BOREAL ENVIRONMENT RESEARCH 7: 379–387 ISSN 1239-6095
Helsinki 23 December 2002

Area averaging of land surface–atmosphere fluxes in NOPEX: challenges, results and perspectives

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Gryning, S.-E., Halldin, S. & Lindroth, A. 2002: Area averaging of land surface–atmosphere fluxes in NOPEX: challenges, results and perspectives. — *Boreal Env. Res.* 7: 379–387. ISSN 1239-6095

The NOPEX experimental campaigns dealt with the land-surface-atmosphere exchange of momentum, heat, water and CO_2 on local and regional scales. In this paper emphasis is put on the NOPEX experiences with respect to the spatial integration of fluxes of momentum, heat, humidity and CO_2 over the mosaic of forest, agricultural land, lakes and mires that make up the southern part of the NOPEX area. It is found that the forest dominates both the regional momentum and heat fluxes but in very different ways. Furthermore, results from a NOPEX experiment in the northern zone of the boreal forest in Finnish Lapland highlights the very unique processes associated with the energy exchange within a forest in wintertime. The interaction of the forest canopy with sunshine provides a considerable energy source, particularly at low solar angles. A considerable improvement in model simulations of fluxes and surface temperature was achieved when this effect and the heat storage of the canopy were taken into account.

Introduction

The many aspects of the interaction on both large and small scales between the surface and the atmosphere in the climate system has become gradually more recognised in the last decade. However, because of the topographical and surface heterogeneity within the regions and the non-linearity inherent in the interaction of the fluxes between the scales, it is not generally possible to scale up point fluxes to regional scales by simple extrapolations. With the aim to improve our understanding of the exchange processes of water and energy and to improve the climate change predictions on both the global and regional scales, a number of continental scale experiments (CSE) has been initiated (Stewart *et al.* 1998) under the umbrella of the Global Energy and Water Cycle Experiment (GEWEX). Because of the complex interaction between the scales there is a clear need in continental-scale experiments to get many and good micrometeorological and flux measurements for model validation purposes. The need for extensive small-scale, integrated surface experiments embedded within the larger, continental-scale experiments (CSEs) sponsored by GEWEX has consequently become well recognised. Prominent examples are BOREAS (Sellers *et al*. 1997), LITFASS (Beyrich *et al*. 2000) and NOPEX (Halldin and Gryning 1999).

BALTEX is a GEWEX continental scale experiment dealing with the Baltic Sea and its catchment (Raschke *et al*. 2001). A large effort in BALTEX is devoted to climate predictions by global and regional climate models. Therefore, field measurements both over land covering various vegetation types and snow, over sea and over sea ice appear to be essential experimental contributions to the overall goals of a BALTEX. The NOPEX (NOrthern hemisphere climate-Processes land-surface EXperiment) is a small-scale concentrated effort carried out in the BALTEX study area. NOPEX is devoted to studying land-surface-atmosphere interaction in northern European forest-dominated landscapes. NOPEX is specifically aiming at investigating fluxes of energy, momentum, water, and CO_2 between the soil, the vegetation and the atmosphere, between lakes and the atmosphere as well as within the soil and the atmosphere on local to regional scales ranging from centimetres to tens of kilometres. In NOPEX, equal weight is put on long-term measurements and time-limited, areally extended concentrated field efforts. The original NOPEX study region represents the southern part of the boreal zone, situated in the Baltic Sea drainage basin near Uppsala, Sweden. A northern study region, centred on the Arctic Research Centre of the Finnish Meteorological Institute (FMI-ARC) near Sodankylä in northern Finland, was introduced 1996 in connection to wintertime studies. FMI-ARC represents the northern part of the boreal-forest zone.

Selected results from the NOPEX field experiments

Here we present selected results from the concentrated field efforts in 1994, 1995 (NOPEX-summer) and 1997 (NOPEX-winter) on the regional scale studies of the fluxes to the atmosphere. Results from the local-scale studies focusing on small-scale processes, including lakes, the remote sensing studies and the long-term monitoring programme are not discussed here, and can be found in the special issue of *Agricultural and Forest Meteorology* (Vols. 98–99, 1999) devoted to NOPEX-summer and similarly for NOPEX-winter in *Theoretical and Applied Climatology* (Vol. 70, 2001). Both issues include a CD with the measurements from the campaigns. Further articles on NOPEX-winter can be found in *Boundary-Layer Meteorology* (Vol. 99(3), 2001).

