Land surface processes at high latitudes.

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The tundra biome covers about 7% of the land surface. In addition many of the physical processes which characterise the biome, such as snow, frozen soil and low productivity, are also important further south in the boreal zone. These regions have the potential for considerable change under a varying climate (e.g. Myneni *et al* 1997). The feedbacks between the lower atmosphere and snow will amplify the climatic effects of increasing CO_2 levels leading to the predicted increased warming at high latitudes. There are, however, other feedbacks, such as the interactions between snow and vegetation cover and the possibilty of increased carbon turnover which are not included in current climate models and which might lead to unforseen reactions to climate change (Smith & Shugart 1993).

The predominant characteristics of high latitude land surface processes, as they affect the energy and mass transfers, are listed in table 1. The predominant control is snow cover, this has an impact in both snow-free and snow covered periods. During the snow covered periods the control is direct; the high short-wave albedo, the low roughness length and the temperature limitation of the surface to below zero causes the surface fluxes to be small and the turbulent sensible heat flux to be always into the surface. The insulating effect of the snowcover also modifies the thermal structure of the underlying soil. The length of the summer 'active' season is determined by the spring melt (Harding & Lloyd 1998). At high latitudes, this occurs in May or June when the solar radiation is high and thus the persistence of the snow has a dramatic effect on the potential vegetational activity and evaporation. A second consequence of the high radiation levels occuring during melt is that this is the primary energy source for the snowmelt. The rate of this melt is limited by the radiant energy, with the result that the persistence of the snow is frequently controlled by the depth of the early spring snowpack. Thus the length of the active season and the overall summer fluxes can vary by a factor of 2 depending on the the early spring snow conditions (e.g. figure 1).

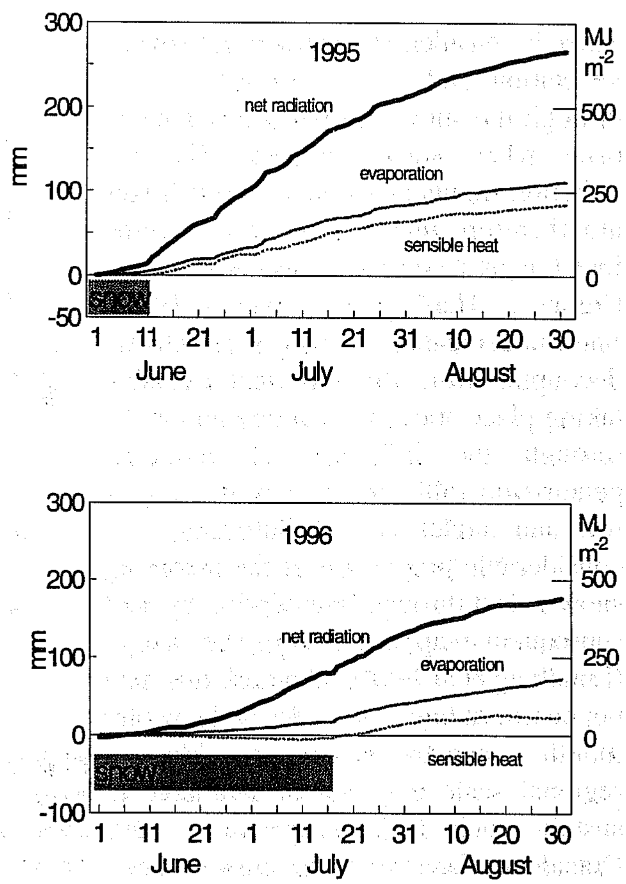

Figure 1: *The cumulative energy fluxes measured at Ny Ålesund, Svalbard for two years with very different snow conditions.*

Table 1. Characteristics of arctic surfaces:

Heteorogenity:	**small and large scale**
Snow processes:	**modifies energy balance short active season Snow melt provides a substantial input of water Interaction with vegetation**
Frozen ground and permafrost:	**Modifies energy balance Prevents water infiltration Surface erosion**
Water logging:	**Organic soils (low hydraulic conductivity) Permafrost Low annual evaporation Uniform topography**
Mosses and lichens:	**No roots Unique photosynthetic response**

There is considerable interaction between vegetation and snow. Forest extends through the snow and has a low albedo, even when snow covered. The net radiation inputs and sensible heat fluxes are therefore high for a snow covered forest in great contrast to open snow areas (figure 2, Harding & Pomeroy 1996). Snow underneath the canopy is effectively decoupled from the turbulent transfers taking place above the canopy and melts through the influence of radiation penetration (although this is limited by low sun angles at high latitudes). A considerable proportion of the incoming snow is lost through interception by, and subsequent evaporation from, the canopy (Lundberg et al 1998), although this may not be true at higher latitudes in the winter months when the energy available at a regional scale may not be available to sustain such high evaporation rates. Outside the forest blowing snow causes a substantial sublimation of snow in open and exposed areas (Pomeroy *et al* 1997). It is evident that the boreal forest/ tundra boundary is one of considerable contrast in energy and water relationships with potential for a number of sustaining feedback processes (Pielke and Vidale 1995).

