Land Surface Heat Exchange over Snow and Frozen Soil

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Measurements and Simulations of Scales from Pedon to Field

David Gustafsson

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Abstract

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The energy exchange in the soil-snow-vegetation-atmosphere system was studied to improve the quantitative knowledge of the governing processes. The lack of such knowledge contributes to the uncertainty in the applicability of many existing models independent of the temporal or spatial scale. The theoretical background and available methods for measurements and numerical simulations were reviewed. Numerical simulation models and available data sets representing open land and boreal forest were evaluated in both diurnal and seasonal time-scales.

Surface heat fluxes, snow depth, soil temperatures and meteorological conditions were measured at an agricultural field in central Sweden over two winters, 1997-1999. Two one-dimensional simulation models of different complexity were used to simulate the heat and water transfer in the soil-snow-atmosphere system and compared with the measurements. Comparison of simulated and observed heat fluxes showed that parameter values governing the upper boundary condition were more important than the formulation of the internal mass and heat balance of the snow cover. The models were useful to evaluate the lack of energy balance closure in the observed surface heat fluxes, which underlined the importance of improved accuracy in eddy correlation measurements of latent flow during winter conditions.

The representation of boreal forest in the land surface scheme used within a weather forecast model was tested with a three-year data set from the NOPEX forest site in central Sweden. The formulation with separate energy balances for vegetation and the soil/snow beneath tree cover improved simulation of the seasonal and diurnal variations of latent and sensible heat flux compared with an older model version. Further improvements of simulated surface heat fluxes could be expected if the variation of vegetation properties within and between years and a new formulation of the boundary conditions for heat flux into the soil is included.

Keywords: Surface energy balance, Snow, Boreal forest, SVAT models, Eddy-correlation Measurements, Latent heat flux, Sensible heat flux, Net radiation, Soil temperature, Aerodynamic roughness, Surface resistance

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Preface

This thesis is based on the following papers that are referred to by their Roman numerals:

I. Gustafsson, D. The energy exchange at the land surface during winter - existing theories and their limitations. *Manuscript from a PhD course at the Department of Soil Sciences, Swedish University of Agricultural Sciences, 1999.*

II. Gustafsson, D., M. Stähli and P.-E. Jansson 2000. The surface energy balance of a snow cover: Comparing measurements to two different simulation models. *Theoretical and Applied Climatology*, in press.

III. Gustafsson D., E. Lewan, B.J.J.M. van den Hurk, P. Viterbo, A. Grelle, A. Lindroth, E. Cienciala, M. Mölder, S. Halldin and L.-C. Lundin 2000. Boreal-forest surface parameterisation in the ECMWF model – 1D test with NOPEX long-term data. Manuscript.

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I would especially like to thank my supervisor Per-Erik Jansson for his support and good advice concerning my work and writing, and his enthusiasm for all kind of wintertime processes. I am also indebted to Elisabet Lewan for our encouraging common work, and for all her creative ideas and critical comments in the analysis and writing process. I would like to thank Manfred Stähli for introducing me to snow and frozen soil physics, and for all his valuable comments concerning field experiments and writing. Thanks also to Lars-Christer Lundin and Emil Cienciala for comments on the manuscript and valuable discussions. Several people have been involved in the installation and maintenance of the field experiment and thanks are due to Christina Öhman, Lave Persson, Mats Larsbo, Achim Grelle, Bengt Norén and Per-Erik Mellander. Financial support for the thesis work from the Swedish Natural Science Research Council is gratefully acknowledged.

Finally, I wish to send my warmest thanks to my family who always have supported my on the way. I wish to dedicate this thesis to my grandfather Evert Johansson, who died one year ago.

David Gustafsson
Stockholm, January 2001

'Att ta från de rika och ge åt de fattiga'
Robin Hood

Introduction

The underlying reasons for the weather phenomena we all are familiar with are nicely described by the words of Robin Hood: *'to take from the rich and give to the poor'.* The physical analogy is the second law of thermodynamics that states that natural processes can only increase the entropy of a system (Alberty and Silbey, 1992), i.e. spatial differences in energy states will be evened out. Consequently, wind, rain, snow, freezing and thawing of soil etc. are all phenomena driven by the transport of energy from locations with a higher energy state than their surroundings. Eventually, everything would come to an equilibrium if the sun were not constantly feeding the earth with new energy, unevenly spread out over the globe - the energy gradients between the equator and the poles remain and the weather goes on and on. We can simplify the climate system by looking at the fluxes of energy at a single spot on the land surface. The radiation from the sun is absorbed by the surface; the heat is stored in the ground or is emitted back to the atmosphere as thermal radiation. If the surface is hotter than the air, heat will flow from the surface to the air until the temperature gradients have evened out. Water is a key factor in the climate system, due to the large amount of latent heat released in the phase changes of water. Latent heat is exchanged at the surface by evaporation and condensation, rain and snowfall.