NOPEX-summer

NOPEX-summer was devoted to studying land-surface-atmosphere interaction in the southern part of the boreal zone, centrally situated in the Baltic Sea drainage basin west of Uppsala in central Sweden. The study area is representative for the mixture of forests, agricultural fields, mires and lakes found in the Scandinavian boreal-forest zone. It covers approximately 50 km times 50 km corresponding to a single cell in a Global Climate Model. The experiments took place in the summer of 1994 and in spring/summer of 1995.

Regional fluxes of momentum

Measurements of momentum fluxes performed at locally homogeneous sites are not suitable for the determination of regional momentum fluxes because inhomogeneities such as the form drag caused by isolated trees, houses or sharp edges between forest and grassland are major contributors to the regional flux of momentum (Batchvarova *et al*. 2001, Gryning *et al*. 2001).

Some success has been achieved by applying methods that make use of wind profiles to estimate the regional fluxes of momentum. Only the part of the wind profile measured at heights well above the ground in order to represent regional conditions (the so-called blending height) can be applied in such an analysis. The blending height depends on the character of the landscape inhomogeneities. It is typical 100 to 200 metres over land in northern Europe.

Hiyama *et al.* (1999) suggest two methods, both based on wind profiles, to the spatial integration of the momentum fluxes. One of the methods requires knowledge of the regional roughness length — which is a problem in itself. The wind speed profile within the surface layer is described by Monin-Obukhov similarity theory

$$u(z)=\frac{u_{*s}}{\kappa}\left[\ln\left(\frac{z-d_0}{z_0}\right)-\psi_m\left(\frac{z-d_0}{L}\right)\right] \quad (1)$$

where $u(z)$ is the wind speed at height z above the surface, κ the von Karman constant, L the Obukhov, z_0 the roughness and d_0 the zero displacement lengths; ψ_m is a stability correction function. Having estimated z_0 and d_0 from parameterisations, the friction velocity u_{*s} can be obtained by fitting wind profile observations to Eq. 1.

The other method is based on the difference between the wind speeds in the surface layer and in the mixed layer. It is assumed that there exists a finite region of overlap where both the surface sublayer and mixed layer wind profiles are valid. Joining the two similarity expressions gives

$$u_{\mathrm{ABL}}-u(z)=\frac{u_{*\mathrm{sm}}}{\kappa}\times\left[\ln\left(\frac{h_{\mathrm{b}}}{z-d_0}\right)-B+\psi_m\left(\frac{z-d_0}{L}\right)\right] \quad (2)$$

where u_{ABL} and h_{b} are the characteristic wind velocity and height scale of the atmospheric boundary layer and B is a similarity function, for details *see* Hiyama *et al* (1999). An advantage of this method is that it can be applied without knowing the regional roughness length. Derived regional momentum fluxes for the NOPEX area from the two methods are compared in Fig. 1. The methods were only applied for measurements carried out during daytime.

It is seen that the surface fluxes of momentum that can be estimated by the two methods are about the same. Furthermore by inspecting Hiyama *et al* (1999) it can be seen that they are 5 to 10 times larger than the locally measured friction velocities at the release point, being representative for grassland.

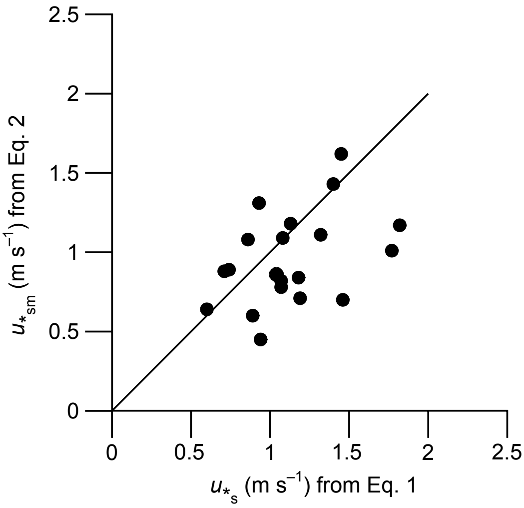

Fig. 1. Comparison between the regional friction velocities derived from wind profiles obtained by radiosondes by two methods outlined in chapter "Regional fluxes of momentum". The regional friction velocities on the *x*-axis require an estimate of the regional roughness length, and those on the *y*-axis are based solely on the measured wind profile. The measurements represent daytime conditions in May and June 1994 and 1995.

