Nordic Hydrology, 29 (4/5), 1998, 267-284

Fluxes of Water and Energy from Three High Latitude Tundra Sites in Svalbard

Paper presented at the 11th Northern Res. Basins Symposium/Workshop
Prudhoe Bay to Fairbanks, Alaska, USA – Aug. 18-22, 1997

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Measurements of the surface fluxes of radiation, heat and water vapour were made at three tundra sites near Ny-Ålesund, Svalbard for the active seasons (June to September) of 1995 and 1996. In 1995 the snow melted completely in early June, in 1996 the deeper snow pack resulted in the persistence of snow until July. Thus the snow free period was 50% longer in 1995 resulting in larger cumulative evaporation and energy inputs. In this region the snow melt is dominated by radiation input, a result of the low air temperatures and possible control of the air temperature by the surrounding sea, snow and ice fields. During the snow-free period the evaporative ratio [$LE/(LE+H)$] varied with surface type. At two sites, where there was a continuous cover of soil, the evaporative ratio was consistently equal to 0.5, except for a few days after rainfall when it rose to unity. This latter rise was probably due to the increased evaporation from the soil, mosses and lichens after wetting by rainfall. At a third site, with a predominantly stony surface, the evaporative ratio was lower (between 0.2 and 0.3), again rising during and after rainfall. The measurements from 1995 show the summer evaporation was 160% of the summer rainfall. However there was no evidence of a reduction of evaporation during extended dry periods. In 1996 the radiation inputs and evaporation were much reduced by the shorter active season and rainfall exceeded evaporation. The timing of the snow and snowmelt and thermal condition of the surface layers is thus important to the hydrology, the surface energy balance and the carbon balance of this region.

Introduction

Sensitivity studies with Global Climate Models suggest that the atmospheric warming due to increasing CO_2 levels will be greatest at high latitudes (*e.g.* Kattenberg *et al* 1996). This is primarily because of the strong positive feedback between the air temperature, ice and the snow cover at these latitudes. There are, however, other possible feedbacks involving the carbon stores in the arctic which may release greenhouse gases (CO_2 and CH_4) following an atmospheric warming (Smith and Shugart 1993), which are currently not included within the GCM sensitivity studies. However the integrated response of the arctic biome to climate change is largely unknown because increased carbon fixation, associated with enhanced growth and change of species composition, may also accompany the increased decomposition of carbon stores following a climate warming. Changes in the permafrost and soil moisture will also have a strong influence on carbon release due to decomposition and plant growth. What is clear is that the various basic meteorological and hydrological states, such as snow cover, soil moisture, energy balance and permafrost state, play an important and controlling role in the arctic biome.

The annual energy balance in the tundra is strongly controlled by the snow cover. The high albedo reduces the radiation input and the smooth surface reduces the turbulent fluxes (see *e.g.* Harding *et al.* 1995). In addition, during the melting phase a large uniform snow surface may keep the surface air temperature at, or near to zero, further restricting the turbulent heat fluxes (for more discussion see Harding *et al.* 1998). During the snow free period net radiation can be large, in excess of 10 MJ m^{-2} day^{-1} (*e.g.* Rott and Obleitner 1992) and the total summer evaporation frequently exceeds the summer rainfall (Ohmura 1982). However, soil moisture frequently limits the evaporation (Rott and Obleitner 1992) although there can be considerable variability of soil moisture and the consequent evaporation (Harding *et al.* 1995; Saunders and Bailey 1994). Typical Bowen ratios of 1 are commonly observed at sites which are well supplied with soil moisture (see *e.g.* Rott and Obleitner 1992; Ohmura 1982; Fitzjarrald and Moore 1992). Rouse *et al.* (1987) demonstrate a strong temperature dependence of the bowen ratio in the Hudson Bay area (with high Bowen ratios, *i.e.* low evaporation, at low temperatures). This behaviour was not observed by Fitzjarrald and Moore (1992) in Alaska who suggested that the difference in behaviour may have been because of a difference in the surface type (sedge in the Hudson Bay area and lichens and mosses in the Alaskan study). Ostendorf (1996) demonstrated that variability in the vegetation community and soil moisture affects not only the mean evaporation but also the carbon dioxide exchanges.

As part of a wider study into the water, energy and carbon balance of European arctic sites two years of surface flux measurements (1995 and 1996) were made at a number of maritime, high arctic sites in Svalbard during the summer seasons. This paper presents the water and energy fluxes obtained from these measurements. Because snow is such an important feature of the landscape in the high arctic, the paper includes a detailed description of the snow state and melt for the two years and energy balance of the snow surface prior to and during the melt. Surface flux and snow measurements are presented for three sites close to Ny-Ålesund, Svalbard to demonstrate the high variability which can be found in this region.