Adequate representations of the physical processes governing the energy exchange in the atmosphere and between the atmosphere and the land/sea-surface are the key to understanding the climate system. Large efforts have been made during the years to develop numerical models for meteorological and hydrological predictions on different temporal and spatial scales. Each application may have its own demands on the description of the land surface-atmosphere interaction. One-dimensional models of the heat and water transfer at the land surface are often referred to as SVAT models (soil-vegetation-atmosphere-transfer). For a numerical weather prediction model, a SVAT model is needed to provide correct surface fluxes of heat, moisture and momentum at an hourly timescale, since they constitute the lower boundary of the atmospheric processes (Garratt, 1993). In a large-scale hydrological model it may be most important to estimate the evaporation and the snowmelt rates (Bergström, 1996) at a daily timescale. In applications at a local small-scale of 2 by 2 meters it is important to estimate the diurnal variation of surface temperature, e.g. in detailed studies of the water and heat balance of soils (Alvenäs and Jansson, 1997). Nevertheless, the number of included details is no guarantee for the success of a model; compensating errors in different model parts or inadequate representations of single processes may be difficult to distinguish (Pomeroy et al 1998).

One important way to evaluate how well a model concept represents the intended system is to compare simulated results with observations. Numerical models are discrete, which means that the model variables represent a spatial and temporal average of some scale. To be able to make meaningful evaluations, it is important to compare with observations representing the same scale as the model, or at least to consider the impact of differing scales. The number of available data sets is increasing for different vegetation and climate regions, since several measurement projects have been initiated over the last decade. However, such data have only recently been available for the winter period. The present study was done within the WINTEX[1] framework, the winter

[1] Land-surface-atmosphere interactions in a Winter-Time boreal landscape

continuation of the NOPEX[2] project (Halldin et al, 1999) devoted to the land surface processes of the boreal forest zone in northern Europe.

This thesis deals with the exchange of heat at the land-surface mainly during winter conditions, when the surface conditions are altered by the presence of snow and ice. The objective was to improve the understanding of the governing processes on a small scale, to contribute with quantitative knowledge that might be useful also at larger scales.

The available theoretical and experimental findings were reviewed and some different modelling approaches were compared (**I**). Detailed measurements of surface energy balance components of an agricultural field represented the local scale of a single soil profile to a few hundred metres (Figure 1, left). A one-dimensional model of the water and heat transfer in the soil-snow-atmosphere system (SOIL; Jansson, 1998) was combined with two snow models of different complexity to evaluate the importance of the formulation of internal snow properties for the estimation of surface fluxes (**II**). Two versions of a one-dimensional SVAT scheme used within a global circulation model used for operational weather predictions at ECMWF[3] (Viterbo and Beljaars, 1995; Viterbo et al, in prep.) was compared with measurements from the NOPEX forest site on Norunda Common (**III**), which represented a scale from a few meters to several kilometres (Figure 1, right).

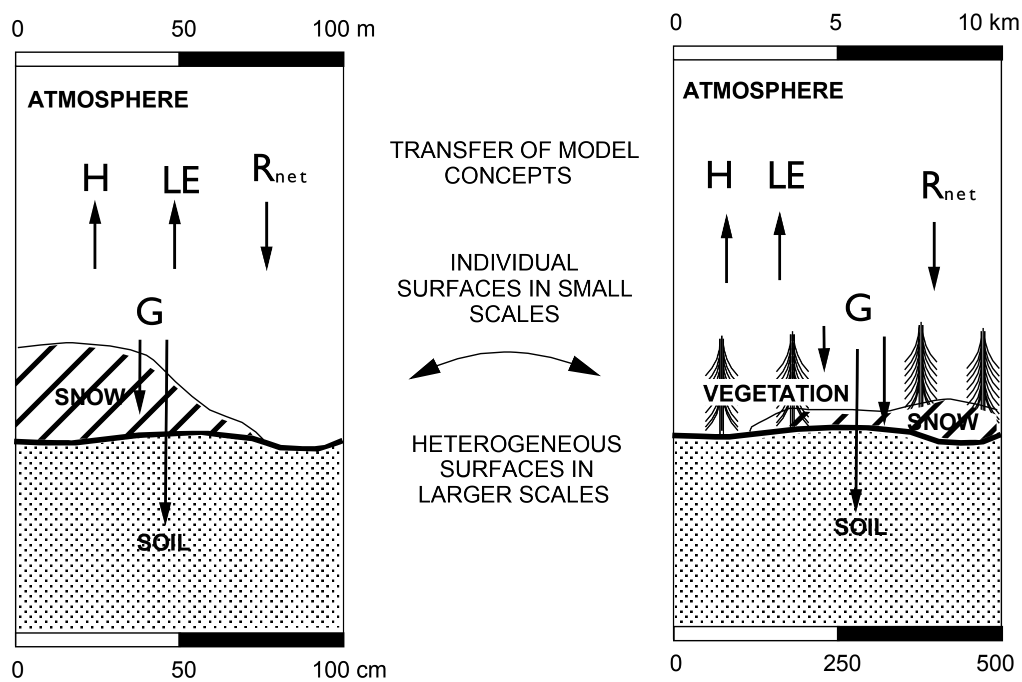

Figure 1: Conceptual view of the heat balance in the soil-snow-(vegetation)-atmosphere system at two approximate scales of measurements and models considered in the present study (arrows signify the positive sign). Symbols refer to eq. (1) below.

