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Shrub tundra snowmelt

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Abstract:

Observations of land surface and snowpack energetics and mass fluxes were made over arctic shrub tundra of varying canopy height and density using radiometers, eddy covariance flux measurements, and snow mass changes from snow surveys of depth and density. Over several years, snow accumulation in the shrubs was found to be consistently higher than in sparse tundra due to greater retention of snowfall by all shrubs and wind redistribution of snowfall to tall shrubs. Where snow accumulation was highest due to snow redistribution, shrubs often became buried by the end of winter. Three classes of shrub-snow interactions were observed: tall shrubs that were exposed over snow, tall shrubs that were bent over and buried by snow, and short shrubs buried by snow. Tall shrubs buried by snow underwent 'spring-up' during melt. Though spring-up was episodic for a single shrub, over an area it was a progressive emergence from early to mid melt of vegetation that dramatically altered the radiative and aerodynamic properties of the surface. Short shrubs were exposed more rapidly once snow depth declined below shrub height, usually near the end of melt. Net radiation increased with increasing shrub due to the decreased reflectance of shortwave radiation overwhelming the increased longwave emission from relatively warm and dark shrubs. Net radiation to snow under shrubs was much smaller than that over shrubs, but was greater than that to snow with minimal shrub exposure, in this case the difference was due to downward longwave radiation from the canopy exceeding the effect of attenuated shortwave transmission through the canopy. Because of reduced turbulent transfer under shrub canopies and minimal water vapour contributions from the bare shrub branches, sublimation fluxes declined with increasing shrub exposure. In contrast, sensible heat fluxes to the shrub surface became more negative and those to the underlying snow surface more positive with increasing shrub exposure, because of relatively warm shrub branches, particularly on clear days. From well-exposed tall shrubs, both a large upward sensible heat flow from shrub to atmosphere and a downward flow that contributed substantially to snowmelt were detected. As a result of radiative and turbulent transfer in shrub canopies, melt rates increased with shrub exposure. However, shrub exposure was not a simple function of shrub height or presence, and the transition to shrub-exposed landscape depended on initial snow depth, shrub height, shrub species and cumulative melt, and this in turn controlled the melt energetics for a particular site. As a result of these complex interactions, observations over several years showed that snowmelt rates were generally, but not always, enhanced under shrub canopies in comparison with sparsely vegetated tundra. Copyright © 2006 Crown in the right of Canada. Published by John Wiley & Sons, Ltd.

KEY WORDS shrub tundra; snow accumulation; snowmelt; blowing snow; net radiation; sensible heat flux; sublimation; arctic; Yukon

INTRODUCTION

Snowmelt is the major annual hydrological event in the sub-arctic and arctic, and provides from 40 to 90% of the annual flow of freshwater to streams, lakes and oceans at high latitudes. The reduction in surface albedo (from ~0·9 to ~0·1) associated with ablation of seasonal snow cover profoundly affects regional climate and

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weather patterns (Viterbo and Betts, 1999). Large areas of the global surface are covered with both seasonal snow cover and vegetation; for instance, boreal and sub-arctic forests cover over 20% of land and are snow covered for over 6 months per year. The processes controlling the rates and magnitude of snow ablation under vegetation canopies remain one of the greatest uncertainties in snowmelt calculations (Link and Marks, 1999; Koivusalo and Kokkonen, 2002; Gelfan *et al*., 2004).

Shrub-tundra is a newly investigated land surface type that consists of discontinuous and continuous canopies of deciduous shrubs of dwarf alder, willow and/or birch from roughly 30 cm to 3 m in height (Jorgenson and Heiner, 2004). Vegetation less than 30 cm tall is not considered shrub tundra, but is the more familiar 'sparse tundra'. Shrub tundra has highly variable properties and is grouped into two major ecological classes in this paper: shrubs of dwarf willow and birch less than 0·75 m tall are considered 'short shrub tundra' and the taller alder shrubs that form canopies over 0·75 m tall are termed 'tall shrub tundra'. However, some tall shrub tundra can become buried by snow, particularly when a snowdrift forms over it.

Shrub tundra occupies the latitudes and altitudes above the coniferous forest tree line and is snow covered for from 6 to 8 months per year. There is evidence that areas of tall shrub tundra are increasing (Sturm *et al*., 2001a, 2005a), and that these areas profoundly change the surface water, nutrient and energy balance dynamics as they develop (Sturm *et al*., 2001b, 2005b). McCartney *et al*. (2006) suggest that, because of its effect on snow accumulation, location near stream channels and good soil drainage, tall shrub tundra exerts an inordinately large control on the streamflow regime during snowmelt of tundra basins. The differences between shrub tundra and sparse tundra are primarily due to contrasts in snow accumulation and ablation processes.

Using observations and blowing snow modelling, Pomeroy *et al*. (1997) found that shrub tundra north of Inuvik, NWT, near the Beaufort Sea coast accumulated four to five times more snow than sparsely vegetated tundra. Blowing snow transport from sparse to shrub tundra and retention of snowfall by shrubs controlled the snow accumulation regime in this region. Using long snow depth and density transects, Pomeroy *et al*. (1995) observed that the greatest accumulations in shrub tundra were not associated with the densest or tallest shrub vegetation but were when next to large open plains of sparse tundra from which there was high potential for snow erosion and transport. Essery and Pomeroy (2004) used a blowing snow model to show that the higher accumulation of snow in shrub tundra compared with sparse tundra was largely due to exposed shrubs increasing the aerodynamic roughness and, hence, suppressing blowing snow transport and sublimation. A secondary effect was redistribution into shrubs. Their research indicated that snow accumulation in shrubs was sensitive to both the regional shrub areal coverage and height.

Liston *et al*. (2002) showed that tundra shrub height and density have an extremely important role in regulating both the accumulation and ablation of snow. Sturm *et al*. (2001b) showed that, because shrubs collect blowing snow from sparsely vegetated tundra and become buried, this deeper snow maintains a high early spring albedo. However, the albedo decreases as shrubs become exposed in middle to later spring. This effect is extremely important in governing the snowmelt rates in shrubs. Pomeroy *et al*. (2003) showed that differences in insolation on north- and south-facing shrub tundra slopes initially caused small differences in net radiation in early melt; but, as shrubs emerged from melting snow faster on the south-facing slope, the albedo differences resulted in net radiation becoming positive and large for the south-facing slope, but remaining slightly negative on the north-facing slope. Melt rate differences were magnified by this phenomenon.

Shortwave radiation reflection from, and transfer through, shrubs is complex due the progressive exposure of shrubs during melt. Low-albedo shrub stems exposed above the snow surface will absorb net shortwave radiation, reducing direct shortwave radiation at the snow surface and heating the atmosphere (Strack *et al*., 2003; Lee and Marht, 2004; Sturm *et al*., 2005b). Techniques developed for energy partitioning in sparse vegetation have not been fully tested over snow, yet there is significant potential for advection of sensible heat from bush stems to adjacent snow. Advection of sensible heat from bare ground has been shown to be a large source of melt energy in tundra environments (Marsh and Pomeroy, 1996; Essery *et al*., 2006; Granger *et al*., 2006).

Sturm *et al.* (2005b) very extensively documented the albedo and net shortwave radiation and associated melt rate changes with varying degrees of shrub exposure in Alaska. However, the effect of shrubs on snowmelt is believed to be much more extensive than simple albedo effects, and no known studies have documented the comprehensive radiative and turbulent exchanges during snowmelt in shrub tundra. There is also little information on the types of snow accumulation and ablation regimes found in various shrub and sparse tundra ecosystems, nor on the long-term variability of snow accumulation and ablation regimes in these ecosystems. The energy and mass exchanges can be considered using the following coupled equations, in reference to the snowmelt rate in a control volume consisting of a unit area of snow cover under a shrub canopy. The melt rate, as governed by the energy equation from a unit area of snowpack, can then be expressed as

$$m\lambda_f = Q_m = Q^* + Q_e + Q_h + Q_d + Q_g - \frac{dU}{dt} \quad (1)$$

where m (mm s^{-1} or kg m^{-2} s^{-1}) is the melt rate, λ_f (J kg^{-1}) is the latent heat of fusion, Q_m (W m^{-2}) is the energy available for snowmelt, Q^* (W m^{-2}) is the net all-wave radiation to snow, Q_e (W m^{-2}) is the latent heat flux to the surface due to vaporization, Q_h (W m^{-2}) is the sensible convective heat flux from the atmosphere, Q_d is the energy transported to the snowpack by deposited precipitation, Q_g (W m^{-2}) is the conductive heat flux from the ground and U is internal energy of the snowpack, changing over time t. Similar energy terms relate to a shrub canopy, but melt, latent heat flux and ground heat flux would be minimal for the canopy. Cumulative snowmelt $M = \sum(Q_m\lambda_f)$ (mm or kg m^{-2}) over a melt period is also governed by a mass balance:

