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Modelled changes in arctic tundra snow, energy and moisture fluxes due to increased shrubs

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Abstract

In arctic tundra, shrubs can significantly modify the distribution and physical characteristics of snow, influencing the exchanges of energy and moisture between terrestrial ecosystems and the atmosphere from winter into the growing season. These interactions were studied using a spatially distributed, physically based modelling system that represents key components of the land–atmosphere system. Simulations were run for 4 years, over a 4-km^2 tundra domain located in arctic Alaska. A shrub increase was simulated by replacing the observed moist-tundra and wet-tundra vegetation classes with shrub-tundra; a procedure that modified 77% of the simulation domain. The remaining 23% of the domain, primarily ridge tops, was left as the observed dry-tundra vegetation class. The shrub enhancement increased the averaged snow depth of the domain by 14%, decreased blowing-snow sublimation fluxes by 68%, and increased the snow-cover's thermal resistance by 15%. The shrub increase also caused significant changes in snow-depth distribution patterns; the shrub-enhanced areas had deeper snow, and the non-modified areas had less snow. This snow-distribution change influenced the timing and magnitude of all surface energy-balance components during snowmelt. The modified snow distributions also affected meltwater fluxes, leading to greater meltwater production late in the melt season. For a region with an annual snow-free period of approximately 90 days, the snow-covered period decreased by 11 days on the ridges and increased by 5 days in the shrub-enhanced areas. Arctic shrub increases impact the spatial coupling of climatically important snow, energy and moisture interactions by producing changes in both shrub-enhanced and non-modified areas. In addition, the temporal coupling of the climate system was modified when additional moisture held within the snowcover, because of less winter sublimation, was released as snowmelt in the spring.

Keywords: energy balance, shrubs, snowmelt, sublimation, runoff, land-cover change

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Introduction

Arctic vegetation responds dynamically to climate variations, as shown in both palaeoecological reconstructions (Payette *et al*. 1989; Brubaker 1995) and field experiments simulating environmental changes (Chapin *et al*. 1995; Hobbie & Chapin 1998). These studies suggest that an important response of arctic vegetation to warmer and/or nutrient-enhanced conditions is an expansion of deciduous shrubs, especially *Betula nana* (dwarf birch), in the current tussock–tundra vegetation. In light of the potential for increased arctic shrubs, it is important to understand the coupled ecological, hydrologic and atmospheric consequences of such changes.

In arctic tundra, changes in the growth and distribution of shrubs can significantly alter the snow distribution, the length of time the snow is on the ground and the

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snowcover's physical characteristics. These snowcover changes arise from interactions between shrubs and two pervasive features of the arctic winter environment: low air temperatures and high wind speeds capable of transporting snow over horizontal distances of meters to a few kilometres. Because shrubs are taller than other tundra vegetation, they capture and hold more snow (Liston & Sturm 1998; Sturm *et al*. 2001). The deeper snow held within and around shrubs has significantly different structural and thermal characteristics than snow located in areas where shrubs are less abundant or absent (Sturm *et al*. 2001). The non-shrub vegetation types covering the majority of tundra areas are typically wind swept, and the upper snowpack contains hard 'wind slabs' that result from snow particles breaking into small ice grains (Benson & Sturm 1993). These slabs have relatively high thermal conductivity and strength (Sturm *et al*. 1997). Below these wind slabs is a relatively loose and large-grained snow structure called depth hoar. Depth hoar forms under the large temperature gradients that exist within the snowpack during autumn and early winter (Sturm & Benson 1997), and it has relatively low thermal conductivity and strength. Shrub vegetation can alter this two-layer structure; the upper wind-slab layers may be nearly absent, with almost the entire snowpack made up of depth hoar (Sturm *et al*. 2001). This shrub-related snowcover is several times more insulative per unit thickness (because of its greater depth hoar content) than non-shrub snow (Sturm *et al*. 1997).