[2] Northern Hemisphere Climate-Processes Land-Surface Experiment
[3] European Centre for Medium Range Weather Forecasts, Reading, UK.

Fundamental assumptions - Surface energy balance

The important processes for the energy balance of the land surface are, as summarized by Male and Granger (1981):

- radiation balance of the surface
- turbulent exchange of momentum, heat and humidity
- storage of energy in the land surface system.

which is described in the fundamental energy balance equation for the land surface:

$$R_{net} = H + LE + G \quad (1)$$

where the net radiation (R_{net}) equals the sum of the turbulent surface fluxes of sensible (H) and latent (LE) heat, the heat flux to the ground and/or vegetation (G). A positive value of the terms on the right is directed from the surface, whereas a positive value of the radiation is directed to the surface. In other words, the net radiation at the land surface is either stored in the soil-snow-vegetation system or transferred to/from the atmosphere by the turbulent exchange of sensible and latent heat.

The net radiation of the surface is the sum of net short-wave and long-wave radiation. The ratio of the incident solar radiation that is reflected at the surface is defined as the surface albedo, which of course is greatly altered in the presence of snow. The albedo of newly fallen snow is about 90 % (Plüss, 1997), which is high compared to the albedo of bare soil (10-30 %) and vegetation (10-25 %) (Monteith and Unsworth, 1990). Long-wave radiation is emitted by the surface depending on the surface temperature. Gases in the atmosphere absorb part of the terrestrial long-wave radiation, which raises the temperature of the atmosphere. Downward long-wave radiation emitted by the atmosphere is therefore an important component in the surface energy balance, keeping the Earth's surface temperature higher than it would be without this greenhouse effect (e.g. Houghton, 1997).

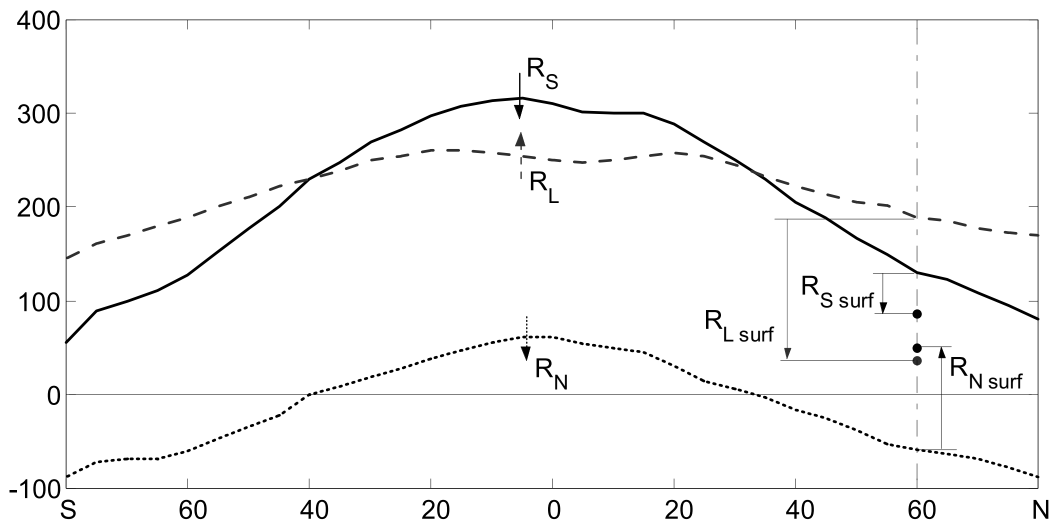

Figure 2: Absorbed solar radiation (R_S), outgoing terrestrial radiation (R_L) and net radiation (R_N) above the atmosphere as function of latitude (after Graedel and Crutzen, 1993) and the net short-wave radiation ($R_{S\ surf}$), net long-wave radiation ($R_{L\ surf}$) and the net radiation ($R_{N\ surf}$) below the atmosphere at Marsta Meteorological Observatory 60°N, Uppsala, Sweden (Halldin et al, 1999) 1998-1999.

The radiation budget of the Earth as a function of latitude is shown in Figure 2. The radiation balance at the Marsta Meteorological Observatory (60°N) illustrates the importance of the atmosphere for the radiation budget at the surface (Figure 2). On average, about 65 % of the absorbed solar radiation is absorbed by the Earth's surface, and the net loss of long-wave radiation at the surface is only about 25 % of the net loss to outer space (Graedel and Crutzen, 1993). In fact, the short-wave radiation at Marsta was 66 % of the total absorbed solar radiation according to Figure 2. However, the net loss of long-wave radiation was only 20 % of the outgoing terrestrial radiation, which probably can be related to a larger than average downward long-wave radiation due to the influence of the Gulf Current. It is interesting to see that the land surface in this case is a net source of energy to the atmosphere even at 60°N, i.e. net radiation is positive. Thus, the pole-ward transport of heat is transferred to the surface mainly as downward long-wave radiation from the atmosphere and not as sensible or latent heat.