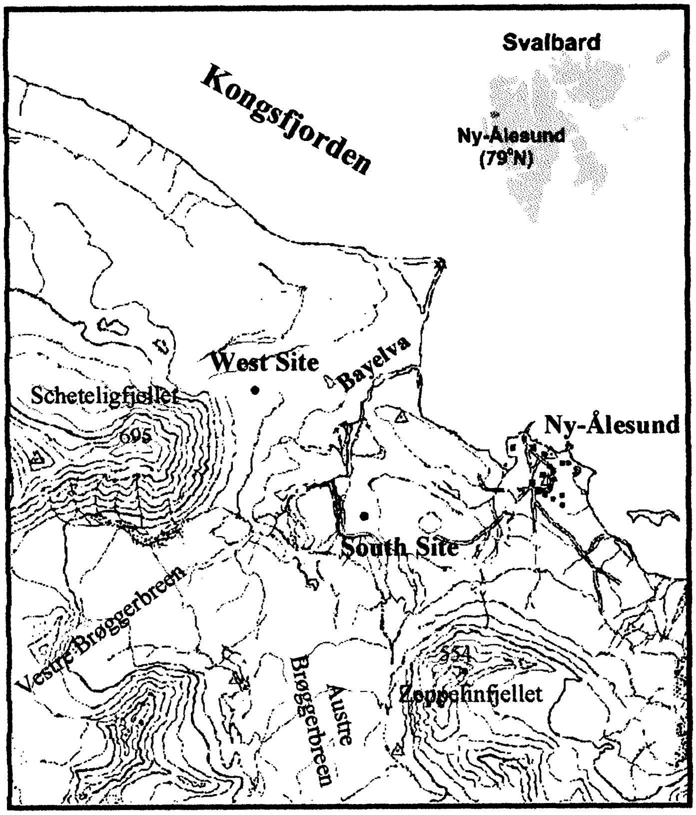

Fig. 1. Map of Svalbard and sites.

Sites and Equipment

The measurement sites were located on the coastal plain to the north and east of Ny-Ålesund, Svalbard (Lat. 78° 56', Long. 11° 55'). The measurement sites are described in detail in Lloyd *et al.* (1996) and only relevant details are included here. Measurements were taken at three locations (see Fig. 1): on a 5° north facing slope of approximately 200 m in length at the south site (south site slope), on an adjoining flat region (south site flat) and on a gently undulating plateau region at a site approximately 2 km north-west of the south site (west site). The surface covers at all the sites are a mixture of low vascular plants (*Luzula, Saxifraga oppositifolia*), lichens, mosses and bare soil. The vegetation at the south sites is described as a *Luzula* lichen heath (Norsk Polar Institutt 1980). The soil on the south site slope is a thin (0.02m) organic soil overlying clay silt with stone stripes. At the south site flat, the soil again is a thin organic soil but now overlying schist and psammite gravels. The west site has sparser vegetation described as 50-10% *Saxifraga oppositifolia* lichen heath (Norsk Polar Institutt 1980) on a 'soil' surface largely composed of carboniferous limestone gravel and boulders.

Measurements of weather, surface runoff, soil temperature and soil moisture were made at a central position on the south site slope for the whole period. Eddy correlation measurements of heat and water vapour were made at the south site flat during the snow free periods of both years. Eddy correlation measurements were also made during the snow melt period at the south site flat in 1995 and at the west site in 1996. The reasons for the change of measurement site in the snow melt period of 1996 was to investigate the effect of the greater snow patchiness at this site (compared with the south site flat). Extensive snow depth measurements were made at all three sites in 1995 and at the west site in 1996.

During 1995 surface fluxes were also measured at the south site slope and at the west site using two Bowen Ratio systems (Cambell Scientific Ltd, Shepshed, UK), with sensors at 0.5 m and 1.5 m above the surface. As an integral part of these systems, measurements of net radiation (using a Radiation Energy Balance Systems, Seattle, Washington, USA, model Q*6 radiometer) and soil heat flux (using 2 soil heat flux plates, Thornthwaite, New Jersey, USA, at 8 cm depth with soil temperature measurements at 2 and 6 cm) were included. Table 1 lists the flux measurements made at the three sites.

The eddy correlation measurements described here were made using the Hydra MkII portable eddy correlation system described by Shuttleworth *et al.* (1988). This comprises a 1D sonic anemometer, a lightweight cup anemometer, a fine thermocouple and a infrared hygrometer coupled to an online computer for the calculation of surface fluxes. The sonic anemometer was mounted vertically at 3.2 m. As well as

Table 1 – Deployment of flux measurements in 1995 and 1996.

	1995	1996
SNOW		
South site slope	Bowen ratio	-
South site flat	eddy correlation	-
West site	Bowen ratio	eddy correlation
SNOW-FREE		
South site slope	Bowen ratio	-
South site flat	eddy correlation	eddy correlation
West site	Bowen ratio	-

the measurement of the fluxes of heat and water vapour the system also provides measurements of momentum flux, net radiation, air temperature, humidity and wind speed. Short wave albedo measurements were provided by the automatic weather station on the south site slope and also by a weather station at the west site.

At the south site flat, where the majority of the eddy correlation measurements were made, the uniform and horizontal fetch is at least 150 m in all directions, with gentle hillslopes beyond this. A footprint analysis using the method of Lloyd (1995) indicates that between 75 and 95% of the flux comes from this flat area (depending on stability). Thus, although the site is not perfect from the micrometeorological point of view, the majority of the flux came from the uniform area and the effects of advection were assessed as minimal. The uniform region surrounding the flux measurement at the west site is larger than at the south site and therefore the advection effects would be even smaller. This latter site is undulating, with changes in elevation of approximately 2 m, however the Hydra was only operated when snow covered the ground, when the variable snow cover smoothed out this variation.

Meteorological Conditions during 1995 and 1996

Figs. 2 a and b show the 24-hour average albedo, the hourly air temperature (at 1.2 m) and the daily rainfall totals for the measurement periods in 1995 and 1996, from the beginning of June to the first week in September, as measured at the south sites. The low albedo defines the snow free period (85 days for 1995 and 43 days for 1996). In 1996 the snow free period was shortened by a later melt and snow showers in mid August. The curtailment in August 1996 was of less importance to the overall energy balance than the later spring melt because by mid August the radiation inputs were low (solar radiation less that 10 MJ m^{-2} day^{-1}) and the air temperature has dropped to less than 5°C. The albedo was most evidently influenced by the snow cover but there were changes during the snow free period, from the very low value of 0.08 immediately following the melt, increasing to 0.12 later in the season. There is very little seasonal growth of vegetation at this latitude and the decrease through the season is likely to be the effect of the drying of the surface soil, which was saturated immediately following melt and was observed to dry out during prolonged dry periods.