An additional consequence of arctic wind-transported snow is that a significant fraction (15–45%) of the snowcover is returned to the atmosphere by sublimation of wind-borne snow particles (Benson 1982; Liston & Sturm 1998; Essery *et al*. 1999; Pomeroy & Essery 1999). When moved by the wind, snow particles expose their entire surface to the surrounding air, and can thus experience relatively high sublimation rates (Schmidt 1972). This aspect of the arctic snowcover has important implications for arctic shrub increases because shrubs can capture and hold snow, thus preventing wind transport and the associated sublimation fluxes. Even under identical precipitation inputs, this represents a potential for (i) deeper end-of-winter snowcover and (ii) reduced amount of moisture sublimated back to the atmosphere. This deeper snow influences the insulating character of the snow, spring snowmelt runoff and snow-free season length.

Changes in snowcover associated with shrub expansion could significantly impact the hydrologic cycle and ecological processes throughout the year. Snowcover affects terrestrial components such as soil-moisture conditions, runoff, and active layer and permafrost characteristics (e.g. Kane *et al*. 1991; Everett *et al*. 1996; Hinzman *et al*. 1998; McNamara *et al*. 1998; Nelson *et al*. 1998). From a biological perspective, the snowcover influences both plants and animals (e.g. Adams 1981; Brown & Theberge 1990; Rominger & Oldemeyer 1990; Nelleman & Thomsen 1994; Gese *et al*. 1996; Wooldridge *et al*. 1996; Bradshaw *et al*. 1997; Stuart-Smith *et al*. 1997; DelGiudice 1998; Reynolds 1998; Gerland *et al*. 1999). For example, snowcover thickness and distribution affects the length and timing of the snow-free period and snow drifts provide water to snow-bed plant communities (Billings & Bliss 1959; Billings 1969; Evans *et al*. 1989; Walker *et al*. 1993). Any increase in arctic shrubs will modify many snow-related characteristics (e.g. depth, density, grain size, iciness, strength and adhesion), and this, in turn, will influence plant, animal and hydrologic systems.

In this paper, we examine how shrub expansion would affect the arctic snow–atmosphere–biosphere system. We use a three-dimensional snow-transport model and an energy-balance snowmelt model to simulate the effects of increased height and distribution of arctic shrubs on (i) end-of-winter snow-depth distributions, (ii) winter blowing-snow sublimation fluxes, (iii) winter snowpack thermal properties, (iv) surface energy and moisture fluxes during snowmelt, (v) the length of snow-covered and snow-free (growing) seasons, and (vi) the timing and magnitude of snowmelt runoff.

Model description

We simulated the autumn and winter snowcover evolution using a numerical snow-transport model (SnowTran-3D, Liston & Sturm 1998), and simulated spring snowmelt and the energy and moisture exchanges between the snow, land and atmosphere using an energy-balance model (Liston & Hall 1995; Liston *et al*. 1999). Because the model simulations were performed for a region of arctic Alaska that experiences virtually no snowmelt throughout autumn and winter, and virtually no snow accumulation during snowmelt (Kane *et al*. 1991), it is appropriate to model the processes of accumulation and melt separately.

Winter snow redistribution

SnowTran-3D is a three-dimensional model that simulates snow-depth evolution over topographically variable terrain. Its primary components are (i) the computation of the wind-flow forcing field, (ii) the wind-shear stress on the surface, (iii) the transport of snow by saltation, (iv) the transport of snow by turbulent suspension, (v) the sublimation of saltating and suspended snow, and (vi) the accumulation and erosion of snow at the snow surface. The required model inputs are: (i) temporal fields of precipitation, wind speed and direction, air temperature and humidity, usually obtained from a meteorological station located within the simulation domain; and (ii) spatially distributed fields of topography and vegetation type. Within the model, each vegetation type is assigned a canopy height, which defines a vegetation snow-holding capacity. This is functionally used to define the snow depth that must be exceeded before snow becomes available for wind transport (i.e. snow captured within the shrub canopy by either precipitation or blowing-snow deposition cannot be removed by the wind).