$$M = P(s) - \frac{dT}{dx} - E \quad (2)$$

where $P(s)$ (mm or kg m^{-2}) is cumulative snowfall, T (kg m^{-1}) is the cumulative blowing snow transport over the unit area of snow, diverging over downwind distance x (m), and E is the cumulative sublimation $\sum(-Q_e\lambda_s)$ from the snowpack (surface or blowing snow), where λ_s is the latent heat of sublimation. Equations (1) and (2) are linked by the melt and sublimation terms. It is hypothesized that increasing shrubs will increase the negative magnitude of dT/dx by trapping blowing snow, decrease Q^* to snow by attenuating shortwave radiation, increase Q_h to snow by providing a warm boundary above the snow and reduce sublimation losses from snow by suppressing turbulent transfer. The purpose of this paper is to describe the snow accumulation term $P(s) - dT/dx$, the net shortwave and net longwave radiation fluxes (K^* and L^* respectively) that control Q^*, the sensible heat Q_h and latent heat or water vapour fluxes (Q_e, E) and their control on snowmelt rates (Q_m, m) and total snowmelt M in tundra of differing shrub canopy height and structure. Both detailed melt periods and multiple seasons are examined in order to document the diversity and interannual variability of snow regimes found in shrub tundra.

FIELD SITE AND METHODS

Observations were made in the Wolf Creek Research Basin near Whitehorse, Yukon Territory, Canada: 60°32′N, 135°11′W. The basin has been subject to hydrological research since 1992 and was classified into ecozones based on vegetation identification from remote sensing and site visits (Francis, 1997). The sub-alpine ecozone in Wolf Creek forms a transition between the forested lowlands and sparsely vegetated alpine ecozones, and is vegetated primarily by open white spruce and willow–dwarf birch shrub communities with dwarf alder shrubs in wet areas and near streams. The sub-alpine ecozone occupies 58% of Wolf Creek basin and its elevation ranges from approximately 1100 to 1500 m. White spruce occur at the low-elevation margins, but most of the sub-alpine ecozone is shrub tundra. Pockets of dwarf shrubs also occur in the alpine ecozone, which occupies another 20% of the basin. The shrub tundra zone may, therefore, be considered to occupy much of the sub-alpine ecozone and part of the alpine ecozone, approximately 60% of the basin.

The research sites, their characteristics and the instrumentation used to study this shrub tundra are shown in Table I.

At the long-term sparse and shrub tundra sites, snow depth was measured half-hourly with a Campbell UDG01 sonic transducer controlled by a Campbell 21X datalogger, and density measured monthly using a snow tube on a 25-point snow course. Density changes over time were interpolated between measurements and used to calculate snow water equivalent (SWE) by multiplying with the snow depth (Pomeroy and Gray, 1995). Snowfall was measured with a Nipher-shielded Meteorological Service of Canada, Environment Canada (MSC), cylinder that was emptied monthly and corrected for wind undercatch from an adjacent wind speed measurement using MSC algorithms. Blowing-snow transport occurrence was observed with an optoelectronic blowing-snow particle detector which measured the blowing snow particle flux crossing a beam of infrared radiation (Brown and Pomeroy, 1989). The blowing-snow particle detector provided voltage pulses proportional to the number of blowing snow particles detected, and these pulses were measured and digitally recorded by the Campbell 21X datalogger.

At the three flux sites, depth and density were measured similarly with more frequent density observations (every few days). Eddy covariance flux and radiation sensors were controlled with Campbell 23X dataloggers and values stored every 30 min. Quality control was performed on the flux measurements using signal quality data, and mean vertical wind speeds and radiometers had been recently calibrated and intercomparisons were made. The sites were continuously serviced and monitored during the melt period.

Infrared thermographs were taken with an Infrared Solutions thermal infrared imaging radiometer with a resolution of 120×120 pixels; the use of this instrument to measure plant canopy temperatures during snowmelt has been documented by Rowlands *et al.* (2002).

RESULTS AND DISCUSSION

Snow accumulation in shrubs

Essery and Pomeroy (2004) predicted with a blowing-snow model that, where shrub coverage is extensive, increases in shrub height control increases in accumulated snow depth in shrubs up to a maximum that is close to the snow depth due solely to accumulation of snowfall. In other words, where there is extensive shrub coverage, the wind redistribution to shrubs is a small term in the mass balance. The result of this suppression of erosion by shrubs is evident in Figure 1, where SWE from depth and density measurements and snowfall from a wind-speed-corrected Nipher-shielded snowfall gauge are shown for a short vegetation 'sparse tundra' and tall shrub vegetation 'shrub tundra', both at long-term measurement sites in Wolf Creek. The winter season of 1994–95 is shown because there were no midwinter melts and the site was visited frequently.

Snow quickly filled the sparse tundra vegetation, with its depth reaching the 20 cm vegetation height by the beginning of November and then ranging from 13 to 20 cm (35 to 55 mm SWE) over much of the winter, only briefly reaching a maximum of 26 cm (69 mm SWE) just before melt commenced (Figure 1a). Blowing snow was observed on 32 of the 217 days with snow cover, and was associated with snow erosion events that led to snow transport from the site. Of the 141 mm of snowfall at the sparse tundra site, only one-half accumulated on the ground. Increases in cumulative snowfall were not reflected by increased snow accumulation after mid November; rather, repeated accumulation and snow erosion events are evident. The increase in SWE towards late winter was due to a wet snowfall event being wind packed onto the surface, resulting in both increased density and a small increase in snow depth due to greater cohesion and hence resistance to wind erosion.

In contrast, SWE and snow depth at the shrub tundra site continued to increase until early March, when a maximum of 63 cm depth (106 mm SWE) was reached (Figure 1b). Tall shrubs were bent over and eventually buried during the course of the winter by snow accumulation, after this any subsequent snowfall was subject to blowing snow erosion. Because the shrubs suppressed blowing snow until their burial, blowing snow occurred on only 13 days out of the 212 days with snow cover. Snow accumulation was maintained at over 60 mm

Table I. Observation sites, characteristics, instruments

Site	Vegetation	Plant height	Plant area index	Elevation (m)	Snow depth	Density	Eddy flux	Radiation[a]	Snowfall
Sparse tundra long-term	Grasses, willow, birch	20 cm	0·05	1615	Campbell UDG01	ESC30	n/a	n/a	Nipher
Shrub tundra long-term	Alder	1–3 m	0·7	1250	Campbell UDG01	ESC30	n/a	n/a	Nipher
Tall shrub tundra flux	Alder	2·35 m	1·09	1411	Campbell SR50	ESC30	Campbell CSAT, LICOR LI7500	*Sub-canopy*: K&Z CNR1, Exergen IRTC *Above canopy*: K&Z NRlite, Exergen IRTC, K&Z incoming and outgoing solarimeters	Nipher
Short shrub tundra flux	Willow, birch	35 cm	0·36	1510	Campbell SR50	ESC30	Campbell CSAT, LICOR LI7500	REBS net radiation, K&Z incoming and outgoing solarimeters	n/a
Buried tall shrub tundra flux	Willow-birch, sparse alder	1–2·5 m (alder)	0·39–0·68 (alder)	1515	Campbell SR50	ESC30	Campbell CSAT, KH20	K&Z CNR1 above and below canopy	n/a

[a] REBS: Radiation Energy Balance Systems; K&Z: Kipp and Zonen; IRTC: infrared thermocouple.