The hourly air temperature was remarkable for its lack of variation, this was particularly marked through the prolonged snow melt period of 1996 when for a month the hourly air temperatures varied only between 0 and 5°C. The air temperature rose after the snow melted, but only to between 5 and 10°C. The relative humidity (not shown) was also fairly constant, averaging 81% (with a standard deviation of the hourly values of only 8.7%). The soil temperature measurements at the south site show that the permafrost thawed through the summer to below 0.8 m in both 1995 and 1996.

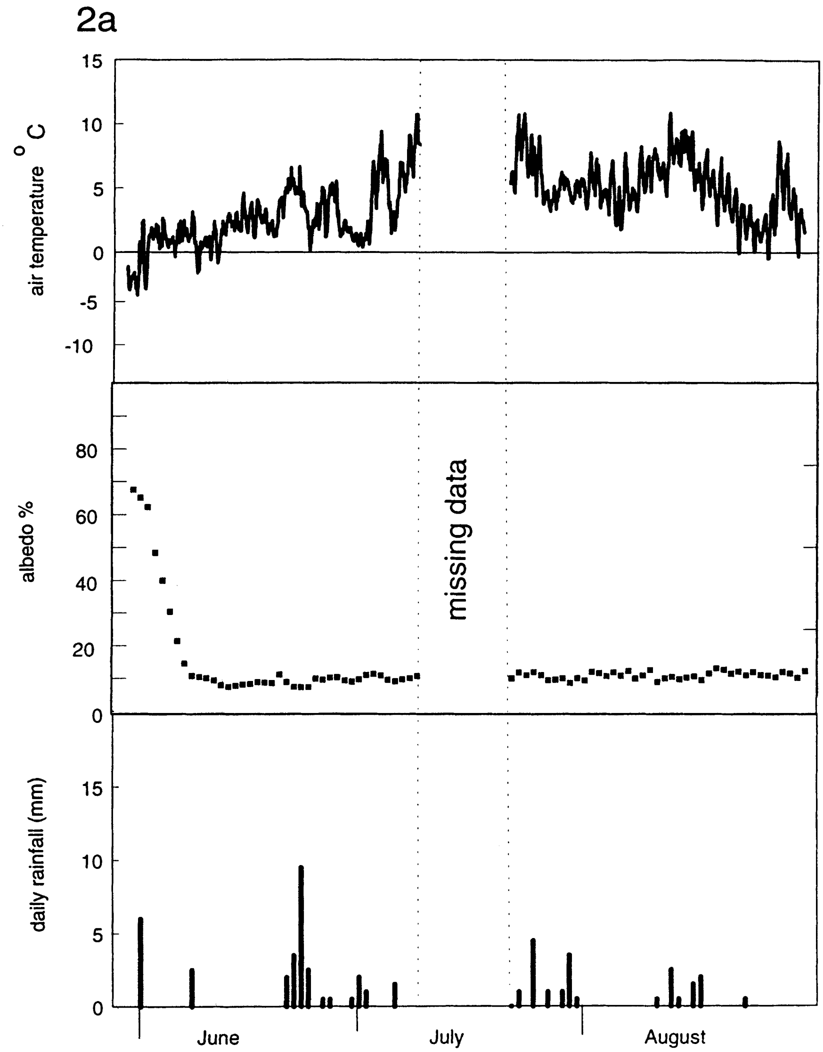

Fig. 2. a) Mean hourly air temperature and daily albedo and rainfall for June to August 1995.

The rainfall during the summer period (June to August) was low (59 mm in 16 rain events in 1995 and 114 mm in 13 rain events in 1996) with each event giving 10 mm or less of rain. (A rain event is defined here as a period of rain, possibly with gaps in it insufficient to dry the surface.) Generally the rainfall intensities were light.