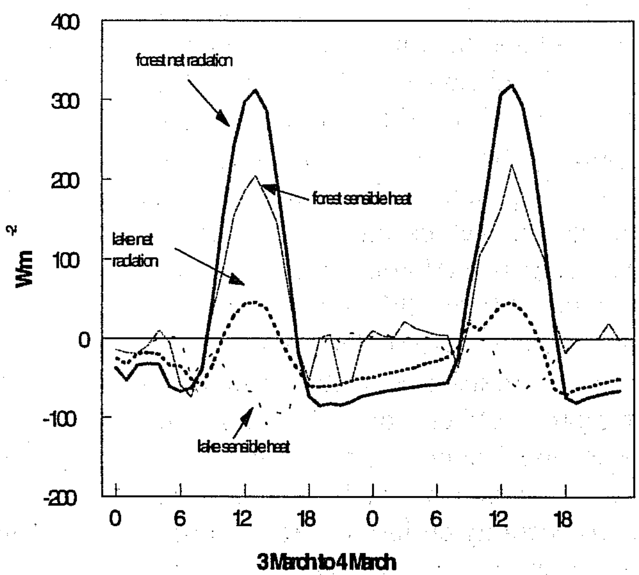

Figure 2: *Net radiation and sensible heat flux measured over Jack Pine forest and a snow covered lake in the BOREAS southern region, 1994.*

These regions experience low precipitation and the predominant input of liquid water is due to the spring snowmelt. Infitration during this time is limited by the frozen soil leading to considerable surface runoff and, more frequently, water ponding. The occurence of a permafrost layer leads to more permanent water logging, often exacerbated by the low evaporation.

Plant development and transpiration in these regions is limited by temperature and the short growing season. Lack of nutrient availability is also a significant factor but is also determined by the low temperatures limiting weathering and decomposition rates. Mosses and lichens are predominant vegetation types and these have some unique features, with no root systems or stomatal control. In such species the photosynthetic rate and evaporative loss pregressively decrease as the surface wetness decreases and bith ultimately stop when cellular moisture content reaches a low level. The vascular plants have short rooting systems (typically less than 10cm), reflecting the low evaporative demands and frequently water logged or frozen soils.

There is considerable spatial variability in tundra regions. In the high arctic the vegetation cover is low, the soils thin and the proportions of bare soil and rock high. In contrast in more southern regions there are huge areas of thick peat bog with a continuous cover of vegetation. In both regions the vegetation and soil cover can be locally quite variable, depending on the topography and hydrology.

The properties of the organic peat soils are unique. Their thermal capacity is high, particularly when water logged, and their thermal conductivities low. Their water holding capacity and hydraulic conductivity depend strongly on depth from the surface. In the surface layers active, or at least undecomposed, mosses occur, these hold comparatively little water and are very permeable and behave in a similar manner to sandy soils. At depth the hydraulic conductivities decrease (by as much as a factor of 1000) and are essentially impermeable (see e.g. Boelter 1965). It is quite likely that these characteristic thermal and hydraulic properties may have to be uniquely represented in numerical models.

A small but useful number of land surface experiments have been undertaken in the Arctic and a number of others are planned under the sponsorship of IGBP or GEWEX. The primary focus of the majority of these experiments has been the carbon budget and its possible response to climate change but radiation, energy and water fluxes are available and should provide a basis for a better description of arctic surface in numerical prediction models.

<u>ARCSS-LAI</u>

This is a study based on the north slope of Alaska with measurements made on a transect between Prudhoe Bay and Toolik lake. Measurements started in 1983, initially with chambers to measure carbon dioxide fluxes but in recent years the whole range of flux measurements have been made using eddy correlation at a number of sites, along with permafrost and meterological measurements. Efforts to spatially extrapolate the measurements have included the use of flux measuring aircraft and hydrological models. (Web site: http//sonofsun.sdsu.edu/gcrg/).