The foundation of SnowTran-3D is a mass-balance equation that describes the temporal variation of snow depth at each point within the simulation domain. Deposition and erosion, which lead to changes in snow depth at these points, are the result of (i) changes in horizontal mass-transport rates of saltation, Q_s (kg m^{-1} s^{-1}), (ii) changes in horizontal mass- transport rates of turbulent-suspended snow, Q_t (kg m^{-1} s^{-1}), (iii) sublimation of transported snow particles, Q_v (kg m^{-2} s^{-1}), and (iv) the water-equivalent precipitation rate, P (m s^{-1}). Combined, the time rate of change of snow depth, ζ (m), is

$$\frac{d\zeta}{dt} = \frac{1}{\rho_s}\left(\rho_w P - \left(\frac{dQ_s}{dx} + \frac{dQ_t}{dx} + \frac{dQ_s}{dy} + \frac{dQ_t}{dy}\right) + Q_v\right)$$

where t is time (measured in seconds), x and y are the horizontal coordinates in the west-east and south-north directions, respectively (measured in metres), and ρ_s and ρ_w are the snow and water density, respectively (measured in kg m^{-3}). Equation 1 is solved for each individual grid cell within a domain, and is coupled to the neighbouring cells through the spatial derivatives (d/dx, d/dy). In this formulation we have assumed that sublimation from a static snow surface (no blowing snow) is negligible compared to the blowing-snow sublimation fluxes. Complete formulation details for each term in Equation 1 can be found in Liston & Sturm (1998).

Spring ablation

After generating the end-of-winter snow distribution using SnowTran-3D, we simulated the spring melt period using a surface energy balance model of the form

$$(1 - \alpha)Q_{si} + Q_{li} + Q_{le} + Q_h + Q_e + Q_c = Q_m, \qquad (2)$$

where Q_{si} is the solar radiation reaching Earth's surface, Q_{li} is the incoming longwave radiation, Q_{le} is the emitted longwave radiation, Q_h is the turbulent exchange of sensible heat, Q_e is the turbulent exchange of latent heat, Q_c is the conductive energy transport, Q_m is the energy flux available for melt, and α is the surface albedo. Details of each term in Equation 2, and the model solution, can be found in Liston & Hall (1995) and Liston *et al*. (1999). In this model, each term in the surface energy balance is computed by applying equations that have been cast in a form that leaves the surface temperature as the only unknown. The melt energy is defined to be zero, and Equation 2 is solved iteratively for the surface temperature. In the presence of snow, surface temperatures greater than 0 °C indicate that energy is available for melting. This energy is computed by fixing the surface temperature at 0 °C and solving Equation 2 for Q_m. The melt energy is then used to reduce the snow depth. The energy-balance melt model requires temporally evolving inputs of air temperature, relative humidity and wind speed. In the absence of incoming radiation observations, Q_{si} and Q_{li} are calculated as part of the model formulation.

Model simulations

Our simulations were performed over a 4-km^2 domain (Fig. 1) at Imnavait Creek, in arctic Alaska (68° 37′ N, 149° 17′ W, 900 m a.s.l.). The vegetation at the site is composed of low-growing sedges and grasses, with dry rocky areas on ridges and a relatively small area covered by taller shrub vegetation located in hillside water tracks (Fig. 1). The topography is characterized by gently rolling north–south ridges and valleys approximately 1 km apart and 50 m high (Fig. 1). The topography, physiography and vegetation of the watershed are representative of the area north of the Brooks Range and south of the Arctic Coastal Plain (Walker & Walker 1996).

Model simulations were run from 1 September through to 15 June for the years 1986–87, 1987–88, 1988–89 and 1989–90. In the discussions that follow, these simulation periods are referred to as 1987, 1988, 1989 and 1990, respectively. The winter snow distributions were simulated by running SnowTran-3D over the period 1 September through to 30 April, for each of the winters. The spring snowmelt period was simulated by running the energy-balance snowmelt model from 1 May through to 15 June. Based on data collected at the Imnavait Creek watershed between 1985 and 1993, the simulations included two winters with 'average' end-of-winter snow accumulation (1987 and 1990), one with 'light' accumulation (1988) and one with 'heavy' accumulation (1989) (Kane *et al*. 1991; Hinzman *et al*. 1996; Liston & Sturm 1998). During the melt season (May–June), these four years were characterized by a cold period in the middle of the melt (1987), an early melt (1988), a late melt (1989), and a uniform early melt (1990) (Kane *et al*. 1997). In previous work, simulations with

SnowTran-3D over this domain were found to compare well with observed snow distributions (Liston & Sturm 1998), and snowmelt simulations using a similar energy-balance model compared well with observed snowmelt rates (Kane *et al*. 1997).