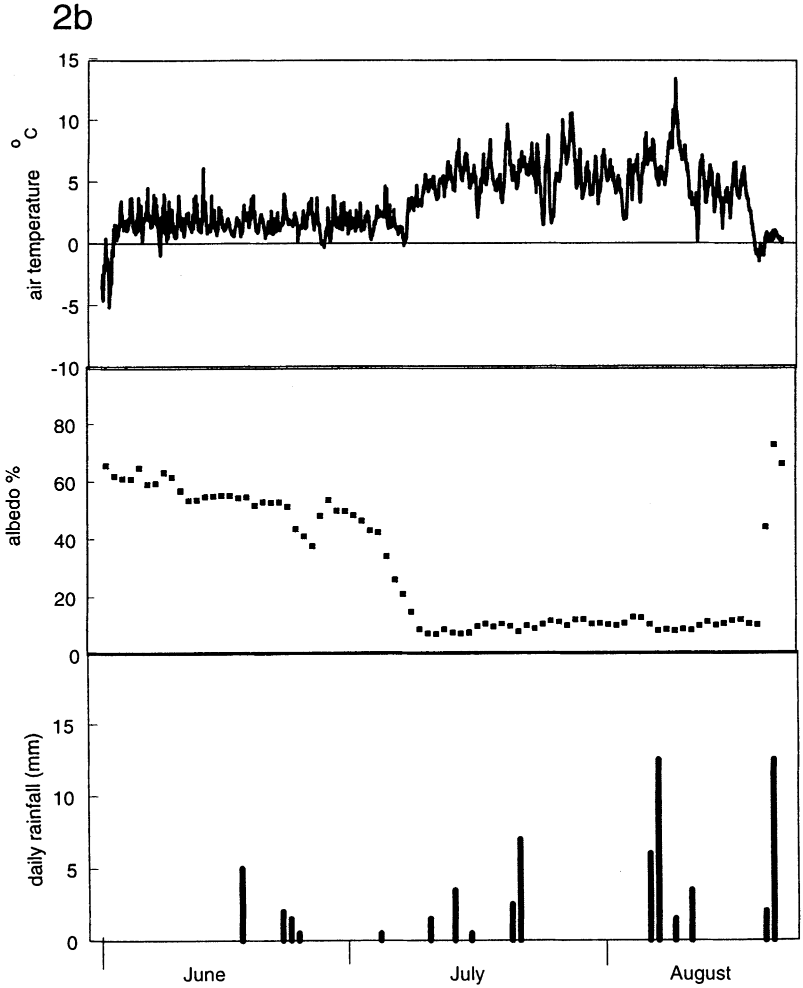

Fig. 2. b) Mean hourly air temperature and daily albedo and rainfall for June to August 1996.

Snow Period Melt and Energy Balance

In 1995 a network of snow stakes were measured daily at all three sites. These networks were: a grid of 10 by 6 stakes with 10 m spacing centred on the weather station on the slope at the south site. At the south site flat a transect of 21 stakes orientated north/south, again with 10 m spacing and centred on the Hydra and at the west site a grid of 6 by 11 stakes again with 10 m spacing centred on the weather station. In 1996 only the west site stakes were measured. Periodic snow density measurements were made at all sites. The mean snow density was 0.44×10^3 kg m^{-3} with no evidence of a variation between sites. These extensive networks provide information

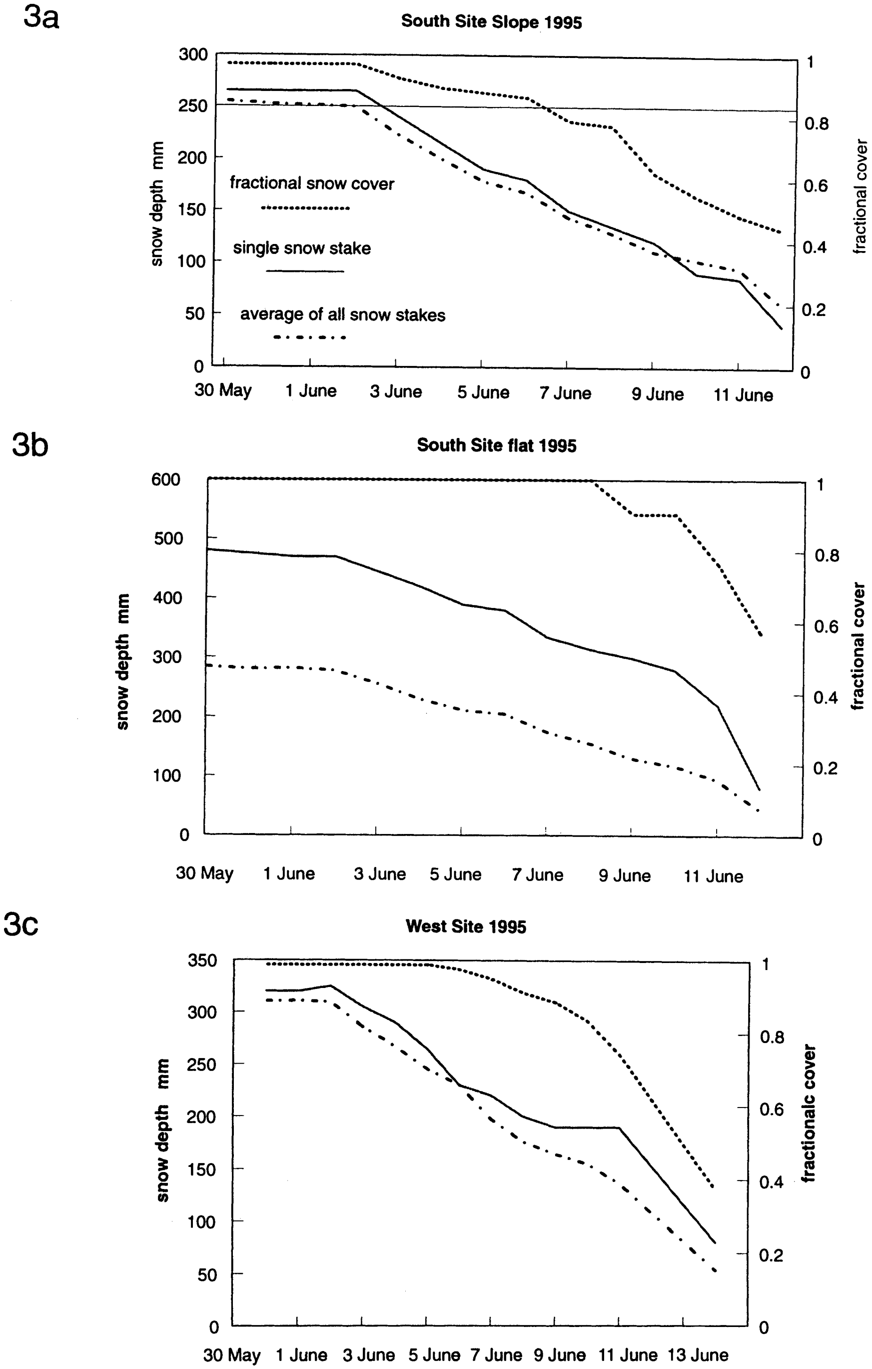

Fig. 3. a) to c) Changes of snow depth and snow coverage at the three sites for 1995.