Regional fluxes of sensible and latent heat

The mixed layer grows in response to the regional turbulent fluxes including the aggregation of small-scale processes. A method to determine the regional integrated heat flux from measurements of the evolution of the mixed layer is presented in Gryning and Batchvarova (1999). Application of the method is based on inversion of a model for the growth of the mixed-layer,

$$\left\{\frac{h^2}{(1+2A)h-2B\kappa L^{\mathrm{eff}}}+\frac{Cu_*^2T}{\gamma g\left[(1+A)h-B\kappa L^{\mathrm{eff}}\right]}\right\}\times\left(\frac{dh}{dt}\right)=\frac{\left(\overline{w'\theta'}\right)_{\mathrm{s}}^{\mathrm{eff}}}{\gamma} \quad (3)$$

where t is time, L^{eff} — the effective Obukhov length; g/T — the buoyancy parameter; A, B and C are parameterisation constants. Commonly accepted values are $A = 0.2$, $B = 2.5$, and $C = 8$. The potential temperature gradient, γ, the height of the boundary layer h, and its growth rate, dh/dt are input parameters, use of the method therefore requires measurements of the mixed-layer growth. The aggregated fluxes of heat

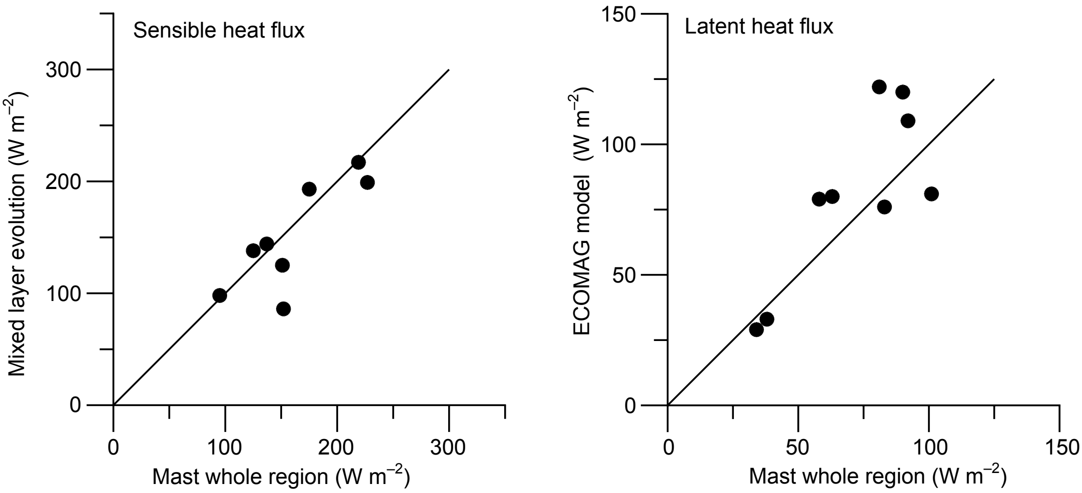

Fig. 2. The left panel shows regional sensible heat fluxes estimated by the mixed layer evolution method. The measurements represent mean values over the periods covered with intensive radiosoundings, typically between 10:00 to 17:00 local time. The right panel shows 24-hour averages of the regional latent heat fluxes determined from the ECOMAG model (Gottschalk *et al.* 1999), both plotted against land use weighted average mast measurements. The data are from May and June in 1994 and 1995.

determined from the mixed layer growth method is compared to straightforward area averaging of the heat fluxes over the various sub-areas (so-called tile method), and the agreement is fair (Fig. 2 left panel).