Turbulent exchange processes

The turbulent boundary layer

Two fundamental processes, conduction and advection, can transfer heat. Conduction is the transfer of molecular motions within a media. Advection is the transfer of heat due to the motion of the media. The exchange of heat at the land surface involves both processes: molecular motions transfer heat to a very thin air layer above the surface, which is transferred vertically and horizontally by advection in the turbulent wind field above. The velocity of air blowing over a solid surface increases with height above the surface, due to the friction between the air molecules and the surface. The friction between the air molecules travelling with different velocities will transfer horizontal momentum vertically in the wind field. The flow is laminar in a very thin layer close to the surface and breaks down to a chaotic pattern of swirling motions in the air above, which is called the turbulent boundary layer. The behaviour of the turbulent boundary layer depends on the relationship between mechanical and buoyancy forces, the latter being due to temperature dependent density gradients. This relationship is expressed in the Richardson number:

$$Ri = \frac{g}{T_0}\frac{\partial\theta}{\partial z} \Big/ \left(\frac{\partial \overline{u}}{\partial z}\right)^2 \tag{2}$$

where T_0 is absolute air temperature, θ is the potential air temperature, u is the wind speed, z is the height above the surface and g is the gravitational acceleration. The boundary layer is called stable if potential air temperature is increasing with the distance from the surface, i.e. $Ri>0$, since the denser air close to the ground tends to reduce the turbulent motions. Or, vice versa, the boundary layer is called unstable when potential air temperature is decreasing with height ($Ri<0$). At neutral stability the wind profile is logarithmic:

$$u(z) = \frac{u_*}{k}\ln\left(\frac{z}{z_{0m}}\right) \tag{3}$$

where u(z) is the wind speed at the height z over the surface, u_* is the characteristic friction velocity, z_{0m} is the roughness length and k is von Karman's constant. A similar logarithmic profile for temperature defines the characteristic temperature scale T_* and the roughness length for momentum z_{0m}. The vertical fluxes of momentum (τ) and heat are defined by u_* and T_*:

$$\tau = -u_*^2, \quad H = -\rho c_p u_* T_* \tag{4}$$

where ρ and c_p are density and specific heat of air

Methods

There is no general theory for the turbulent transport of momentum and heat in the surface layer that describes the corresponding wind and temperature profiles at non-neutral stability. However, the Monin-Obukhov similarity theory predicts the transport based on the general transport equations for the turbulent flow and a statistical hypothesis (Högtröm and Smedman, 1989). The vertical energy fluxes are assumed to be constant with height within a layer above the surface. *It is assumed that the behaviour of this layer can be described by u_*, T_*, g/T_0 and z*. Consequently, these assumptions lead to a prediction that the wind and temperature profiles in the surface layer can be described by universal functions of the atmospheric stability:

$$\frac{\partial u}{\partial z}\frac{z}{u_*} = \phi_m\left(z/L\right), \quad \frac{\partial \theta}{\partial z}\frac{z}{T_*} = \phi_h\left(z/L\right) \tag{5}$$

where the Obukhov length L is a stability parameter constant with height. The wind and temperature profiles and thus the fluxes of momentum and heat from the surface to height z follow from integration of equation (5):

$$\tau = \rho C_M u_z^2, \quad H = -\rho c_p C_H u_z\left(\theta_z - \theta_s\right) \tag{6}$$

where C_M and C_H are the exchange coefficients for momentum and heat respectively. The exchange coefficient for heat is described by:

$$C_H = \frac{k^2}{\ln\left(z_a/z_{0M}\right) - \psi_M\left(z_a/L\right) + \psi_M\left(z_{0M}/L\right)} \times \\ \times \frac{1}{\ln\left(z_a/z_{0H}\right) - \psi_H\left(z_a/L\right) + \psi_H\left(z_{0H}/L\right)} \tag{7}$$

where Ψ_H and Ψ_M are the integration of ϕ_m and ϕ_h respectively.

Högström (1996) reviewed the experimental support for the theory, and concluded that it applies for unstable to near-neutral stable conditions. However, the stability parameter *z/L* cannot be calculated directly from the gradients of temperature and wind, i.e. the Richardson number *Ri*, without a numerically expensive iteration. Therefore, analytical approximations of the empirically derived exchange rates are often used (e.g. Louis, 1979). The properties of the formulation previously used in the SOIL model (Jansson, 1998) originating from Pruitt et al (1973) have been compared with an empirically based method adopted from Beljaars and Holtslag (1991) and the analytical expressions suggested by Louis (1979) (**I**) (Figure 3):

- The formulation in the SOIL model was not able to account for differences between the surface roughness for momentum and heat in a consistent way.
- The parameter values in the SOIL model formulation could be changed to correctly estimate the exchange coefficients for selected sets of surface characteristics.
- The original formulation largely overestimated the exchange coefficients in the stable regime.