<u>Makenzie Basin GEWEX Study (MAGS)</u>

The objectives of MAGS are to understand, quantify and model the critical components of the energy and water cycles that affect the climate of the Mackenzie Basin and to improve our capability to model the water resources in the basin. The programme contains extensive climatological and hydrological modelling and process studies at sites in the tundra and boreal forest areas. Point process studies and small catchment experiments are planned at tundra site

(Inuvik), a discontinuous tundra site (Fort Simpson) and a mountain tundra site (Wolf Creek). At these sites snow, evaporation and permafrost studies will take place. Modelling studies have started on the Mackenzie Basin; the processes measurements will take place from 1997 to 1999. (Web site: http://www.dow.on.doe.ca/GEWEX/gewex_homepage.html/).

BOREAS

BOREAS is an experiment in the Canadian boreal forest. There are two experimental areas, one at the southern edge of the Boreal Forest in Saskatchewan and one at the northern edge in Manitoba. During 1994 and 1996 an extremely comprehensive set of flux, meteorological and physiological data were taken. Some of the sites are being maintained for long-term monitoring. Although not strictly arctic these sites do represent conditions which might pertain following global warming (see Sellers *et al*, 1996).

Understanding Land Arctic Physical Processes (LAPP)

LAPP is an experiment designed to improve our understanding of the effect of global warming on water, carbon dioxide and methane balances in the European Arctic. Detailed studies of surface climatology, micrometeorology and surface hydrology are being made at four sites: Ny-Ålesund in Svalbard, Zackenberg in east Greenland, and Kaamanen and Kevo in Finland. Automatic Weather Stations are being run continuously at all sites while measurements of the surface fluxes of energy, water and carbon are being measured during summer periods, from before the snowmelt through to the autumn. Soil climate, water balance and permafrost measurements are also being made (Lloyd *et al* 1996). Measurements at some sites started in 1995 and by 1997 the full suite of measurements were operational.

GEWEX Asian Monsoon Experiment (GAME)

GAME is a programme to improve our understanding and description of the Asian monsoon. It is looking at the role of land surface processes in four study areas - one of which is in eastern Siberia. Modelling and field campaigns are being undertaken, based around the Lena River Basin. Studies of the active layer of the permafrost, comparison of the tundra and taiga regions and studies of hydrological processes in permafrost regions are all taking place. Measurements of climate variables and fluxes are planned at a range of sites in the taiga and tundra regions and these will be coupled with aircraft and catchment measurements. There are plans for a range of atmospheric modelling on scales ranging from the very small scale cloud resolving models up to global climate models. Some measurements have started but there are intensive campaigns planned for 1998 and 1999 (see JNCP 1994).

Northern Eurasian Study (NES)

NES is a transect study sponsored by IGBP covering the boreal forest/tundra interface. The unifying theme of this study is the terrestrial carbon cycle with the overall aim of understanding how this cycle will change with global climate change. The detailed goals of NES are to predict the effect of global change: on the cycling of carbon, on the exchanges of energy and water and on the structure of the boreal and tundra ecosystems. Measurements are planned on two transects, along the Yenesei and Lena Rivers in eastern Siberia (the latter will be in collaboration with the GAME programme). The study is still in the planning stages with activities centred around a review of existing data. It is expected that process based measurements will start in 1998 and continue until at least 2000 (see Steffen & Shvidenko 1996).

SCANTRAN

This is a network of transects planned across Scandinavia, Greenland, Iceland, the British Isles and Svalbard. The focus is primarily ecological but a substantial suit of physical measurements are planned (Heal *et al* 1996).

There is a substantial amount of data to calibrate and verify land surface scheme of numerical models. However much of these data are discontinuous in space and time. The standard synoptic data are extremely patchy, although the data sets from Russia in this regard are comparatively good (as are those from Scandinavia). Satellite data has great potential in the arctic, probably with more potential than at lower latitudes. Maps of snow cover are already available and maps of snow depth are becoming increasing available from microwave sensors. Microwave sensors also have the capability to provide maps of surface soil water - a variable of particular interest in the arctic where a lot of the hydrological processes take place near the surface. A circumpolar network of detailed land surface measurements is developing as part of the land surface experiments and these should provide extensive data sets for calibration and verification. One important issue in these sets is their continuation. In the past many have been for short duration and there is a need for longer term measurements, over a number of years, or even decades.

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