To examine the effects of increased shrubs, for each year we compared a control simulation using the observed vegetation distribution (Fig. 1) to a 'shrub-enhanced' simulation, in which we substituted shrub tundra for the moist- and wet-tundra vegetation classes. The vegetation change was imposed by modifying SnowTran-3D's vegetation snow-holding capacity (Table 1). The vegetation snow-holding capacity was increased to 50 cm for the moist-, wet- and shrub-tundra (together covering 77% of the domain), and the dry-tundra type was left the same as in the observed-vegetation simulations. A 50-cm shrub snow-holding capacity was used because it is typical of *Betula nana* shrub-tundra heights currently found throughout the circumpolar Low Arctic (Bliss & Matveyeva 1992). System sensitivity to the snow-holding capacity was examined by performing a series of simulations where this parameter was varied from 30 to 50 cm, in 5-cm increments.

Model simulations were driven with air temperature, humidity, wind speed and wind direction data from the Imnavait Creek meteorological station run by the Water Research Center, University of Alaska, Fairbanks. The data used for the winter SnowTran-3D simulations are given in Liston & Sturm (1998), and the air temperature forcing data for the 1987 and 1990 melt-period simulations are provided in Fig. 2 (relative humidity and wind

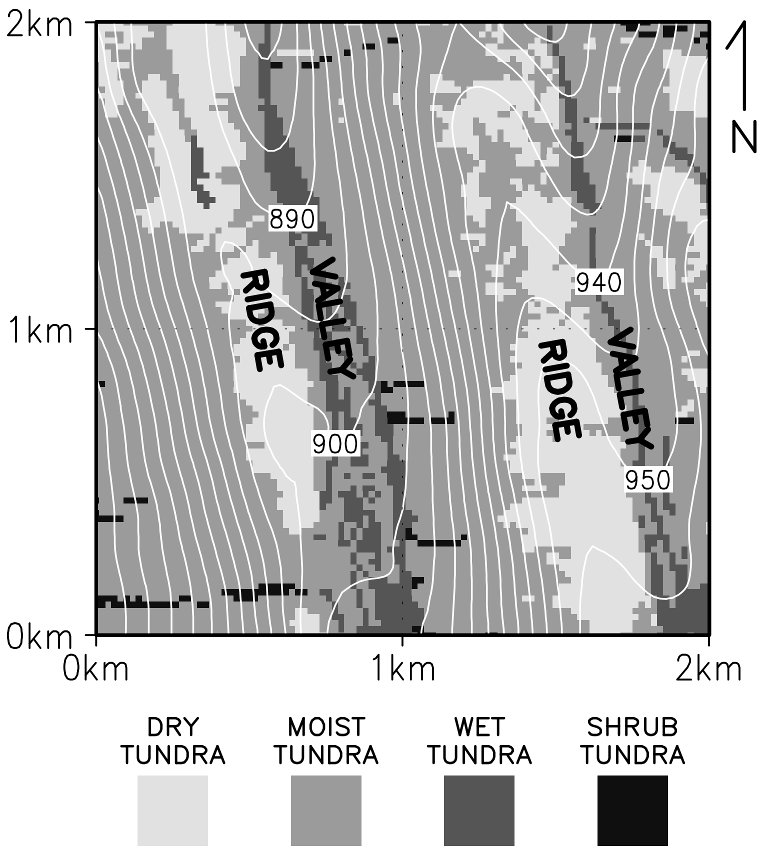


Fig. 1 Vegetation and topography for the Imnavait Creek simulation domain. Topographic contour interval is 5 meters, and the ridges and valleys have been labelled. (Data courtesy of D. A. Walker, Institute of Arctic Biology, University of Alaska, Fairbanks).