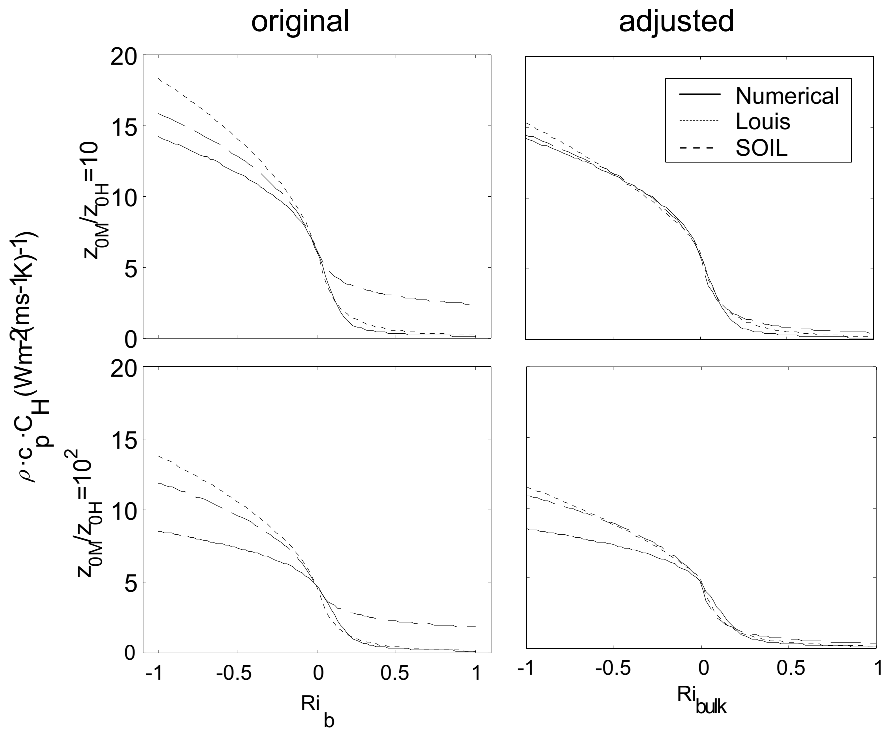

Figure 3: Exchange coefficients for heat derived from empirically found stability functions ("Numerical") and analytical approximations ("Louis" and "SOIL") for $z/z_{0M}=10^2$ and $z_{0M}/z_{0H}=10$ and 10^2; *left:* original parameter values from Louis (1979) and Jansson (1998); *right:* the analytical formulations have been calibrated to the empirically derived exchange coefficients for $z_{0M}/z_{0H}=10$.

A new formulation has been implemented in the recent version of the CoupModel[4] (former SOIL), which is based on the empirically derived method described by Beljaars and Holtslag (1991). Analytic expressions could be used for specific surface characteristics, and procedures for calibration to the empirically derived exchange rates have been presented in (**I**).

Water and heat balance of snow cover

Snow energy balance models

The heat fluxes between the soil and the atmosphere are very dependent on the presence of snow. The net radiation is considerably reduced by the high albedo of the snow surface. On the other hand, snow is a porous medium and therefore a poor heat conductor (Gray, 1970), which keeps the soil temperature higher during wintertime than it would be with a bare soil. The heat flux through the snow depends on the thermal conductivity, which is related the total density of the snow pack (Snow Hydrology, 1956). Newly fallen snow has a density of about 100 kgm^{-3}. The density increases with age due to deformation of the snow crystals, the pressure of overlying snow and snowmelt (Jordan, 1991), resulting in an increased density closer to the ground. Stähli and Jansson (1998) showed that the estimation of snow surface temperature was crucial for the simulation of soil frost, assuming a steady-state heat flux through the snow. The importance of the formulation of the internal structure of the snowpack for the surface heat fluxes was

[4] A detailed description of the COUP-model and instructions about how to download the model can be found on the Internet http://amov.ce.kth.se/Coup.htm.

investigated in (**II**). Two snow models of different complexity was used as an upper boundary for the soil in the SOIL model (Jansson, 1998): (1) the one-layer snow model described in Stähli and Jansson (1998) and (2) the multi-layer heat and mass-balance model SNTHERM developed by Jordan (1991). Field measurements of the water and heat balance components from an agricultural field were compared with simulations with the two different snow models.

Material

The field site was situated in a flat agricultural area in Marsta, 9 km north of Uppsala, Sweden, where several sub-projects within WINTEX/NOPEX contributed to cover most of the different components of the land surface-atmosphere interaction (Halldin et al, 1999). Data from two winters 1997/98 and 1998/99 are presented in (**II**): i.e. sensible and latent heat flux (discussed below), net radiation, snow depth, snow/soil surface temperature, soil temperature and meteorological driving variables from the site.