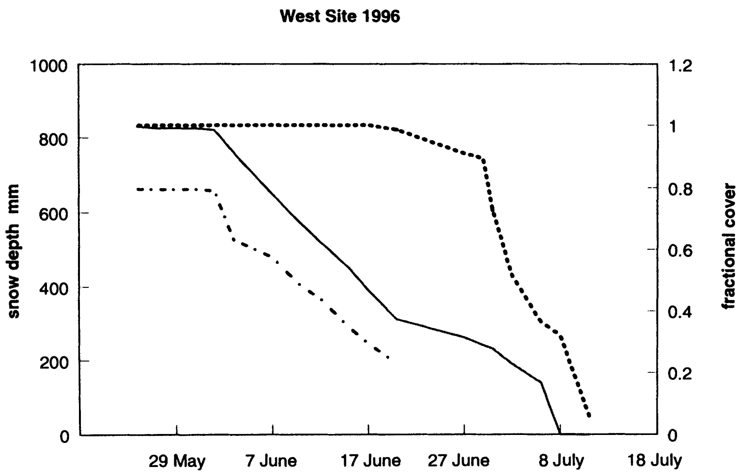

Fig. 4. As Fig. 3 but for west site in 1996.

on the change in snow depth and development of snow free areas. Figs. 3 a-c and 4 show the mean snow depths, averaged over all the stakes, plus the percentage of the stakes with measurable snow and the depth at a single stake, chosen because it was in snow for the entire period (and thus gave an estimate of melt in the snow patches).

In 1995 at the beginning of June, the mean snow depths at the three sites ranged from 250 mm to 300 mm, with the greater snow depths at the west site. Persistent snow melt appears to have started on 2 June at all sites. Immediately bare patches began to develop on the south site slope. In contrast, on the south site flat, the snow remained continuous until 9 June by which time the snow depth had reduced by more than half, to 120 mm. The west site showed intermediate behaviour, with bare patches appearing on the 7 June. It might have been expected that snow at a patchy site would melt faster with the local advection of sensible heat from snow free patches. However, there was no evidence that the development of patches affected the rate of snow melt at least in the early part of the melt. This was noticeable from the comparison of melt rates at south site (Fig. 5). Towards the end of the melt period the rate of decrease in the mean depth was greater at the flat site with more continuous snow, the result of a larger number of snow stakes within snow at this site. Overall, from 2 June to 12 June, the rate of decrease was fairly uniform at between 19 and 20 mm per day, equivalent to between 8.4 and 8.8 mm water equivalent of melt per day.

In 1996 the snow was deeper at all sites. At the west site the mean snow depth was 670 mm at the beginning of June. The melt again started in the first week of June with a similar rate of decrease, 20 mm per day. However, because of the large snow depth, the snow persisted into July. The snow became patchy on 21 June, when the snow depth had reduced to 200 mm (a similar level to the onset of patchiness in 1995) and persisted until 8 July.

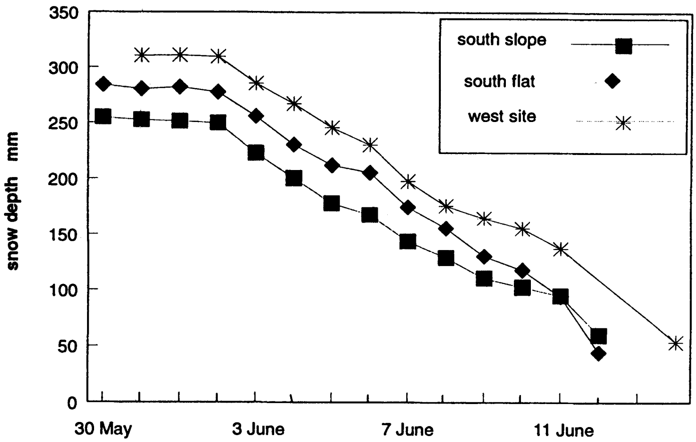

Fig. 5. Comparison of mean snow depths for three sites in 1995.

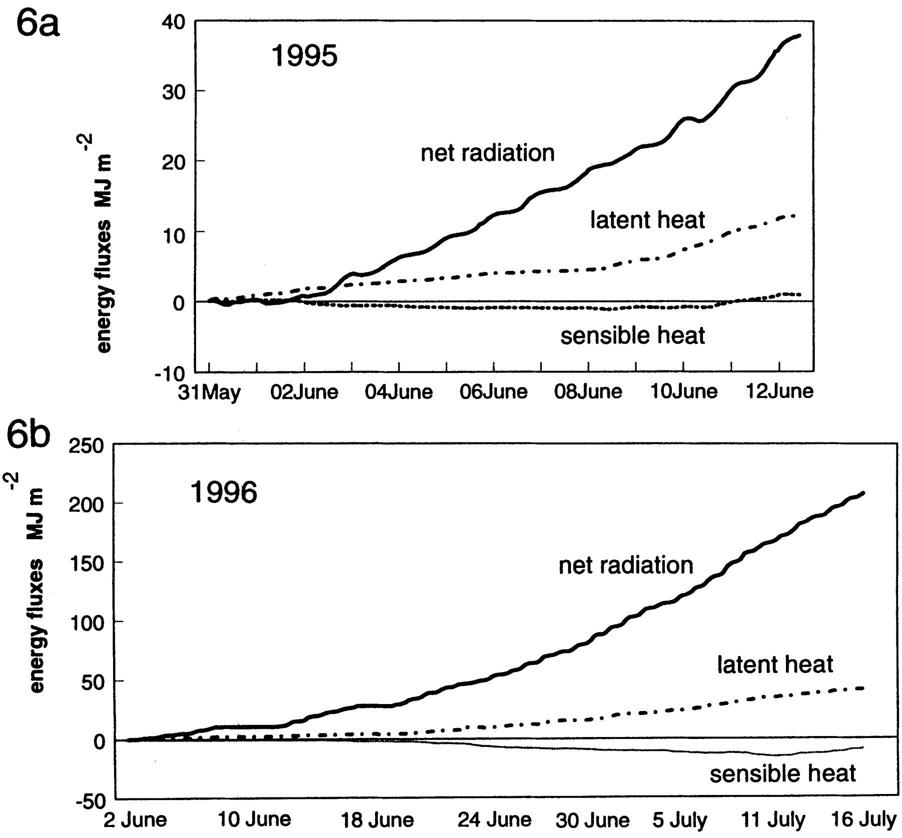

Fig. 6. a) and b) Cumulative energy components during snow melt period for a) 1995 and b) 1996.