Table 1 Vegetation snow-holding capacities (SHC), in units of cm of snow depth, used in the model simulations. Also shown is the areal fraction covered by each vegetation type

	Dry tundra	Moist tundra	Wet tundra	Shrub tundra
Observed-vegetation SHC (cm)	10	20	30	40
Shrub-enhanced SHC (cm)	10	50	50	50
Percentage of domain covered	23	68	8	1

speed not shown). The simulations used a 20 × 20 m horizontal grid spacing, and SnowTran-3D and the melt model used 1-day and 1-h time steps, respectively. All SnowTran-3D user-defined constants other than the vegetation snow-holding capacity are the same as those used by Liston & Sturm (1998).

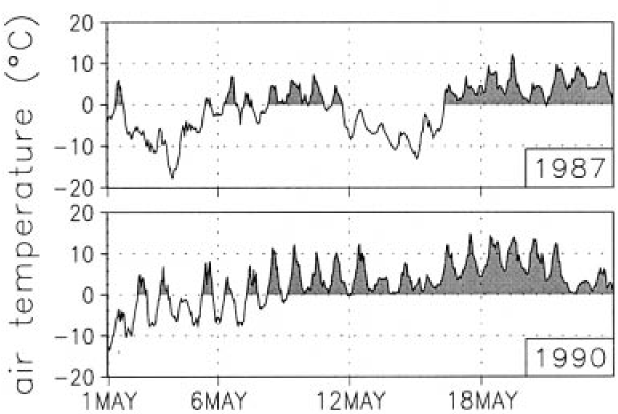


Fig. 2 Hourly air temperature forcing used in the 1987 (top) and 1990 (bottom) snowmelt simulations. Temperatures above zero are shaded. (Data courtesy of Doug Kane and Larry Hinzman, Water Research Center, University of Alaska, Fairbanks).

The modelling system used in this experiment includes all of the known first-order processes and interactions that exist within the natural system we are trying to simulate. However, second-order features and processes exist that are either highly simplified or not taken into account. For example, shrubs frequently exist in groupings smaller than the model's 20-m grid cells; the model assumes that these groupings can be represented in some average sense on a 20-m grid. While natural shrubs also typically have a wide range of heights, stem diameters and branch densities that influence their interactions with wind-blown snow, the model assumes that the influence of all their physical characteristics can be lumped into one model parameter, the vegetation snow-holding capacity. For our purpose of investigating the effect of a potential *Betula nana* expansion, this assumption is reasonable because this erect shrub is capable of holding snow over the range of vegetation heights we studied. Field observations comparing shrub and shrub-free areas show that the relatively low shrubs currently occurring in tussock tundra and the taller shrubs occurring in water tracks have a similar ability to increase snow accumulation (Sturm *et al*. 2001). Another example is that during snowmelt the dark shrub branches absorb solar radiation and emit longwave radiation that, in turn, accelerates the melt of nearby snow. This melt acceleration would increase the

Table 2 Domain-averaged end-of-winter snow depth and sublimated snow depth for observed- and shrub-enhanced vegetation. Also shown is the percent change in those quantities when shrubs were enhanced, and the total winter snow-precipitation inputs. The moisture imbalance (snow depth ≠ precipitation – sublimation) is due to saltation and suspended transport out of the domain (see Liston & Sturm 1998). The lower section presents the breakdown of snow depths averaged over the portion of the domain coincident with each of the different vegetation types (Fig. 1)

	1987		1988		1989		1990	
	Observed	Shrubs	Observed	Shrubs	Observed	Shrubs	Observed	Shrubs
Precipitation (cm)	61	61	44	44	75	75	48	48
Snow depth (cm)	41	49	31	38	58	63	41	42
Change (%)		+20		+23		+9		+2
Sublimation (cm)	15	6	10	2	15	7	5	1
Change (%)		–60		–80		–53		–80
Dry tundra snow depth (cm)	36	24	26	16	65	43	40	20
Change (%)		–33		–38		–34		–50
Moist tundra snow depth (cm)	40	56	32	44	54	68	40	48
Change (%)		+40		+38		+26		+20
Wet tundra snow depth (cm)	56	60	41	44	70	72	48	48
Change (%)		+7		+7		+3		0
Shrub tundra snow depth (cm)	53	57	42	44	63	69	47	48
Change (%)		+8		+5		+10		+2