Gottschalk *et al.* (1999) compared fluxes of sensible and latent heat over the NOPEX region calculated with five methods (airborne and balloon-sounding measurements, weighted mast measurements, the ECOMAG distributed hydrological model, and the mesoscale meteorological model at the Meteorological Institute of Uppsala University (MIUU model)) and found rather large differences between some of them. The aircraft measurements of sensible heat fluxes were generally lower than those obtained from ground measurements whereas latent heat fluxes showed a fair agreement (Fig. 2 right panel). Good agreement was found between all the different methods when it came to evaporation fluxes. This indicates that evaporation fluxes can be aggregated from land-use-weighted mast fluxes in this boreal-forest region during summer conditions. Tests with a new parameterisation scheme in the HIgh Resolution Limited Area Model HIRLAM (Bringfelt *et al.* 1999) confirmed the conclusion that straightforward area-weighted flux averaging gave results as good as more complex aggregation schemes.

Regional fluxes of CO_2

In principle, the convective boundary layer can be treated as a large chamber in which the surface fluxes can be inferred from measured changes in the CO_2 concentration and the height of the convective boundary layer as function of time. As photosynthesis at the surface increases with irradiance, the CO_2 concentration in the convective boundary layer is reduced below that in the free atmosphere above the mixing layer. The method was used (Levy *et al.* 1999) to calculate regional-scale fluxes of CO_2 over the NOPEX area. The applied method is rather similar to the one used to determine the regional sensible heat flux. Use of the method is restricted to cases where the effect of advection is negligible, which is not a severe restriction. The regional fluxes of CO_2 derived from boundary layer budget method were compared to fluxes measured by eddy covariance at a single forest site at 35, 75 and 100 metres. As the source areas are different for the two methods the agreement between the fluxes should not be exact but can be expected to be within the same range and show similar variations.

Good agreement was found on two days when the air mass was maritime in origin such that the CO_2 concentration above the mixed layer could be assumed to be equivalent to values measured at oceanic sites. In Fig. 3, the fluxes measured by the eddy covariance are compared with the fluxes determined by the boundary layer method. Small symbols illustrate the measured fluxes at the three levels with their mean value shown by the large filled circles. Poor agreement was found on two days when the air mass has passed over continental Europe and the concentration above the mixed layer was not known but taken as the oceanic values, which seems to be non-valid. It is concluded that the boundary layer budget method has a good potential when the CO_2 concentration in the free air above the mixed-layer is known.

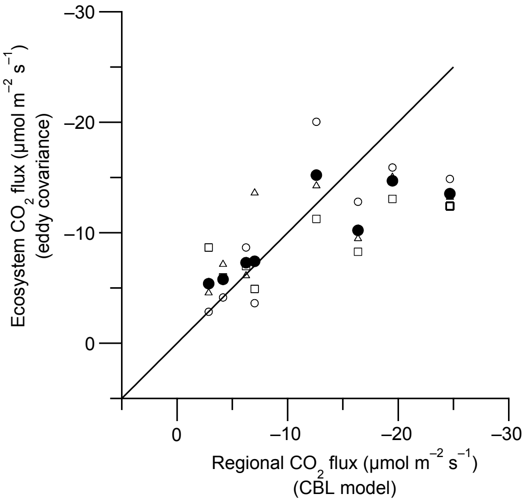

Fig. 3. Fluxes of CO_2 measured at 35 (□), 75 (△) and 100 (○) metres height (small symbols) and the mean value (●) by eddy covariance technique and calculated by the boundary layer budget method. The period represents daytime on 27 and 28 June 1997 with air of maritime origin. The eddy covariance fluxes are averaged over 30 min.

NOPEX-winter

NOPEX-winter — also called WINTEX — was a pilot study with the aim of improving our understanding of the dynamics of land-surface-atmosphere exchanges of water, energy and carbon during winter conditions. A major objective was to test the measurement equipment during the harsh winter conditions and to provide a sensitivity analysis to identify the mechanisms dominating the energy and water exchanges. The core of the programme was a pilot experiment during March and April 1997 at the FMI-ARC (67°22´N, 26°38´E, 180 m) in Finnish Lapland, representing the northern part of the boreal zone. During this experiment a comprehensive set of surface observations was collected over a forest site. In addition radiosonde and aircraft measurements of the lower atmosphere and remote sensing measurements over the region were performed.