Eddy-correlation measurements

Sensible and latent heat flux have been measured with the eddy-correlation technique*,* described in detail in e.g. Grelle (1997). The vertical flux of any component transported by the airflow could be expressed as the product of the vertical wind component (*w*) and the density of the component (*x*). When the airflow above the surface is turbulent (most of the time), both w and x fluctuate. The value of any fluctuating component can be expressed as the sum of the mean ($\overline{x}$) and the fluctuation around this mean (x') according to Reynold's convention. If there are no sources or sinks of *x* within the surface layer and $\overline{w}=0$, the average vertical transfer of *x* from the surface can be expressed as:

$$\begin{aligned}\overline{(\overline{x}+x')(\overline{w}+w')} &= \overline{\overline{x}\overline{w}}+\overline{\overline{x}w'}+\overline{x'\overline{w}}+\overline{x'w'} \\ &= \overline{x}\cdot 0+\overline{x}\cdot 0+\overline{x}\cdot 0+\overline{x'w'} \\ &= \overline{x'w'}\end{aligned} \quad (8)$$

where $\overline{x'w'}$ is the correlation between *x* and *w*. The eddy-correlation technique is therefore dependent on measurements of the vertical wind speed and temperature/humidity at frequencies high enough to capture the turbulent frequencies responsible for the transport. The dominant turbulent frequency varies with height, stability, wind speed and surface roughness (Kaimal et al, 1972). Generally, higher frequencies (~20 Hz) are required closer to the ground above smooth surfaces than high above forests (~4 Hz) (Grelle, 1997).

Eddy-correlation was used to measure the sensible and latent heat flux. The eddy-correlation system consisted of an R3 Gill Sonic Research anemometer and a closed-path gas analyser (LI-COR 6262) as described in Grelle and Lindroth (1996). The sonic anemometer, mounted on a rod 3.5 metres above the ground, measured wind speed and air temperature directly. Air humidity was measured in air sampled at the base of the anemometer, sucked through a small tube into the gas-analyser placed in a box on the ground. The anemometer operated at 100 Hz, but averages were stored in a local computer at a frequency of 10 Hz. The time delay between the air-inlet and the gas-analyser readings was estimated as the time lag at the maximum of the correlation function between vertical wind speed and air humidity.

A source area analysis based on friction velocity and Obukhov length according to Schmid (1994) showed that the main part of the measured fluxes originated from areas within a radius of 50-150 meters (Figure 4). However, the source areas tended to increase during wintertime, when the surface roughness was decreased by snow.

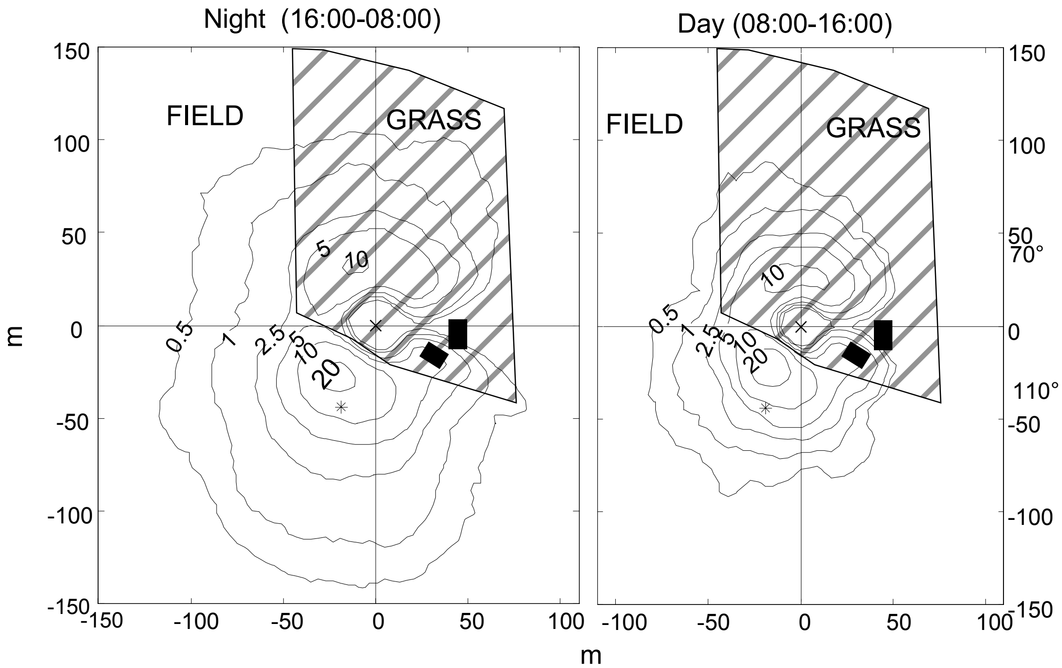

Figure 4: Integration of source areas (%) in the eddy-correlation measurements for night-time fluxes (left) and daytime fluxes (right), 1998-08-18 to 1999-07-29. The position of the soil profile measurements (*), the observatory buildings (filled rectangles) and the border between grassland (shaded area) and agricultural fields are indicated in the graphs.

The robustness of the system was discussed in (**II**) and in Halldin et al (1999). The estimate of latent heat flux was underestimated due to unrealistic frequency losses in the gas analyser vapour signal compared to temperature and vertical wind speed (Figure 5). In addition, the lack of energy balance closure in the measured budget provided strong evidence of an underestimation of latent heat flux.