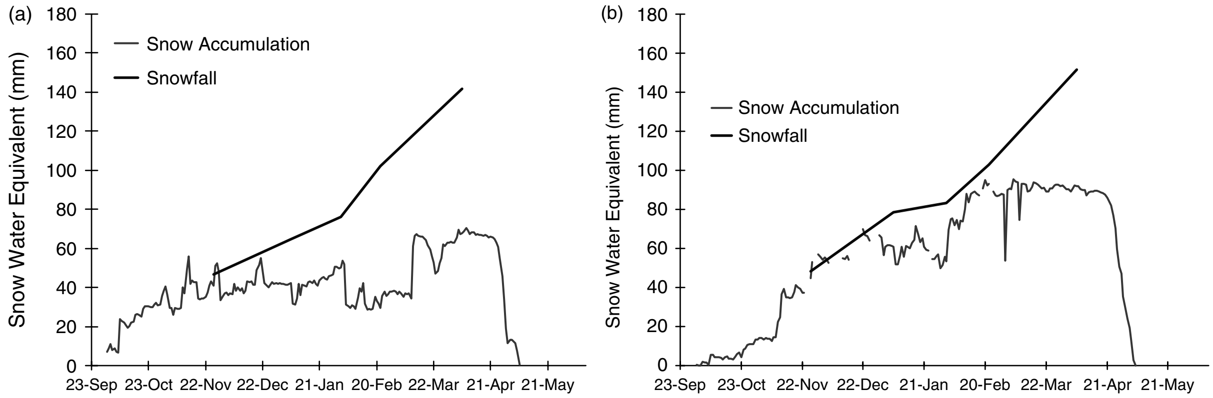
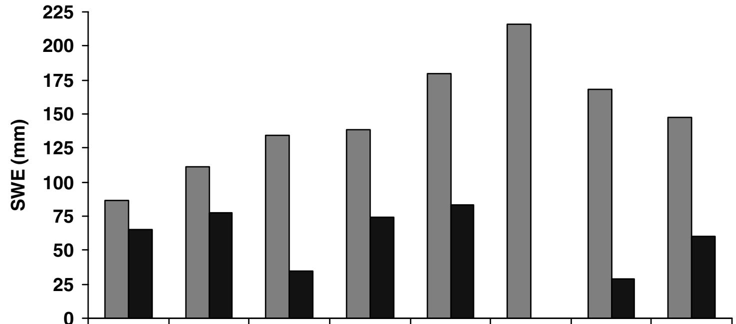


Figure 1. Observed SWE accumulation and ablation regimes and cumulative corrected snowfall for 'sparse tundra' and 'shrub tundra' sites, Wolf Creek, 1994–95: (a) sparse tundra with vegetation height less than 0·2 m; (b) tall shrub tundra with approximately 0·75–1·5 m tall canopy

SWE from 1 January until melt, and the maximum accumulation at the shrub tundra was much greater than that at the sparse tundra: 106 mm SWE from a 168 mm cumulative snowfall. The 38 mm SWE difference in snow accumulation between the sites cannot be fully ascribed to the 27 mm SWE difference in cumulative snowfall; it is also due to the sparse tundra retaining very little snowfall after early December and shrub tundra retaining very little snowfall after early March. It should be noted that lower snowfall at higher elevation, as observed in this year, is unusual for this mountain environment and may reflect some unaccounted for wind undercatch due to high winds around the snowfall gauge at the higher elevation sparse tundra site. If so, then the difference in accumulation between shrub and sparse tundra due to snow retention is even greater than estimated.

To examine interannual variability in the snow accumulation regimes of shrub and sparse tundra, the maximum SWE accumulation was measured for seven seasons using identical methods to that used to collect the data shown in Figure 1. Seasonal snowfall (wind speed corrected) was similar at both sites: in some years the sparse tundra had more and in some the shrub tundra had more; on average, there was 5 mm greater snowfall recorded at the shrub tundra site, with a standard deviation of difference of 16 mm. Figure 2 shows that shrub tundra snow accumulation was always higher than that in sparse tundra, with a mean SWE accumulation in shrub tundra almost 2·5 times that in the sparse tundra. The shrub tundra retained 63 mm more SWE than did the sparse tundra, with a standard deviation of difference of 44 mm (excluding winter 1999–2000 due to instrument failure). The exceptionally low snow accumulation in the sparse tundra in spring 2001 was due to intense midwinter wind scouring of exposed locations, which left much of this surface snow free before melt began. Figure 2 shows that the accumulation differences seen in the detailed analysis of 1994–95 (Figure 1) are much larger in most other years.

It should be noted that the long-term shrub tundra site shown in Figures 1 and 2 is not normally subject to the formation of a large snowdrift, though drifting of snow to and from the site can occur. Shrub tundra hillsides often contain deep snow drifts that form year after year due to the effect of topography on wind flow; drift size has little to do with vegetation height at the drift sites, though wind erosion of snow from adjacent sparse tundra in the primary upwind direction for strong winds seems important to their development, as was found north of Inuviki by Pomeroy *et al.* (1995). The effect of these hillside drifts on snow accumulation and melt energetics has been examined in detail at Wolf Creek by Pomeroy *et al.* (2003). The flux station shrub sites that were intensively examined in 2003 also had large differences in premelt snow accumulation, varying from 51 mm SWE for short shrub tundra (35 cm tall) to 102 mm SWE for tall shrub tundra (235 cm tall) to 103 mm SWE for buried tall shrub tundra (100 cm tall when not bent over).



	1994	1995	1996	1998	1999	2000	2001	Mean
Shrub Tundra	87	111	134	139	179	216	168	148
Sparse Tundra	65	77	35	74	83		29	60

Figure 2. Snow accumulation differences between shrub and sparse tundra over 7 years of observations (spring year is shown). Snowfall inputs were very similar at both sites

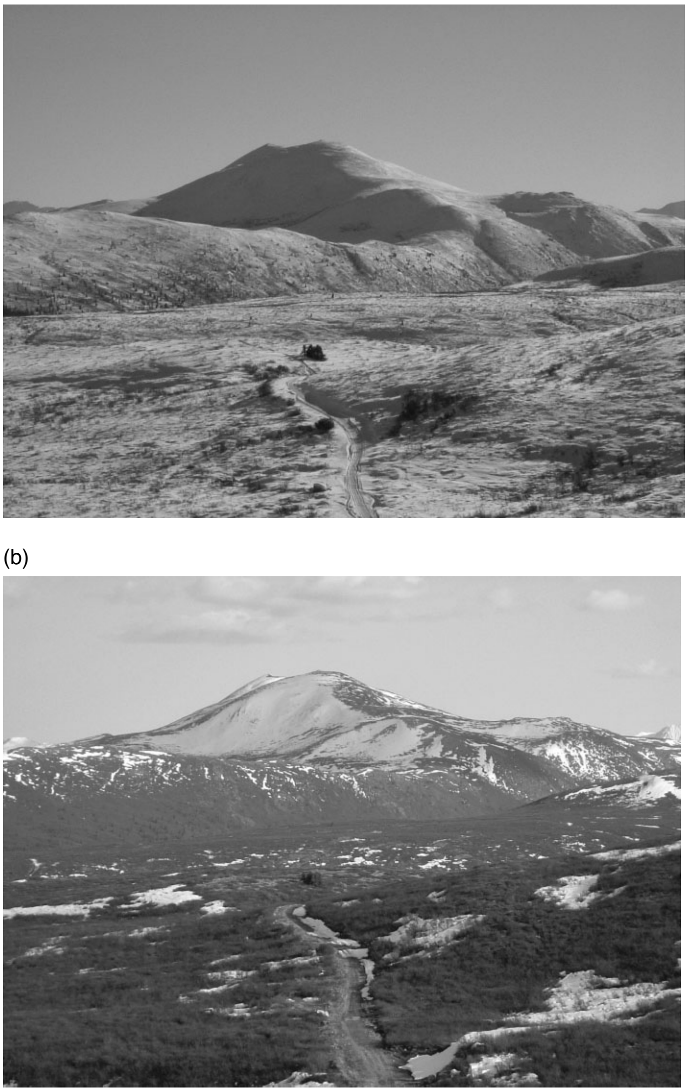
Shrub spring-up and exposure during melt

In the previous section it was noted that tall tundra shrubs can become bent over and buried by snow during the winter. Sturm *et al*. (2005b) describe their observations of this phenomenon in Alaska. Our observations showed that, during the melt phase, these individual shrubs do not emerge gradually from the snowpack, as would be expected for rigid canopy material, but 'spring up' episodically over a few days due to the elastic nature of the tundra vegetation. The burial and spring-up of shrubs completely transforms the winter landscape (Figure 3). Several complete research seasons have provided the basis for the following general observations:

1. Bend-over and burial is caused by a few heavy snowstorms, often with wet snow or heavy rime; shrubs bend rather than break in these storms.
2. Tall willow and birch shrubs, with their thin stems and greater elasticity, are more susceptible to bending over and burial than are the stiffer alder shrubs; however, any tall shrub can become buried.
3. Burial does not occur in all years.
4. Once bend-over occurs, the effective canopy becomes much shorter and further snow accumulation overtops the vegetation. An open, apparently 'pure' snowfield can subsequently develop over the shrubs with almost no visual evidence that shrubs are bent over and buried underneath. Albedo of this snow over shrub is high and identical to snow over sparse tundra.
5. Shrub spring-up occurs episodically, branch by branch and shrub by shrub. The mechanism that allows release of the branches from the snowpack is associated with wet snow metamorphism and development of weak inter-grain bonds during melt, localized melting around the buried shrubs under the snow surface and the changing elasticity of shrubs with branch warming (as for evergreens; see Schmidt and Pomeroy (1990)). These processes vary with snow depth, slope, aspect and weather patterns. Because each shrub springs up at a different time, the emergence of a shrub canopy is gradual and develops primarily over much of the early and middle melt period after snow has ripened, but with relatively small reductions in SWE.