The surfaces at high latitudes are snow covered for as much as nine months of the year. The difference between open snowfields and forests is probably the largest land surface contrast found in the terrestrial biosphere. The presence of a snow cover radically alters the surface radiation budget, reflecting as much as 90% of the incoming solar radiation. It also changes the surface aerodynamic characteristics and insulates the ground preventing very cold air temperatures propagating into the soil. The boreal forest has a low albedo and therefore absorbs most of the incoming radiation. It also has very high roughness. The roughness length was estimated by Batchvarova *et al.* (2001) from the measurements of turbulence and wind speed. Typically the tree height was 8 metres around the meteorological mast and taking the displacement length as 0.66 of the tree height, the forest roughness was estimated from the logarithmic wind profile to be 1.4 metre. The value is higher than for a dense forest (Stull, 1988), but in agreement with values for the boreal forest obtained by Mahrt *et al.* (1997). The high roughness value reflects the sparseness of the forest. The contrasts between the northern and the southern NOPEX sites are significant.

Snow does not stay long on the canopy in the boreal forest, it either evaporates or falls through to the forest floor. At low solar angles the forest canopy intercepts the majority of the incoming

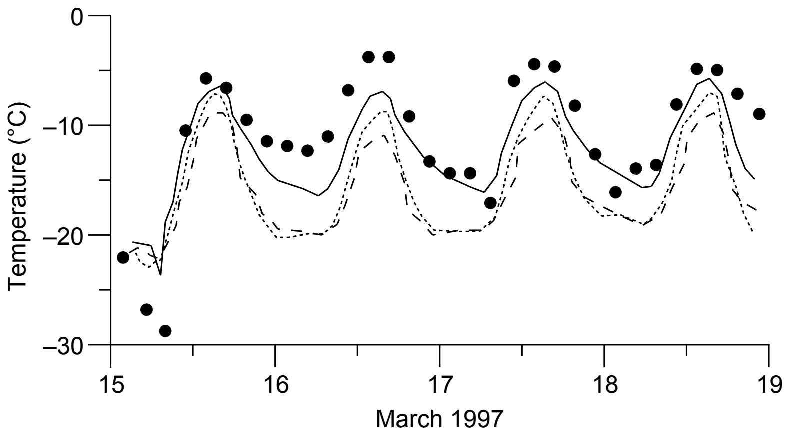

Fig. 4. The variation of the temperature at Sodankylä during 4 days of the WINTEX experiment. (●): SYNOP measurements; dashed line: control simulation with the standard parameterisation of the fluxes; dotted line: simulation with the MIUU model implementing a shading factor; full line: simulation results with the MIUU model with the shading factor and heat storage in the vegetation implemented.

solar radiation (Gryning *et al*. 2001). This is particularly true for sparse canopies, such as that found at the WINTEX site at Sodankylä. In the winter month with low solar angles the forest floor is permanently shaded and the darker forest canopy absorbs almost all the incoming short wave radiation. Gryning *et al*. (2001) provides a model for the fluxes of energy with a combination of a simple geometric radiation model and a two-source energy exchange model. The combination of sparse forest and snow on the ground results in a strong dependence of the large-scale albedo on the sun angle.

The importance of snow and snow interception is illustrated in Savijärvi and Kauhanen (2001). In a case study during WINTEX, the FMI's HIRLAM models overpredicted the night time air temperature at Sodankylä by 12 to 15 °C. A layer of snow of very low density was present on the night of the case study, which insulated the snow surface and the air near the surface cooled strongly overnight. Melas *et al*. (2001) show simulations with the three-dimensional higher order turbulence closure model developed at the University of Uppsala (MIUU model) for 4 days that are characterised with a remarkable diurnal range of temperature. The present surface energy balance scheme in the MIUU model, based on Deardorff (1978), was found to underestimate the observed high values of the sensible heat flux over the forest in the afternoon hours. This discrepancy also affected the temperature, wind speed and friction velocity. In order to improve the simulation the effect of shading together with a transmittancy factor for the forest to compensate for the apparent high vegetation cover due to the low solar angles, and a simple expression for the heat storage in the canopy (Grimmond *et al*. 1991) were introduced. When the simulation by the MIUU model was repeated with the new parameterisation the performance of the model was much improved, both with respect to the prediction of the temperature near the surface (Fig. 4), and the sensible heat flux.