The use of 10 Hz instead of the recommended 20 Hz could not explain the deficiencies, since this would have also affected the temperature and wind speed signals. There is no sign of aliasing (transfer of energy from higher frequencies to low frequencies due to poor sampling) in the power spectra of temperature and vertical wind speed (Figure 5a). Instead, signal damping in the pathway between the air intake and the gas analyser was the main reason behind the loss of frequencies. Corrections for the frequency loss in the tube flow had not yet been applied, but they were believed to be of minor importance. Peters et al (2000) suggested that the filter used to remove particles might have attracted water vapour when it was filled with particles, which would have diluted the high frequency signals. However, the same system has been shown to be very reliable for measurements above forests (Grelle and Lindroth, 1996) where the main frequencies of the turbulence are smaller and the cleaner air makes the system less sensitive to contaminated filters.

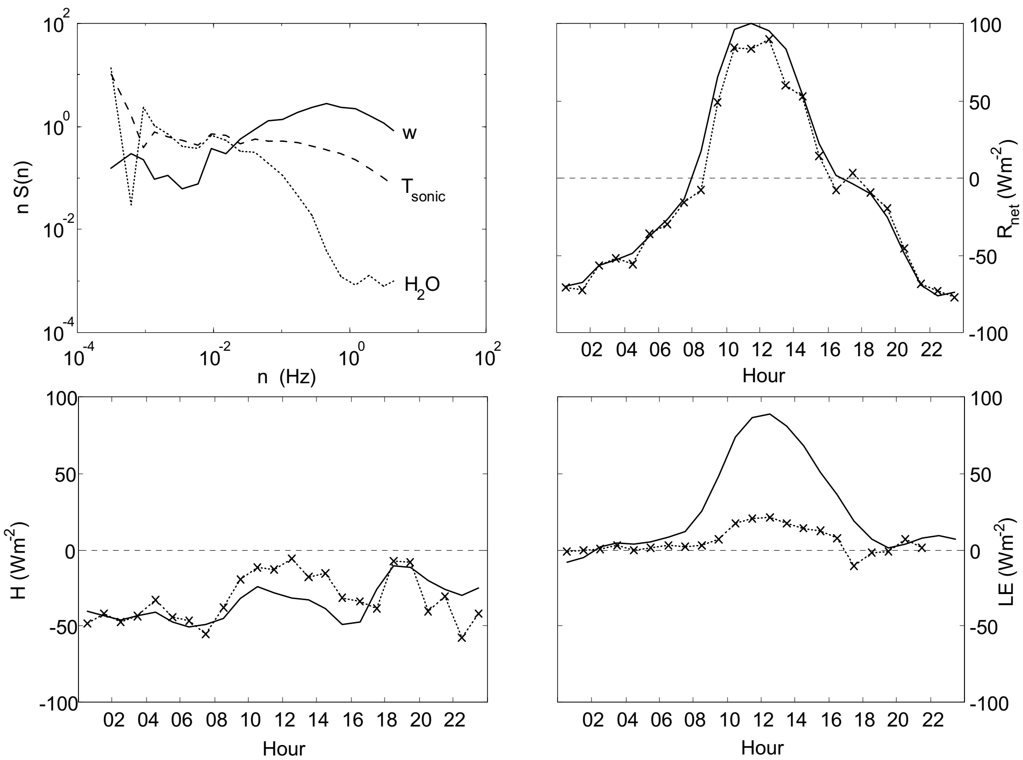

Figure 5 (a): power spectra from the eddy-flux station estimated from 23 February 1998, showing an unrealistic frequency loss in the water-vapour signal compared to vertical wind-speed and sonic temperature signals. *(b-d):* net radiation from the grassland (dashed line with markers) and sensible and latent heat fluxes from the eddy-flux station compared with the Coup Model estimates (solid).

Result

The comparison of the two snow-models and the measurements showed that:

- The surface heat fluxes simulated by the two models were in many cases close to each other but differed substantially from the measurements during snowmelt and patchy snow cover.
- Discrepancies between measured and simulated sensible heat flux were small compared to the uncertainty in the eddy-correlation measurement.
- A substantial discrepancy between measured and simulated latent heat flux was identified as a systematic measurement error.
- Differences in the simulated soil temperature were attributed to differences in the thermal conductivity of snow. The temporal dynamics of the observed soil temperature were somewhat better represented during snow depths above 10 cm when the multi-layer snow model was used.
- The formulation of the internal structure of the snow pack was of less importance compared to the formulation of the boundary conditions, during conditions of shallow and patchy snow pack.

The different measurements represented a rather wide range of scales; soil temperature was measured in four soil profiles located within 10 metres from each other in the field about 50 metres away from the eddy-flux mast; snow depth was measured automatically in a single point above the soil profiles, and manually along a 75-metre transect once a week; the eddy-flux measurements represented the average flux from the area within a radius of several hundred metres. The meteorological driving variables probably represented a larger area than the soil profile measurements. However, the meteorological driving variables were a good and reliable representation of the soil where the soil measurements took place. On the other hand, it was not evident that the eddy-correlation measurements solely represented the area of the soil profiles (Figure 4).