The evolution of albedo (from an area) and apparent snow depth (at a point) at the buried tall shrub flux site in 2003 is shown in Figure 4. This figure exemplifies the difference between the spring-up of shrubs at a point and changes in shrub exposure over a broader area, and illustrates the difficulties of measuring snowmelt in shrub landscapes. An SR50 ultrasonic depth gauge was used to measure the distance from the gauge to the snow surface in order to estimate melt rate; however, the gauge was inadvertently placed over a buried willow shrub. The gauge accurately reported the decline in snow depth during densification and

(a)



(b)

Figure 3. A shrub-tundra landscape in Wolf Creek: (a) late winter, with burial or partial burial of shrub; (b) during melt, when shrubs are largely exposed and dominate the surface despite a snowpack remaining under the canopy

ablation up to 9 May, whereupon a shrub branch beneath sprang up over a few minutes to create a surface 22 cm higher than the snow surface, and over the next 2 days the remaining shrub branches were released from the snowpack to create a surface 30 cm higher than the previous snow surface. This was associated with air temperatures reaching daily highs of 10 °C, but with a small albedo reduction from 0·3 to 0·25 (radiometers were placed well over the shrubs and snow). There was a previous albedo decline of from 0·85 in the premelt period to 0·3 when this spring-up occurred under the SR50. The albedo decay was associated with progressive shrub exposure due to spring-up over the local area as observed by the radiometer, rather than of snow albedo reduction due to dirty, shallow or patchy snow cover. This is consistent with observations of point snow albedo versus areal albedo decay in Saskatchewan (Pomeroy *et al*., 1998) and the Yukon mountain environment (Fortin *et al*., 2000).

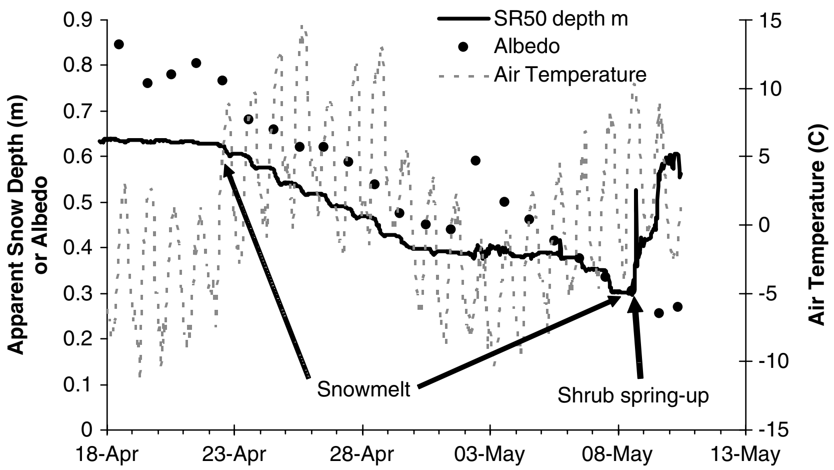


Figure 4. Changes in albedo and surface during melt over buried tall shrubs, 2003. Ultrasonic depth measurements by SR50 to the 'surface' during snowmelt over initially buried shrubs indicate that shrub spring-up directly under the SR50 began on 9 May, causing an apparent increase in the surface elevation from what had been a melting snow surface. The dramatic change at a point is contrasted with the gradual exposure of shrub by spring-up in the area observed by the radiometers, which led to an albedo decline that extended over the whole period (except after fresh snowfall on 22 April and 2 May)

Radiation and turbulent transfer during snowmelt and shrub emergence

The effects of shrub height, shrub exposure, canopy density and snow depth on shortwave radiation balance above the land surface (areal) and to the snowpack were examined using incoming and outgoing shortwave radiation measurements at the tall shrub, the buried tall shrub and the short shrub flux stations and detailed sub-canopy radiation measurements at the tall and the buried tall shrub flux stations in 2003. The sub-canopy radiometers at the tall shrub flux station were placed under a dense canopy of nearly continuous exposed alder shrubs, whereas those at the buried tall shrub flux station were under a single exposed alder shrub (250 cm tall) that had remained erect and exposed through the winter and was surrounded by a mostly open snow cover.

Albedo decay was most rapid at the short shrub site because it had the highest initial albedo and the lowest initial snow accumulation (Figure 5a). The short shrub albedo dropped from 0·86 to 0·17 over 10 days (0·069 day^{-1}), at which time the snow cover was depleted. The albedo decay was partly due to gradual shrub exposure and partly due to the decline in snow-covered area, with albedo a function of snow-covered area as described by Pomeroy *et al.* (1998). In contrast, the tall shrub albedo decayed slowly from 0·42 to 0·12 over 23 days (0·013 day^{-1}) without any depletion of snow cover under the canopy. The buried tall shrub albedo dropped from a value as high as the short shrub albedo and declined slowly from 0·82 to 0·25 over 23 days (0·025 day^{-1}) without any depletion of snow cover at the site. Buried shrubs in the early melt period and a greater degree of patchiness in the shrub canopy at the buried tall shrub site compared with the tall shrub site contributed to the overall higher albedo for the buried tall shrubs during snowmelt.

Net shortwave radiation above the shrub–snow land surface is controlled by the albedo of shrub and snow. Net shortwave radiation at the sub-canopy snow surface is controlled by the albedo and the transmissivity of shortwave radiation through the shrub canopy. Examination of cumulative net shortwave radiation above the canopies during the 2003 study period (18 April–11 May) revealed the greatest net shortwave to the tall shrubs (345 MJ), followed by the short shrubs (48 MJ at snow depletion on 29 April, 248 MJ by 11 May) and the buried tall shrubs (162 MJ) and is shown in Figure 5b. For tall shrubs, the high net shortwave flux was due to the albedo being dominated by shrubs. For short shrubs, the increase in albedo decay rate with time was due to decreasing albedo as shrubs and bare ground were exposed. For buried tall shrubs the slow

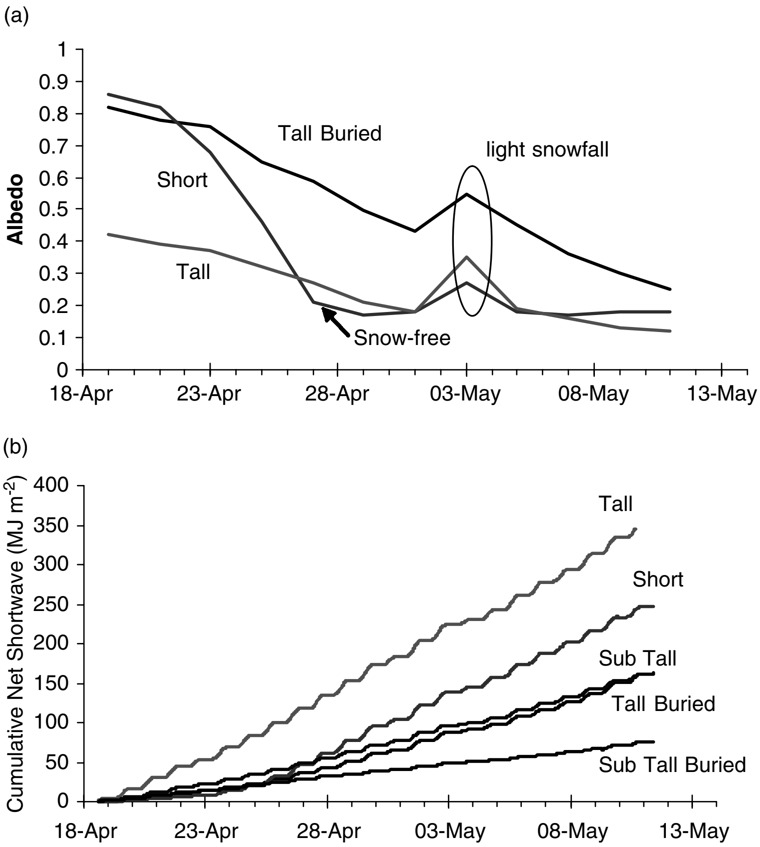


Figure 5. Change in shortwave radiation regime during snowmelt and shrub exposure: (a) albedo of the area observed by the radiometers over the shrub–snow surface; (b) net shortwave radiation over shrub–snow and sub-canopy snow surfaces (note that sub tall shrubs were slightly greater than buried tall shrub values)

albedo decay and small accumulation of flux at the end of the study period were due to shrub burial and gradual exposure during melt.

The net shortwave fluxes under the shrub canopies were in great contrast to above-canopy fluxes, much as for snowpack energetics under forests. The sub-canopy cumulative net shortwave flux under the tall shrubs was 160 MJ, or 46·2% of that above the canopy. Cumulative shortwave flux under the exposed shrub at the buried tall shrubs was 75 MJ and is a remarkably similar percentage of that above the canopy at 46·3%. Though the shrub heights for both sets of fully exposed shrubs were roughly similar, there is not a simple relationship among transmissivity, exposed plant area and canopy gaps.