Figs. 6 a and b show the cumulative turbulent fluxes and net radiation for the 1995 and 1996 snow melt periods. The two years show similar characteristics. The sensible heat flux is very low and negative (into the snow) in the main part of the melt period; only becoming positive at the end of the melt when the snow has become patchy but still it has little role in the energy budget of the snow pack. The net radiation provides the majority of the energy for the melt, appr. 4 MJ m^{-2} day $^{-1}$, enough to melt 12 mm water equivalent of snow per day. The evaporation uses between 20 and 30% of the net radiation, but in terms of quantity of water evaporated this is small. The balances of the measured energy fluxes show a reasonable agreement with the measured melts, accumulated over the melt periods for 1995 and 1996 (Tables 2 a and b). The agreement is particularly good considering the uncertainties in the liquid water within the snow pack, in the ground heat flux and in the density of the snow. It should be noted that during the 1996 melt season there is a two day gap in the measured turbulent fluxes which has been ignored in Table 2b, however given that the turbulent fluxes are small, and of opposite sign, the effect of this gap on the overall energy balance is likely to be small.

Similar values for the snowmelt energy balance at Ny-Ålesund were found by Nakabayashi *et al.* (1996). In their study snowmelt and net radiation were measured but the turbulent fluxes estimated from aerodynamic formulae. In a single year (1993) 69% of the of the total snowmelt was provided by the net radiation, with typical net radiation inputs of 3 to 4 MJ m^{-2} day^{-1}, figures comparable with this study.

Table 2 – Measured energy components and measured snow melt (in units of MJ m^{-2} and mm of equivalent snow melt) accumulated over main snow melt period in :
a) 1995 (2 June to 12 June) at the south site flat,
b) 1996 (31 May to 21 June) at the west site.

a.	Total energy ($MJ\ m^{-2}$)	Total melt equivalent (mm)
net radiation (Rn)	37.8	113
latent heat flux (L.E)	11.1	33
sensible heat flux (H)	-0.76	-2.3
measured snow melt	28.0	84
Rn-L.E-H	25.9	77
b.	**Total energy ($MJ\ m^{-2}$)**	**Total melt equivalent (mm)**
net radiation (Rn)	60.9	182
latent heat flux (L.E)	6.7	20
sensible heat flux (H)	-4.9	-15
measured snow melt	69.5	208
Rn-L.E-H	59.1	177

The predominance of radiation as an energy source for melt results in similar melt rates in the two years (and in the two years studied by Nakabayashi *et al.* 1996); the longer persistence of snow in 1996 is due solely to greater accumulation of snow through the winter and early spring.

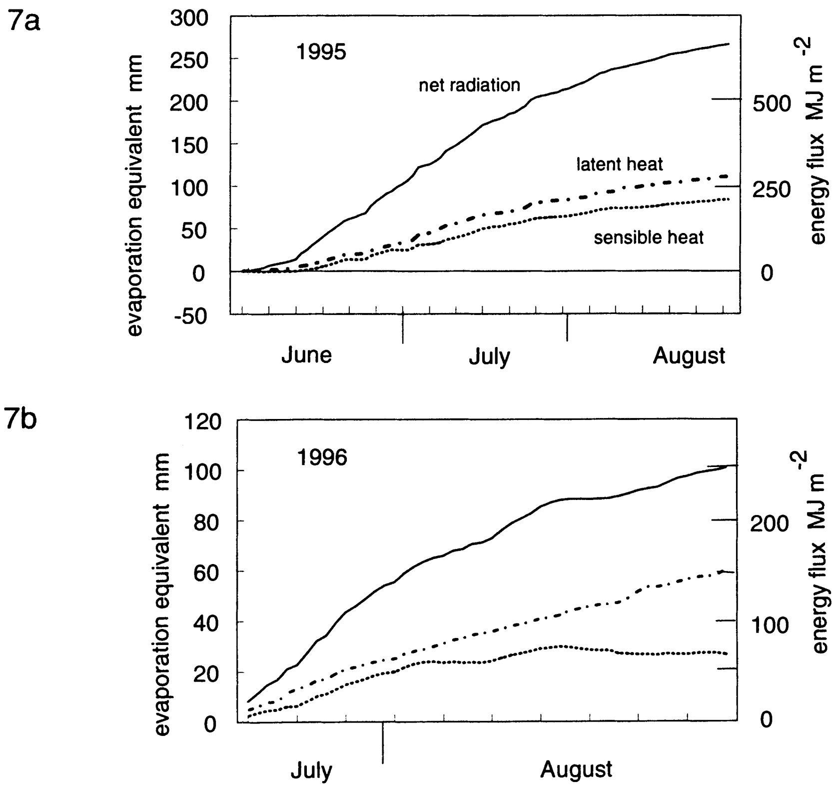

Fig. 7. a) and b) Cumulative energy components during snow free periods, in terms of mm evaporation and MJ m^{-2}, for a) 1995 and b) 1996.