All these modelling studies show the importance of the regional aspects of the snow-vegetation-atmosphere interface to the atmosphere. The improvements in the parameterisations of the fluxes across this interface substantially improved the simulations of the atmospheric boundary layer. These improvements certainly have the potential to lead to improved performance of Numerical Weather Prediction Models and Climate Models in high latitude regions.

Fluxes of momentum and sensible heat on the regional scales were also investigated. The regional momentum flux was estimated from a parameterised blending height method

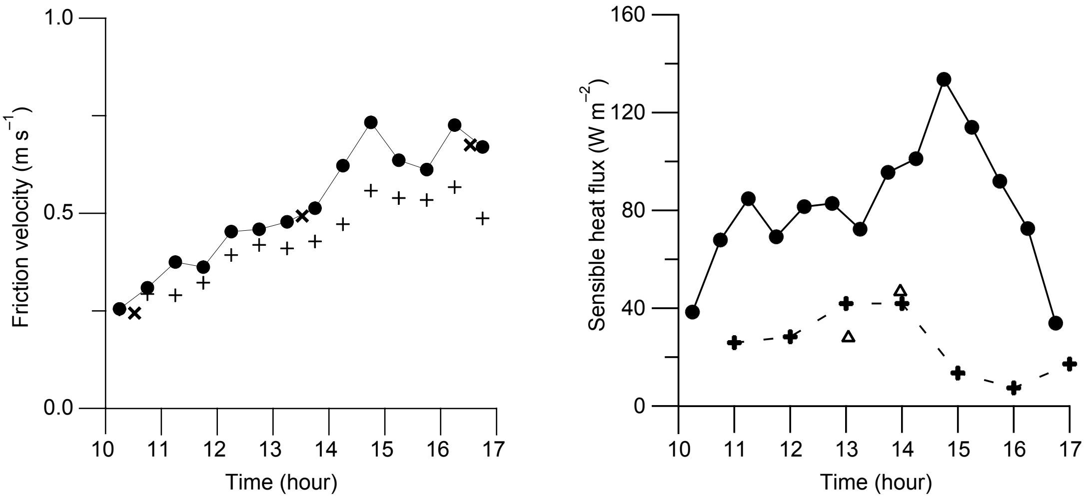

Fig. 5. Daytime evolution of the momentum and sensible heat fluxes over the forest at the FMI-ARC on 15 March 1997. Left panel shows measured local friction velocities (●), derived regional friction velocities from a parameterised blending height method (×), and a numerical aggregation model (+) (*see* Batchvarova *et al.* 2001). Right panel shows measured local sensible heat flux over the forest at the Sodankylä Meteorological Observatory (•), the derived regional sensible heat flux (+), and the flight-track mean values (△).

$$u_*^{\mathrm{eff}} = \frac{\kappa u(l_\mathrm{b})}{\left[\ln\left(\frac{l_\mathrm{b}}{z_0^{\mathrm{eff}}}\right) - \psi_m\left(\frac{l_\mathrm{b}}{L^{\mathrm{eff}}}\right)\right]} \quad (4)$$

where l_b is the blending height, u_*^{eff} is the regional friction velocity, z_0^{eff} is the regional roughness length for the inhomogeneous area and remains to be determined and L^{eff} is the Obukhov length formed from the regional momentum and sensible heat fluxes (for details *see* Batchvarova *et al.* 2001).

Assuming that the drag coefficient for the entire area taken at the blending height can be written as the drag coefficient for the sub-areas weighted in proportion to their fraction of the area

$$\left[\ln\left(\frac{l_\mathrm{b}}{z_0^{\mathrm{eff}}}\right)\right]^{-2} = \sum_i f_i \left[\ln\left(\frac{l_\mathrm{b}}{z_0^{i}}\right)\right]^{-2} \quad (5)$$

where f_i is the fraction of the total area covered by the *i*th surface having the local momentum roughness length $z_0^{\,i}$. The sensible heat flux was estimated from the growth of the mixed-layer applying Eq. 3 as depicted in chapter "Regional fluxes of sensible and latent heat", but using the regional momentum flux estimated from the method described above. It was found (Batchvarova *et al.* 2001) that the forest dominated both the averaged momentum and heat flux, but in quite different ways (Fig. 5). The area averaged momentum flux is dominated by the rough forest elements, and only marginally depends on the roughness of the large snow covered neighbouring areas. The area averaged sensible heat flux is roughly proportional to the fractional coverage of the coniferous forest.