Surface temperatures of shrubs and snow have a strong influence on net longwave radiation, and hence net radiation, and on the sensible and latent heat fluxes from the shrub and snow surfaces. To illustrate the considerable variability in temperature introduced by exposed shrubs, surface temperatures were measured using Exergen infrared thermometers looking at a pure snow surface under the tall shrubs and at a dense clump of shrub branches in the tall shrubs (Figure 6a). Independent tests of these thermometers showed similar radiative temperatures (mean difference $<0{\cdot}2\,^{\circ}$C) to those estimated from Kipp and Zonen CNR1 pyrgeometers when looking at pure snow surfaces when an emissivity of 0·99 was assumed. In the sunny, warm period of rapid melt up to 1 May, shrub temperatures ranged from lows of $-3\,^{\circ}$C to highs of $15\,^{\circ}$C, whereas the snow surface ranged from -2 to $-10\,^{\circ}$C, resulting in daytime differences of from 10 to $20\,^{\circ}$C and night-time differences of 2 to $5\,^{\circ}$C. In the colder, cloudier period after 1 May these differences were reduced

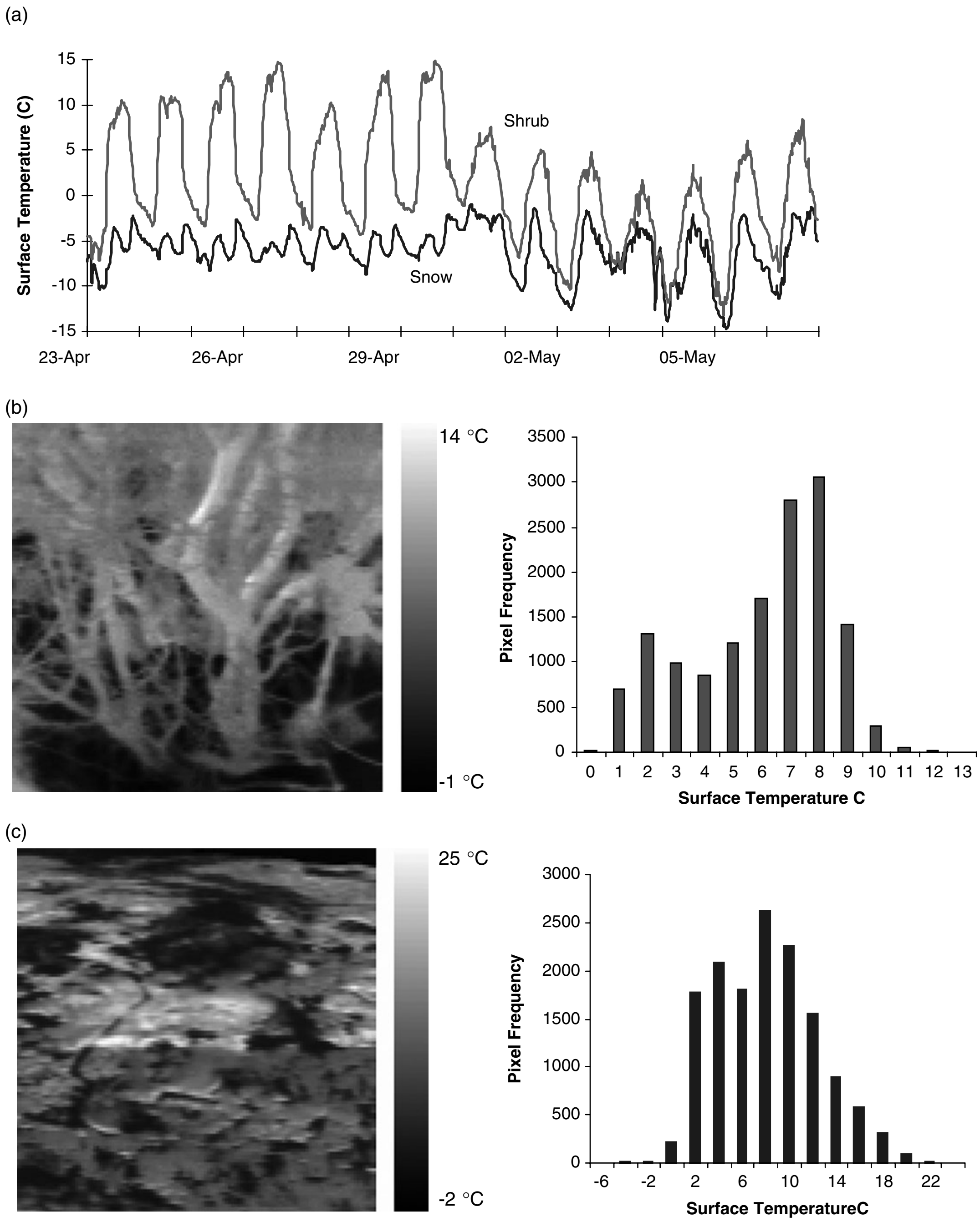


Figure 6. Surface temperature of snow cover and shrubs during snowmelt. (a) Infrared thermometer observations of surface temperature from shrub and snow cover in tall shrub tundra during melt. (b) Close-up infrared thermograph of surface temperatures of shrub stems and snow cover under tall shrubs during strong insolation, along with histogram of surface temperatures in the image (emissivity assumed 0·98). (c) Landscape infrared thermograph of surface temperature of exposed shrubs, bare ground and remaining snow cover; oblique image of a north-facing hillslope under partly cloudy conditions, along with histogram of surface temperatures in the image (emissivity assumed 0·98). Note the packed snow trail up the hillside appears 'cold'; shrubs had been broken and trampled along this trail

by approximately one-third. The shrub thermal structure was not uniform, and infrared thermographs taken with the imaging radiometer showed considerable variation in the surface temperature of shrubs and melting snow (Figure 6b and c). Although these images are instructive, it should be noted that temperatures estimated by this radiometer can be in error by 2 °C; however, differences in temperature across a thermograph have relatively small errors of 0·2 °C. At the small scales of an individual shrub (Figure 6b), sunlit stems were up to 12 °C but shaded stems remained below 8 °C, with snow under the shrub showing temperatures from 0 to +2 °C. At the hillslope scale (Figure 6c) snow patches were cool (−4 to +2 °C), shrub and bare patches were warm (+8 to +22 °C) and there were many mixed pixels of snow, bare ground and shrub with temperatures between these peaks. A hillslope without shrub exposure would have sustained temperatures at or below 0 °C.

The total effect of albedo, transmissivity of shrub canopy and longwave emission from snow and shrubs is to create very distinctive net radiation regimes over short shrub and snow surfaces compared with the snow surface under the tall shrub canopy. Figure 7a shows radiation components over a mixture of short exposed shrub, bare ground, and snowpack as snow cover ablated, and over shrub and ground after short shrub snow depletion at the end of 28 April. The 23–28 April snowmelt period was mostly sunny, and the increase in net shortwave and net radiation in that period was due to declining snow-covered area and associated albedo changes. After 29 April the surface was essentially snow free with a low albedo. Melt was characterized by net shortwave and net all-wave radiation increasing fourfold over 4 days with a steady net longwave loss of ∼50 W m^{-2}. The consistent loss of net longwave radiation was due to the shrub–snow surface being radiatively warmer than the atmosphere (whose emissivity was often much lower than that of the surface). Figure 7b shows the radiation regime under the canopy of tall shrubs and over a melting snow cover. Here, in the early melt period (23 April), when the short shrubs were largely buried but these tall shrubs were exposed, the net shortwave fluxes under tall shrubs were roughly one-third higher than over snow with a few exposed shrubs (Figure 7a). By the end of melt in the short shrubs (28–29 April), net shortwave fluxes were roughly half of those over short shrubs. In contrast to the longwave losses from the shrub-snow surface, the net longwave fluxes under tall shrubs were small, being slightly negative at night and slightly positive during daylight until the later melt period, when cloudier and cooler weather meant that net longwave under the canopy remained negative even during the day. This change in the longwave regime is ascribed to changes in solar heating of shrub stems as a sequence of clear days (23–30 April) changed to cloudier conditions in May. Negative values at night are due to radiatively cool sky conditions and a partially open canopy. The differences between the radiation regimes under tall shrubs and that over short shrubs, when continuous snow cover is present at both sites (early melt), are mainly due to larger longwave losses without tall shrub canopies and lower albedo and greater extinction associated with shrub exposure. The small net longwave fluxes under shrubs suggest small differences in emission temperatures between the combined shrub canopy plus sky and the emerging shrub stems plus melting snow.