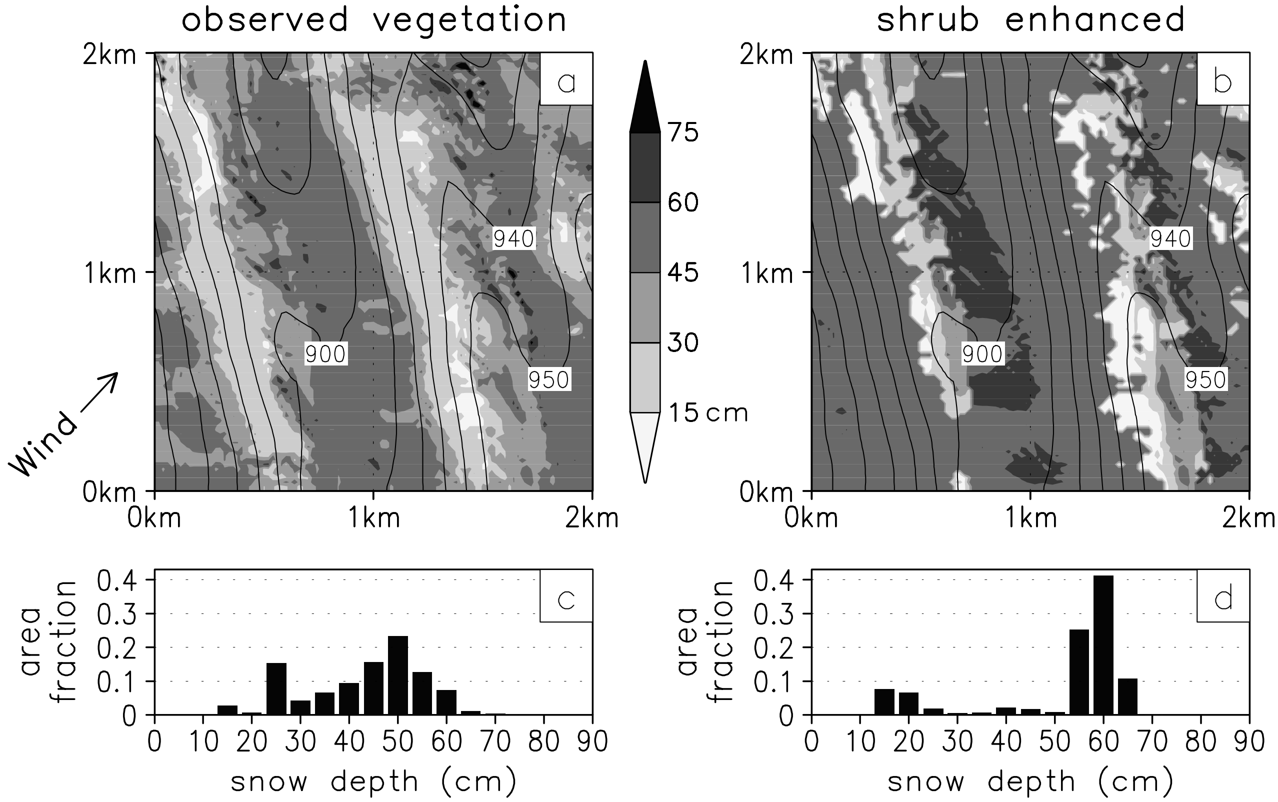


Fig. 3 Simulated 1987 end-of-winter snow-depth distributions for (a) observed vegetation, and (b) shrub-enhanced vegetation. The wind arrow shows the prevailing storm-wind direction that redistributes the snow. End-of-winter snow-depth histograms for (c) observed vegetation (from (a)), and (d) shrub-enhanced vegetation (from (b)).

runoff rate and associated moisture transport from terrestrial to aquatic systems.