Discussion and outlook

The spatial integration over the non-homogeneous surfaces and the estimation of the areally integrated fluxes between the ground and the atmosphere shows that the behaviour of the momentum, sensible and latent heat and CO_2 fluxes differs. The momentum transfer is found to be governed by the roughest surface — in this case the forest — whereas the sensible and latent heat fluxes are determined predominantly by land-cover type. Aggregation of CO_2 was successfully carried out by use of the boundary layer budget method but the results also shows that a prerequisite for applying the methods are trustful estimates of the CO_2 concentration in the air above the mixed layer.

The NOPEX winter experiment revealed a number of special effects that turned out to be important for the simulation of the conditions over snow. Large fluxes of sensible heat are found over the forest. The combination of sparse forest and snow on the ground results in a strong dependence of the aggregated albedo on the sun angle. The area averaged momentum flux is dominated by the rough forest, and only marginally depends on the roughness of large snow covered areas. The area averaged sensible heat flux is roughly proportional to the fractional coverage of the coniferous forest. Model simulations revealed very clearly that the comparison with measurements improves when the effect of the sun angle on the effective albedo (shadowing and transmittancy effects) and the heat storage of the forest were accounted for in the parameterisations. The effective albedo is especially crucial for the sensible heat flux, whereas both the shadowing effect and the heat storage in the canopy affects the temperature forecasts.

Results from the analysis of a number of measurement campaigns that in recent years has been carried out with emphasis on the fluxes in the Baltic Sea and its catchment areas are now beginning to emerge. The topic is very complex because it represents very different climatologically conditions — from the temperate climate zone in the south to the arctic in the north. These recent investigations have revealed that the models presently used only marginally accounts for many effects that have turned out to be important for the correct representation of fluxes in the models. The shadowing effect was not considered to be important until the results from the WINTEX campaign started to emerge. It has been observed recently (Vihma and Brümmer 2002) that even the fluxes that are produced by the boreal forest on the small islands in the Baltic archipelago can influence the micrometeorological conditions both over the sea and in the marginal ice zone. It is promising but also frustrating that whenever the results from intensive campaigns in the Baltic Sea area are being analysed and presented, processes not previously accounted for or even thought of turn out to be essential. This leaves us uncomfortable with the parameterisations of present day's models, questioning the model predictions — but without knowing the effect the errors due to the unaccounted processes have on the final model results. This calls for further investigations on the interaction between the surface and the atmosphere.

In our opinion such efforts should be twofold. They should (1) extend over long periods of time in order to capture the temporal variation and to cover a representative spectrum of episodic and non-frequent events which might have a large impact on the energy and water cycles at the surface and be combined with (2) short term very intensive campaigns with extensive spatial coverage — like NOPEX summer — that allows us to elucidate the spatial variation of these processes and their interaction. The considerable effort that is put into global climate change research in recent decades has identified a high risk of large future climatic and environmental change in the northern latitudes. We believe that the high latitude representation of the boreal land surfaces has in the past been incomplete or even incorrect (Harding *et al*. 2001) and it is especially important to increase our knowledge of the exchange processes in the high latitudes to reduce our uncertainty in the predictions. We therefore believe that a large intensive campaign in the northern boreal zone will have a large scientific potential, considering the many unexpected results from the WINTEX pilot-experiment and at the same time have the potential to improve the model forecasts for climate and numerical weather predictions for this very vulnerable area.

Acknowledgements: The NOPEX programme has received support from a multitude of sources. The core funding for NOPEX summer was the Nordic Council of Ministers and for WINTEX the European Union (ENV4-CT96-0324).

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Received 23 January 2002, accepted 5 October 2002