Cumulative net radiation fluxes were available from all five sites, providing a means of comparison across a broad range of land and sub-canopy surfaces. Cumulative net radiation 18 April to 11 May (Figure 7c) was greatest over the tall shrubs (200 MJ) because of its low albedo, but substantially reduced from cumulative net shortwave (Figure 5) because of longwave losses from the warm shrub canopy. Whilst snow covered, the short shrub net radiation was indistinguishable from that under the tall or buried tall shrub exposed shrubs; however, accumulation of net radiation over the short shrub canopy site increased dramatically after snow cover depletion on 29 April. Net radiation under the tall and buried tall (exposed alder bush) shrub sites remained small during the melt period; however, net radiation fluxes over the tall shrubs were 2·5 times larger. Net radiative fluxes over the buried tall shrubs were initially negative and then roughly similar to those under the shrubs. The similarity of net radiation fluxes over the short shrub with that under two very different tall shrub canopies suggests that net radiation to melting snow may be rather insensitive to substantive differences in shrub density, canopy height or shrub burial because of compensating albedo, transmissivity and longwave emission factors. The greatest contrast in above-canopy net radiation was between tall and buried tall shrubs, where shrub burial was associated with a more than fivefold reduction in net radiation. It is clear from this

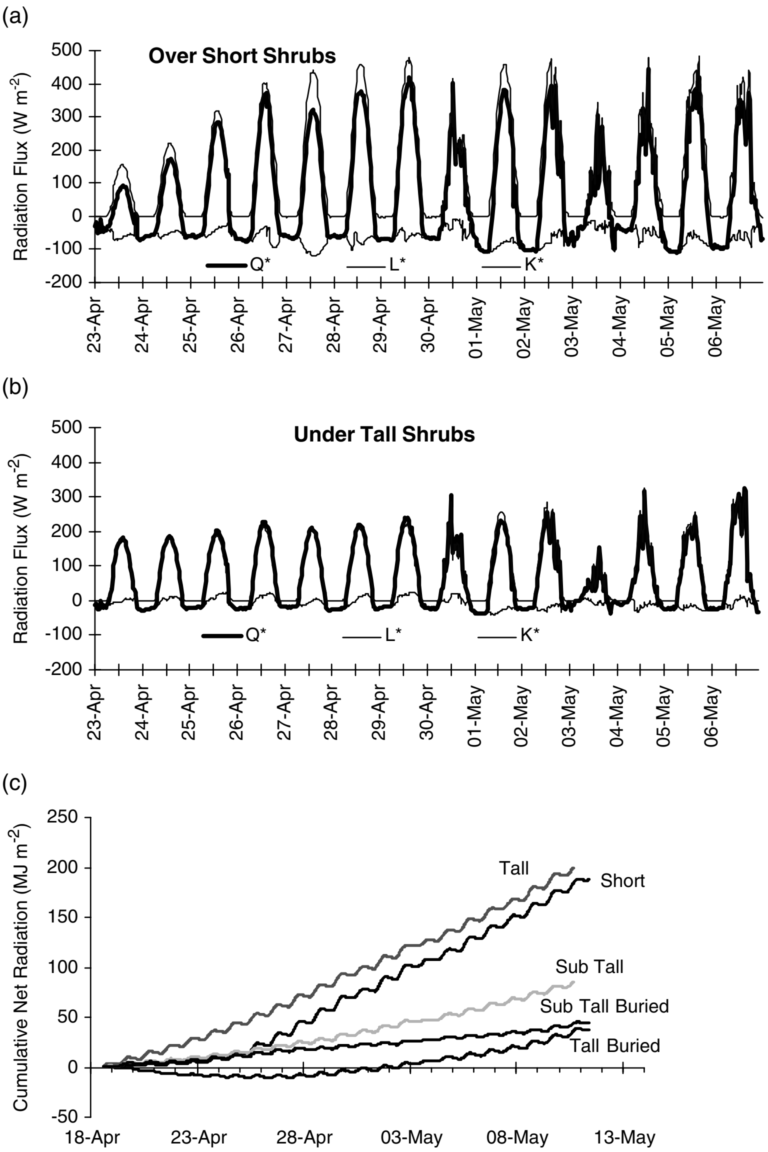


Figure 7. Net radiation Q^* and its components net longwave radiation L^* and net shortwave radiation K^* regimes. (a) *Over* short shrubs (which became snow free after 29 April); note that L^* is always slightly negative. (b) *Under* tall shrubs during snowmelt with increasing shrub exposure; note that L^* is always near zero. (c) Cumulative net radiation above and below tall shrubs, buried tall shrubs (mostly) and short shrubs during snowmelt

that shrub burial and emergence is an extremely important factor in late winter and springtime net radiation over shrub tundra.

Sensible and latent heat fluxes to the surface following the convention of Equation (1) were observed over tall, buried tall and short shrub surfaces. Figure 8a shows typical diurnal sequences of these fluxes over the tall shrubs when there is continuous snow cover underneath. Latent heat fluxes remained very small and negative (indicating sublimation) due to a small energy supply for phase change from net radiation at the sub-canopy snow surface and restriction of turbulent transfer by the tall shrub canopy. Given the frozen

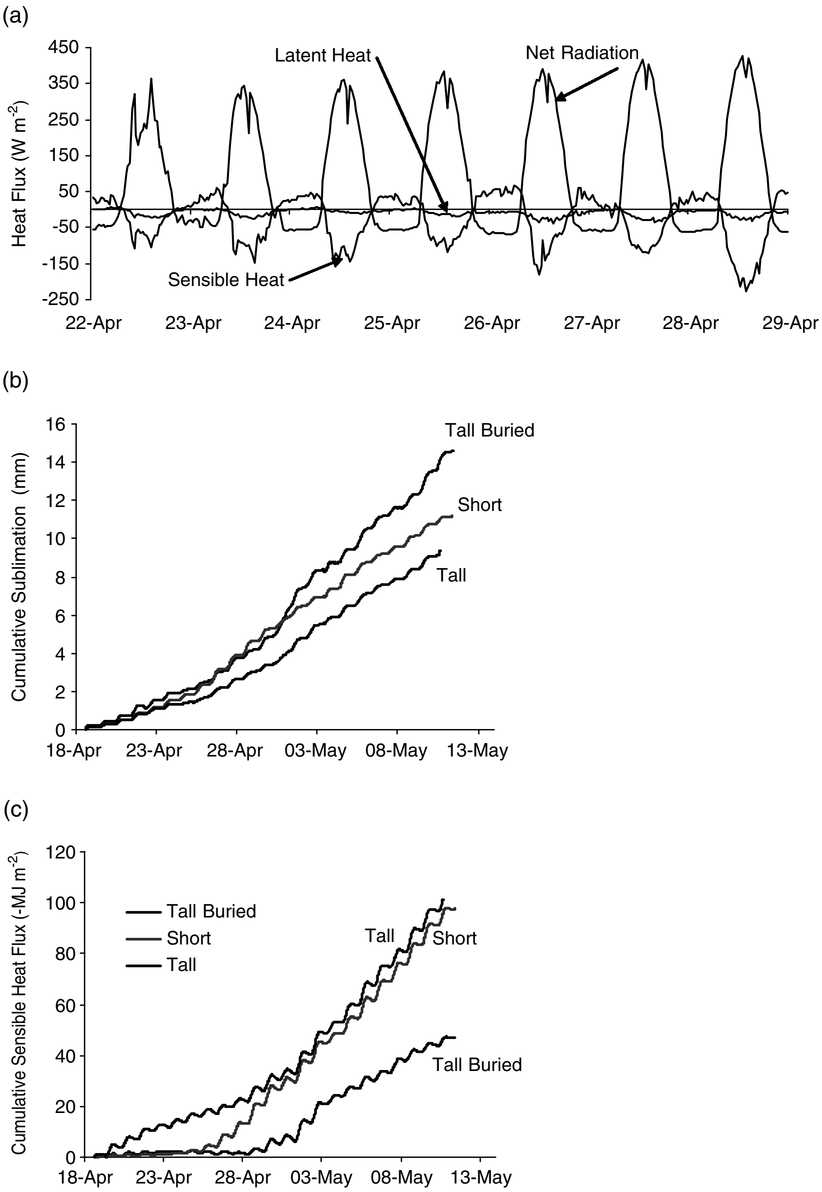


Figure 8. Sensible heat and sublimation (negative latent heat) fluxes to the atmosphere during shrub snowmelt. (a) Diurnal variations in sensible and latent heat fluxes to the surface compared with net radiation over tall shrubs during a snowmelt sequence; note that latent heat hovers near zero. (b) Cumulative sublimation E. (c) Cumulative sensible heat (negative shown for plotting convenience) over buried tall, tall and short shrubs during snowmelt