Snow Free Period

Figs. 7 a and b show the net radiation and the turbulent fluxes in the two years accumulated through the active season from the hourly data, as measured by the eddy correlation equipment at the south site flat. There are a small number of bad data points, primarily associated with rainfall which interferes with the flux measurements, which constitute less than 5% of the total flux and have been put to zero. The cumulative evaporation was between 40 and 50% of the net radiation and slightly in

8a

8b

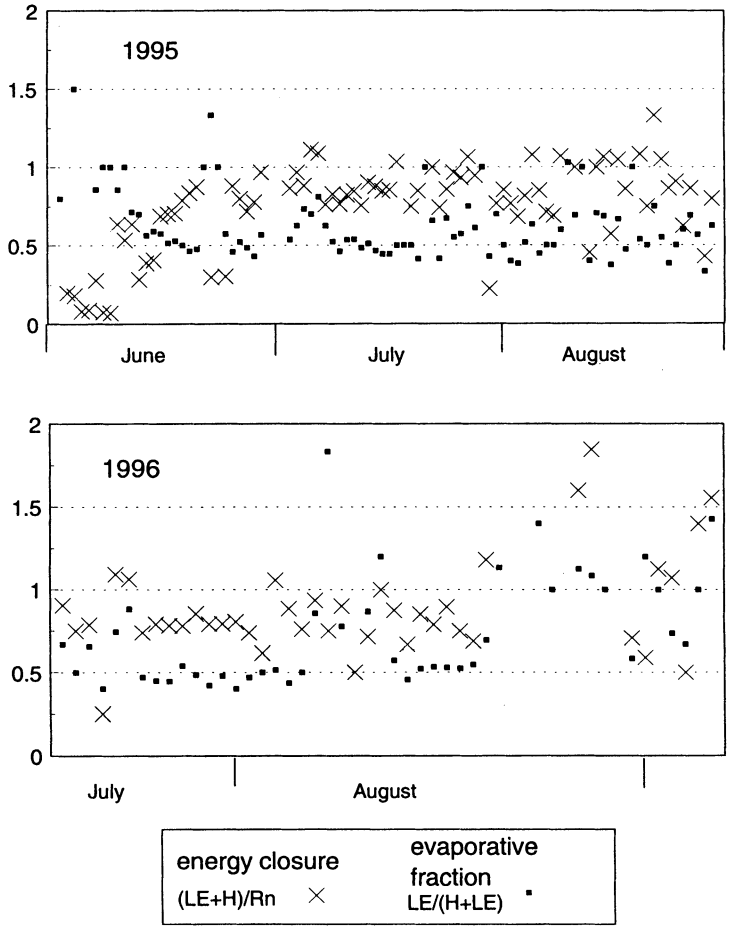

Fig. 8. a) and b) Evaporative fraction and energy closure measured using daily eddy correlation and net radiation measurements for a) 1995 and b) 1996.

excess of the sensible heat flux. It was evident that the sum of sensible and latent heats were less than the net radiation input. The excess energy almost certainly went into heating the soil and melting the permafrost (see discussion of soil heat flux below). The energy partition described here is consistent with flux measurements made by Scherer (1992) at Liefdefjorden, on the north coast of Spitsbergen island. For a 38-day period during July and August 1990 Scherer reported a total net radiation of 300 MJ m^{-2}, a latent heat of 180 MJ m^{-2} (60% of net radiation) and a ground heat flux of 40 MJ m^{-2} (13% of net radiation).

Figs. 8 a and b show the daily energy closure, $(LE+H)/Rn$, and the daily evaporative fraction, $LE/(LE+H)$. The energy closure confirms the previous finding that only about 80% of the net radiation was accounted for by the turbulent fluxes. The evaporative fraction showed a very characteristic pattern. The usual value was approximately 0.5, which rose periodically to nearer one during and following rain events. (There was also some tendency for the energy closure ratio to be nearer to one during these periods.) The increased evaporative fraction following rain was due to increased bare soil evaporation and increased evaporation from the mosses and lichens. The constancy of the evaporative fraction during the dry periods was probably a result of the fairly uniform climate, particularly in terms of temperature and humidity, with no obvious reduction during dry periods suggesting no influence of water stress on the vascular plants. The evaporative fraction rose to above one following the snow falls in mid August 1996; the result of the sensible heat becoming negative during this period.

The overall water and energy balance for the snow free periods (Table 3) shows that in 1995 the evaporation exceeded the rainfall by a factor of two. However despite this the evaporative ratio did not drop below 0.5, even during extended dry periods (Fig. 8), indicating that the soil water storage is sufficent to maintain transpiration. The rainfall in 1996 was similar to 1995, but in half the period, and in 1996 the evaporation was less than the total rainfall. The surface runoff measured from the runoff plots at the south site slope (not shown) was small during the snow free period (less than 15 mm).

Table 3 – The accumulated net radiation, evaporation and sensible heat (in terms of mm evaporation) and rainfall (mm), for the snow free periods (12 June to 4 Sept. in 1995 and 17 July to 21 August 1996).

	1995	1996
net radiation	245	88
evaporation	105	45
sensible heat	83	29
rainfall	43	53

The Spatial Variability of Fluxes

Fig. 9 shows the daily mean evaporative fraction ($LE/(LE+H)$) calculated from the bowen ratio equipment. The south site slope measurements show a similar behaviour to the eddy correlation measurements (*c.f.* Fig. 8a), with values near to one during the snow period and centred on 0.5 during the snow-free period, with some tendency to rise during and following rainfall periods. In contrast at the west site the ratio was between 0.2 and 0.3, except during rainfall when it rose to above 0.5 (being similar to the west site during these periods). The lower ratio at the west site was presumably due to the preponderance of bare stone and lichens, with very few rooted vascular plants. Thus the surface would be expected to dry out very quickly after rainfall.

