaikmetoden, testades i mesoskalemelllen mot flygplanskattningar av sensibla och latenta värmeflöden. Resultaten visar att mosaikmetoden ger bättre resultat speciellt när mindre sjöar finns i modellrutnätet.
7 References


A doctoral dissertation from the Faculty of Science and Technology, Uppsala University, is usually a summary of a number of papers. A few copies of the complete dissertation are kept at major Swedish research libraries, while the summary alone is distributed internationally through the series Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology. (Prior to October, 1993, the series was published under the title “Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science”.)