roots and leafless state of the shrubs, it is reasonable to presume that transpiration was negligible and any water vapour flux measured over the tall shrubs was in fact transmitted through the shrub canopy from the snowpack beneath. At both the buried tall and short shrub sites the snow surfaces were relatively well exposed to turbulent transfer and displayed the largest vapour flux magnitudes (Figure 8b). Cumulative sublimation totalled between 9 and 15 mm over 26 days (0·35–0·55 mm day^{-1}) and was fastest from both the buried tall shrubs and the short shrubs until 1 May, after which the short shrub surfaces became well exposed, then snow free and then dry. Sublimation was lowest from the tall shrubs, where the denser and more continuous canopy suppressed turbulent transfer from the underlying snowpack. Figure 8a also shows that sensible heat was large and negative in the day and small and positive at night, with daytime values as negative as -210 W m^{-2}. This flux sequence is in contrast to the positive daytime fluxes expected to a melting snow cover with air temperatures greater than 0 °C and shows a strong a strong shrub canopy effect on sensible heat. One-third of net radiation to the shrub surface was transformed to an upward flow of sensible heat from shrubs in the daytime, presumably due to low albedo and a consequently warm shrub surface with respect to the atmosphere. Cumulative sensible heat became less negative with the degree of snow cover exposed (Figure 8c). Sensible fluxes were minimal over the buried tall shrub surface, which was effectively an open snow surface until later in melt. When snow covered, the short shrub surface sustained small negative fluxes similar to those received by the buried tall shrubs; but, when the short shrubs and some ground surface became exposed after 27 April, the short shrubs became a source of sensible heat to the atmosphere, with fluxes similar to those from the well-exposed tall shrubs. In summary, increasing shrub exposure diminished sublimation fluxes from the surface and enhanced sensible heat flow to the atmosphere.

Snowmelt rates

Snowmelt under the shrub canopy or next to exposed shrubs is difficult to calculate and measure due to the presence of small branches in the snowpack and the fragile snow structure. Estimates of total ablation were made from half-hourly depth measurements and daily density measurements to estimate SWE and ablation rate (melt plus sublimation). Sublimation from the eddy correlation observations was presumed to be entirely from the snowpack. Total melt was then estimated as equal to ablation less sublimation (Figure 9). Melt rates increased with shrub exposure, being highest under the tall shrub canopy (7·1 mm day^{-1}) and lowest at the buried tall shrub site where there were very few exposed shrubs near the observation site (3 mm day^{-1}). In early melt, the short shrub site had a low melt rate identical to that at the buried tall shrub site. When snow cover depletion permitted small-scale advection from shrubs and bare ground to contribute to melt energy (see Granger *et al.* (2006)) in late melt, the short shrub melt rate increased and exceeded the tall shrub melt rate, producing an overall melt rate of 7 mm day^{-1}.

The partitioning of sub-canopy melt energy is still uncertain. Although net radiation under shrub canopies can be measured by placing a radiometer under the canopy, there are no known methods to measure sensible or latent heat fluxes under shrub canopies directly and dense shrubs prevent the use of snow lysimeters to

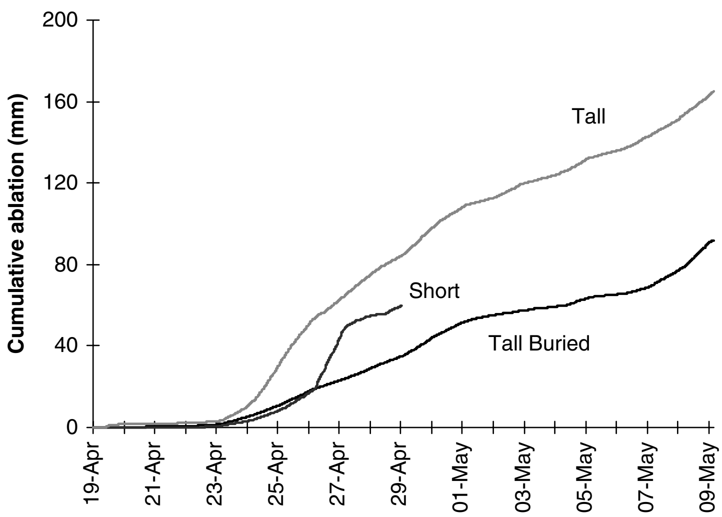


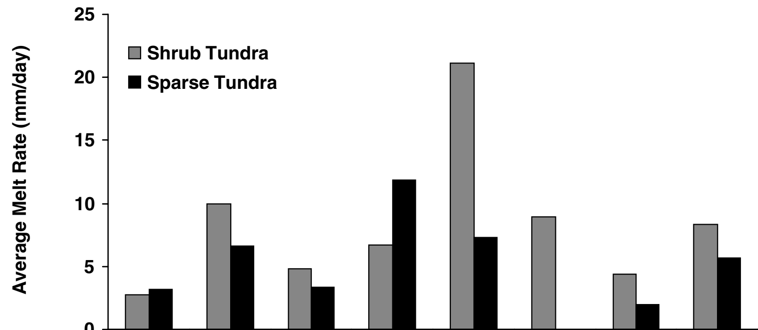
Figure 9. Cumulative snow ablation during melt period for tall, buried tall and short shrubs

estimate sublimation. However, the latent heat flux above the dormant shrub canopy was assumed to be due completely to snow sublimation, and so only the sensible heat term of the snow surface energy balance is unobserved. Internal energy changes and ground heat fluxes were small for this isothermal snowpack over thawing ground, leaving the net radiation term as the major source of melt energy. For instance, at the tall shrub site, the 170 mm of melt over 21 days had a contribution from sub-canopy net radiation of 129 mm of melt energy, less 10 mm of melt energy for sublimation. For the missing 51 mm of melt energy to come from sensible heat would require 17 MJ over the melt period or a sensible heat flux to the snow surface during melt of just over 9 W m^{-2}, compared with the -55 W m^{-2} sensible heat flux observed on average above the shrub surface during the same period. This suggests that the tall shrubs supply sensible heat both upwards and downwards to the colder atmosphere and snow surface. This analysis cannot be confidently carried out at the buried tall shrub site, as snowmelt was measured over a well-exposed snow surface with occasional shrubs and sub-canopy net radiation was measured under an isolated standing alder shrub. There was additional localized melting under the alder shrub that did not occur between standing shrubs. At this site the sub-canopy net radiation provided 132 mm of melt energy, but only 80 mm of melt occurred where measured at the open snowpack.

To evaluate whether the melt of 2003 was exceptional, melt rates from the long-term tall shrub tundra and sparse tundra sites were analysed for 7 years (Figure 10). Mean yearly shrub tundra melt rates varied from just below, to well above, the 2003 observations (range 2·7 to 21·2 mm day^{-1}), with an overall mean of 8·4 mm day^{-1}, which is just above the $\sim$7 mm day^{-1} observed at the tall and short tundra sites in 2003. The differences in melt rates between sparse and shrub tundra were highly variable, with the sparse tundra having the highest melt rates for 2 years out of 7 years and shrub tundra having them for 5 years out of 7 years. This variability is consistent with the changing differences in melt rates observed between short and tall shrub tundra as short shrubs became exposed during melt in 2003 at the flux sites. The overall mean difference was a 2·6 mm day^{-1} greater melt rate in the shrub tundra (excluding 2000), with a standard deviation of difference of 6·3 mm day^{-1}; this resulted in average shrub tundra melt rates being 47% higher than that for sparse tundra. As snow accumulation was 147% greater in shrub than in sparse tundra, the higher melt rate for shrubs led to some compensation in the duration of melt, with it being, on average, 10·5 days for sparse tundra and 17·7 days for shrub tundra, or 68% longer for shrub tundra.