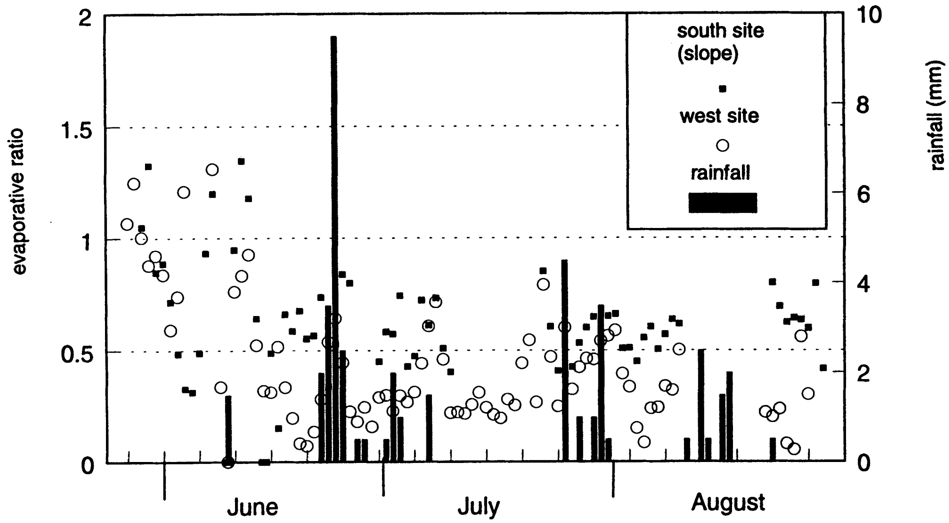

Fig. 9. Daily values for evaporative ratio for south site slope and west sites calculated from Bowen ratio measurements for 1995.

The totals of net radiation are similar at all sites, the two south sites were very close, with a range of only 3%. At the west site the net radiation was 8% lower, a result of the higher snow-free albedo measured at this site. Ground heat flux, *G*, was measured directly at the south site slope and the west site. At the west site *G* was 14% of net radiation, over the snow-free period in 1995 – a figure entirely consistent with the energy closure ratio found from the eddy correlation. At the south site slope the *G* measured by the soil heat flux plates was unrealistically high (60% of the net radiation), suggesting an error in the measurement. A calculation from the temperature profiles from thermocouples in the upper layer of the soil at this site (Lloyd 1998), following the method of Campbell (1985) gives a *G* of 11% of net radiation, *i.e.* close to that of the west site. Thus it seems very likely that the soil heat flux is between 10 and 15% of net radiation for the snow free period and this heat goes towards heating the soil and melting the ice in the active layer through the summer.

Discussion and Conclusions

Measurements of the energy balance of a maritime high arctic surface are presented for two summer seasons, 1995 and 1996. One very obvious feature is the controlling influence of the snow pack on the overall energy and water balance, with very low turbulent fluxes and comparatively low net radiation input during the period of snow cover. There was considerable contrast in the fluxes between the years. Although the melt rates and timing of the onset of melt were similar for the two years, there was a much greater snow depth in the spring of 1996 so the snow persisted into July reducing the active, snow free period to 43 days.

It seems likely that the air temperature is determined by the temperature of the nearby sea, perhaps modulated to some extent by the snow covered land surface. The air temperature remained remarkably constant, between 0 and 5°C, during the snow melt. After the snow melted the air temperature rose to between 5 and 10°C. The low and uniform air temperature during snowmelt certainly restricted the sensible heat flux into the snow pack and appears to be a characteristic of continuous melting snow packs (Harding *et al.* 1998). The result was that the snowmelt was radiation driven and the melt rates are similar in both years. The date for the final disappearance of the snow is determined by the amount of snow remaining at the end of the winter.

The accumulated active season fluxes of heat and water vapour were in turn determined by the length of the snow free season. During this period a substantial fraction (approximately 15%) of the net radiation was used to melt the frozen ground. The latent heat flux was generally about equal to the sensible heat flux, except during and for a few days after rainfall, when all the radiant energy input went into driving the evaporation. Presumably during these latter periods the bare soil, lichens and mosses were wet, leading to a very low effective surface resistance. With substantial amounts of exposed bare soil and shallow rooted vegetation it might have been expected that the evaporative fraction would reduce during the intervening dry periods, however the evaporative ratio does not drop during the dry periods despite the evaporation exceeding the rainfall by a factor of two during 1995. It is evident that the water stored in the soil is sufficient to maintain the evaporation; although some overall drying of the soil profile at the south site slope is indicated by Lloyd (1998).

The distributed flux measurements show considerable variability between sites. After the snow has melted similar evaporative ratios are observed at the two southern sites, which both have thin, but continuous organic soil and a good proportion of vascular plants. In contrast at the west site the surface in dominated by bare stone and lichen and this results in an evaporative ratio of approximately one half that of the other two sites. However directly after rainfall the evaporative ratio is similar at all sites. The ground heat flux is large at all sites – to supply the heat required to melt the frozen soil water during the active season, but there appears to be considerable variation, depending on soil type. There is obviously a need for a calibrated realistic surface model to describe these energy and water transfers – this will be the subject of the next stage in the analysis of these data.

Acknowledgements

The authors would like to thank the field workers from the Institute of Hydrology who assisted with the observations during the two years, in particular Tim Kyte, who ably oversaw the shipping and handling of the equipment. We would also like to thank Nick Cox, Station Manager of the NERC Arctic Station at Ny-Ålesund, who helped in innumerable ways in the shipping and installation of the equipment. The 1995 field season was funded by NERC. The 1996 field season was partially funded through the EU supported LAPP programme (Contract No. ENV4-CT95-0093).

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Received: November, 1997
Accepted: April, 1998

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