Modeling of a boreal forest

Boreal forest in climate models

Adequate representations of the surface energy exchange are essential in climate and weather prediction models, since most of the energy input to the climate system is absorbed by the surface. It has been shown that the climate is sensitive to the vegetation cover and the land surface hydrology. Deficiencies in the land surface models can force the predicted climate into an unrealistic state, e.g. predictions of precipitation regimes are very sensitive to the estimated surface evaporation (McGuffie and Henderson-Sellers, 1997). To ensure that correct descriptions are made of the surface characteristics and the corresponding sensible and latent heat fluxes, it is necessary to evaluate the behaviour of land surface models without the atmospheric feedback, with respect to the long-term effect on the heat and moisture budget (Viterbo and Beljaars, 1995). In most climate models, the surface of the earth is divided into grid cells with sizes of hundreds of kilometres. To represent the average behaviour of a heterogeneous grid surface many models uses different surface types, and calculate the average surface fluxes by fractional area weighting (e.g. van den Hurk et al, 2000). It is important to evaluate not only the composite behaviour of the mixed surface, but also the ability to represent the individual surface types (Verseghy, 2000). The boreal forest zone, with a mixture of evergreen and deciduous trees, characterizes the high latitudes in the northern hemisphere. The interaction of soil-vegetation and atmosphere is further complicated by the presence of snow and frozen soil.

Application of land surface model to a Scandinavian forest

The representation of boreal forest in the land surface scheme used within ECMWF (Viterbo and Beljaars, 1995; van den Hurk et al, 2000) was evaluated in (**III**). Data of surface heat fluxes, sub-surface conditions and meteorological input from the NOPEX forest site (Lundin et al, 1999) were available for a three-year period 1994-1996. Two versions of the land surface model were compared, with different number of sub-grid surface types represented. The principal difference between the models was that the older version (VB95) (Viterbo and Beljaars, 1995) assembled the surface fluxes from the sub-surfaces to one common energy balance, in contrast to the newly developed TESSEL[5] scheme (Viterbo et al, in prep.) in which the energy balance of each surface fraction was calculated separately. Furthermore, several surface processes had been refined with respect to boreal forest based on the evaluation of the VB95 model with data from the BOREAS[6]-experiment in Canada (Betts et al, 1998). Thus, dealing with overestimations of evaporation due to the lack of representation of:

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[5] Tiled ECMWF Scheme for Surface Exchanges over Land
[6] Boreal Ecosystem-Atmosphere Study

(A) increased aerodynamic resistance for evaporation from snow below vegetation
(B) reduced water uptake of vegetation from frozen soil
(C) reduction of transpiration because of vapour pressure deficit that tends to close stomata of forest trees.

The independent assessment of the ECMWF land surface schemes with the NOPEX long-term data presented in (**III**) mainly confirmed the findings in the comparison with data from BOREAS (van den Hurk et al, 2000):

- The seasonal variation of evaporation was significantly improved by the new scheme (TESSEL) compared to the old (VB95) due to the improvements according to (A)-(C), and the use of a higher canopy resistance representative for boreal forest.
- Seasonal variation of sensible heat flux was improved due to the improved latent heat flux.
- Diurnal variation of evaporation was improved due to the inclusion of a transpiration response to vapour pressure deficit.

Comparison with the evaporation estimated with a simple Penman formulation showed that the account for soil moisture stress substantially improved the explanation of observed variability. However, systematic underestimated evaporation in the late summer indicated that the model might be further improved by inclusion of:

- natural seasonal variations in leaf area
- the ability of trees to extract water from deeper levels in the soil during conditions when the uppermost layers are dry
- the variation of vegetation properties within and between years related to climatic conditions during winter.

The new model greatly improved the simulation of the energy balance during winter. The main reason was the extra aerodynamic resistance for snow evaporation, added to represent the effect of vegetation above the snow pack. However, the downward sensible heat flux was largely underestimated compared to the measurements. At the same time, ground heat flux to the surface was overestimated resulting in too low soil temperatures, which indicates:

- that the aerodynamic coupling between the surface and the atmosphere was too low during stable conditions
- and/or the thermal conductivity of the skin layer was too large.

Either of these deficiencies would explain why too much heat was taken from the soil instead of the air. Furthermore, the seasonal amplitude of soil temperature was overestimated by 5-10°C in the top 100 cm of the soil. In addition to the overestimated thermal conductivity of the skin layer, this could most likely be attributed to the lower boundary condition for soil heat flux; a soil profile depth of only 4 meters was not deep enough to be able to assume a zero heat flux on the lower boundary in the seasonal timescale.

The general improvements by the new ECMWF land surface scheme in the representation of a boreal forest were promising. The improvements were mainly due to the introduction of separate energy balances for individual surface types and the improved parameterisations of some key biotic and abiotic processes.

Concluding remarks

Future analysis will focus on the formulation of the boundary conditions and the accuracy of the surface flux estimates, rather than the internal heat and mass balance of snow cover. Calibration and sensitivity analysis of the models presented in (**II**) will further improve the quantitative understanding of system behaviour. New insights both into the formulation of the governing processes and the interpretation of the available data set are expected.

The energy balance of a forest stand has to be further explored, with emphasis on:

- interception of rain and snow
- ground heat flux
- water uptake and vegetation dynamics.

Collaboration between modellers dealing with different scales is important. Development of procedures for how to estimate parameters and how to interpret the values of different scales requires an interdisciplinary approach with contributions from soil science, forest ecosystem research and meteorology.

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