Broader implications

The variability of melt rates both amongst years and amongst land cover types suggests that it would be difficult to set distinct shrub and sparse tundra melt rate coefficients for temperature index or other empirical



	1994	1995	1996	1998	1999	2000	2001	Mean
Shrub Tundra	2.7	9.9	4.8	6.7	21.2	9.0	4.4	8.37
Sparse Tundra	3.2	6.6	3.4	11.9	7.3		1.9	5.70

Figure 10. Average seasonal melt rate for sparse tundra and tall shrub tundra over 7 years of observation

approaches to estimating melt. Similarly, it would be difficult to set relative snow retention coefficients for snow redistribution that would have acceptable accuracy in any given year. Spring-up of buried shrubs causes substantial changes to the surface state, and differences amongst surfaces with shrubs that are tall and do not become buried, shrubs that become buried, and shrubs that are short cause markedly different surface energetics regimes. During melt, net radiation fluxes to the surface and sensible heat fluxes from the surface increase strongly, whilst sublimation rates decrease somewhat with increasing shrub exposure above the snow cover. However, the amount of snow available to melt generally increases with a combination of winter shrub height and topographic sheltering from wind, and deep snow can result in tall shrub burial due to bending. It is likely that only models that recognize the peculiarities of shrub tundra (compared with unvegetated or sparsely vegetated tundra) in trapping and retaining wind-blown snow, becoming buried under the snow and then springing up (or not becoming buried and standing erect through the winter), and then in modifying radiation and turbulent transfer fluxes over snow can be fully successful in describing the snowmelt behaviour of this vegetation cover and the associated energy and mass fluxes over shrub tundra snow. For instance, the albedo of tall shrub tundra remains less than 0·45, but when shrubs are buried the albedo can rise to 0·85. This type of albedo difference can cause dramatic changes in predicted lower atmosphere temperatures in numerical weather models (Strack *et al*., 2003), but the science base needs to be established first. For instance, Pomeroy and Dion (1996) showed that the boreal forest albedo remained low even with substantial intercepted snow loads in the canopy; once a larger database in BOREAS confirmed the low albedo over the winter, it was then used to improve numerical weather model performance (Viterbo and Betts, 1999). Given that (i) much of the arctic tundra is covered by shrub tundra, (ii) vegetation databases do not distinguish between types of shrub tundra, (iii) shrub tundra coverage is expanding (Sturm *et al*., 2001a) and (iv) the conditions that would bend over, bury and permit spring-up of shrub tundra are not yet well understood, then there is much to be learned about this vegetation cover before we can truly understand and predict the dynamics of high-latitude and -altitude surface energetics and snowmelt where shrubs are part of the landscape.

CONCLUSIONS

With respect to snow accumulation in sparse tundra, shrub tundra retained snowfall from wind erosion more effectively; however; the accumulation of deep snow was not specifically related to shrub height, but was also affected by topographic location and upwind vegetation height. As a result of variable snow accumulation and the remarkable elasticity of shrub stems and branches, some shrubs were buried by winter snowfall and shrub burial was not controlled by shrub height. So shrub tundra landscapes are composed of

1. short shrubs that are rapidly exposed at the end of melt;
2. tall shrubs that are exposed all through melt;
3. tall shrubs that are exposed gradually through melt.

For buried shrubs there were important land surface changes during melt associated with shrub exposure by snowmelt and/or spring-up due to weakening of the snow structure. The changes associated with increased shrub (and decreased snow) exposure included substantially lower albedo, greatly reduced transmittance of shortwave radiation to the snow surface, more positive net longwave radiation at the snow surface, much larger net radiation above, but slightly lower net radiation below the shrub canopy, somewhat reduced surface snow sublimation, much greater sensible heat loss from the surface to atmosphere, a more positive sensible heat flux from the canopy to the snow surface, and accelerated snowmelt rates. The rate of shrub exposure differed substantially, however, with some tall shrubs being exposed throughout melt and some being gradually exposed by spring-up during the course of melt, whilst short shrubs were rapidly exposed by melting snow at the end of melt. Over several years of observation, tall shrub tundra snow accumulation was 147% greater and snowmelt rate was 47% higher than in sparse tundra. As a result, snowmelt duration was 68% longer for shrub tundra than for sparse tundra.

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REFERENCES

Brown T, Pomeroy JW. 1989. A blowing snow detection gauge. *Cold Regions Science and Technology* **16**: 167–174.

Essery RLH, Pomeroy JW. 2004. Vegetation and topographic control of wind-blown snow distributions in distributed and aggregated simulations for an arctic tundra basin. *Journal of Hydrometeorology* **5**: 734–744.

Essery RLH, Granger RJ, Pomeroy JW. 2006. Boundary-layer growth and advection of heat over snow and soil patches: modelling and parameterization. *Hydrological Processes* **20**: this issue.

Fortin G, Pomeroy JW, Bernier M. 2000. Albedo and snow properties during ablation in a sub-arctic alpine environment. In *Proceedings of the 57th Eastern Snow Conference*; 23.

Francis SR. 1997. *Data Integration and Ecological Stratification of Wolf Creek Watershed, South-central Yukon*. Applied Ecosystem Management Ltd: Whitehorse, Yukon Territory.

Gelfan A, Pomeroy JW, Kuchment L. 2004. Modelling forest cover influences on snow accumulation, sublimation and melt. *Journal of Hydrometeorology* **5**: 785–803.

Granger RJ, Pomeroy JW, Essery RLH. 2006. Boundary-layer growth over snow and soil patches: field observations. *Hydrological Processes* **20**: this issue.

Jorgenson T, Heiner M. 2004. *Ecosystems of northern Alaska*. Unpublished report by ABR, Inc., Fairbanks, AK.

Koivusalo H, Kokkonen T. 2002. Snow processes in a forest clearing and in a coniferous forest. *Journal of Hydrology* **262**: 145–164.

Lee Y-H, Mahrt L. 2004. An evaluation of snow melt and sublimation over short vegetation in land surface modelling. *Hydrological Processes* **18**: 3543–3557.

Link T, Marks D. 1999. Point simulation of seasonal snow cover dynamics beneath boreal forest canopies. *Journal of Geophysical Research* **104**: 27 841–27 857.

Liston GE, McFadden JP, Sturm M, Pielke RA. 2002. Modelled changes in arctic tundra snow, energy and moisture fluxes due to increased shrubs. *Global Change Biology* **8**: 17–32.

Marsh P, Pomeroy JW. 1996. Meltwater fluxes at an arctic forest–tundra site. *Hydrological Processes* **10**: 1383–1400.

McCartney SE, Carey SK, Pomeroy JW. 2006. Spatial variability of snowmelt hydrology and its controls on the streamflow hydrograph in a subarctic catchment. *Hydrological Processes* **20**: this issue.

Pomeroy JW, Dion K. 1996. Winter radiation extinction and reflection in a boreal pine canopy: measurements and modelling. *Hydrological Processes* **10**: 1591–1608.

Pomeroy JW, Gray DM. 1995. *Snow accumulation, relocation and management*. National Hydrology Research Institute Science Report No. 7. Environment Canada, Saskatoon.

Pomeroy JW, Marsh P, Jones HG, Davies TD. 1995. Spatial distribution of snow chemical load at the tundra–taiga transition. In *Biogeochemistry of Seasonally Snow-covered Catchments*, Tonnessen KA, Williams MW and Tranter M (eds). *IAHS Publication* No. 228. IAHS Press: Wallingford, UK; 191–206.

Pomeroy JW, Marsh P, Gray DM. 1997. Application of a distributed blowing snow model to the Arctic. *Hydrological Processes* **11**: 1451–1464.

Pomeroy JW, Gray DM, Shook KR, Toth B, Essery RLH, Pietroniro A, Hedstrom N. 1998. An evaluation of snow accumulation and ablation processes for land surface modelling. *Hydrological Processes* **12**: 2339–2367.

Pomeroy JW, Toth B, Granger RJ, Hedstrom NR, Essery RLH. 2003. Variation in surface energetics during snowmelt in complex terrain. *Journal of Hydrometeorology* **4**(4): 702–716.

Rowlands AP, Pomeroy JW, Hardy J, Marks D, Elder K, Melloh R. 2002. Small-scale variability of radiant energy for snowmelt in a mid-latitude sub-alpine forest. In *Proceedings of the 58th Eastern Snow Conference*; 93–108.

Schmidt RA, Pomeroy JW. 1990. Bending of a conifer branch at subfreezing temperatures: implications for snow interception. *Canadian Journal of Forest Research* **20**: 1250–1253.

Strack JE, Pielke RA, Adegoke J. 2003. Sensitivity of model-generated daytime surface heat fluxes over snow to land-cover changes. *Journal of Hydrometeorology* **4**: 24–42.

Sturm M, Racine C, Tape K. 2001a. Increasing shrub abundance in the Arctic. *Nature* **411**: 546–547.
Sturm M, McFadden JP, Liston GE, Chapin FS, Racine CH, Holmgren J. 2001b. Snow–shrub interactions in arctic tundra: a hypothesis with climatic implications. *Journal of Climate* **14**: 336–344.
Sturm M, Schimel J, Michaelson G, Welker JM, Oberbauer SF, Liston GE, Fahnestock J, Romanovsky VE. 2005a. Winter biological processes could help convert arctic tundra to shrubland. *BioScience* **55**: 17–26.
Sturm M, Douglas T, Racine C, Liston GE. 2005b. Changing snow and shrub conditions affect albedo with global implications. *Journal of Geophysical Research* **110**: DOI: 10·1029/2005JG000013.
Viterbo P, Betts AK. 1999. Impact on ECMWF forecasts of changes to the albedo of the boreal forests in the presence of snow. *Journal of Geophysical Research* **104**(D22): 27 803–27 810.