Model results

Winter simulations

In the 1987 simulation, shrub enhancement caused a 20% increase in the domain-averaged snow depth (Table 2). Enhancing shrubs increased snow depths over most of the domain but decreased snow depths on the dry-tundra ridge tops (Fig. 3a, b, Table 2). This was because snow held by shrubs upwind of the ridges was not available for transport and deposition into the dry-tundra areas. Shrub enhancement produced a more highly differentiated snowcover over the domain, as reflected in a shift to a bimodal snow-depth distribution (Fig. 3c, d). A similar pattern of snowcover distribution change occurred in the 1989 simulation (not shown), where shrub enhancement caused a 9% increase in the domain-averaged snow depth (Table 2).

In the 1988 and 1990 simulations, the years with the least total precipitation, shrub enhancement increased the domain-averaged snow depths by 23% and 2%, respectively (Table 2). Compared to 1987 and 1989, the 1990 shrub-enhanced simulation caused a more pronounced differentiation of the snowcover across the domain (Fig. 4a, b), but less differentiation of snow depths *within* each vegetation class (Fig. 4c, d). In the 1990 simulation, shrub enhancement caused the entire shrub-covered area (77% of the domain) to be covered by 48-cm deep snow (Table 2). This depth was essentially equal to both the total precipitation input and the assigned shrub snow-holding capacity (Tables 1 and 2). The 1988 simulation produced a similar pattern of snow distribution (not shown), with nearly uniform 44-cm snow depth within the shrub-covered area (Table 2).

To examine the effects of the 50-cm snow-holding capacity assigned to the shrub-enhanced vegetation, we performed a series of model-sensitivity simulations where we varied this parameter from 30 to 50 cm, in 5-cm increments. In these simulations, snow depths increased roughly linearly for the vegetation types that were converted to shrubs, and decreased roughly linearly over dry tundra (Fig. 5a). Thus, snowcover

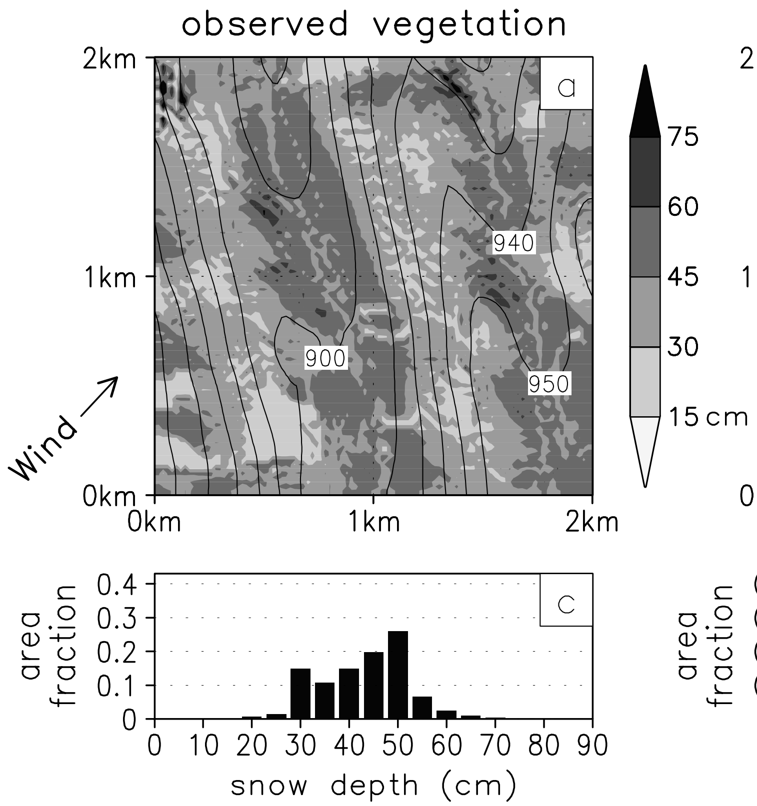
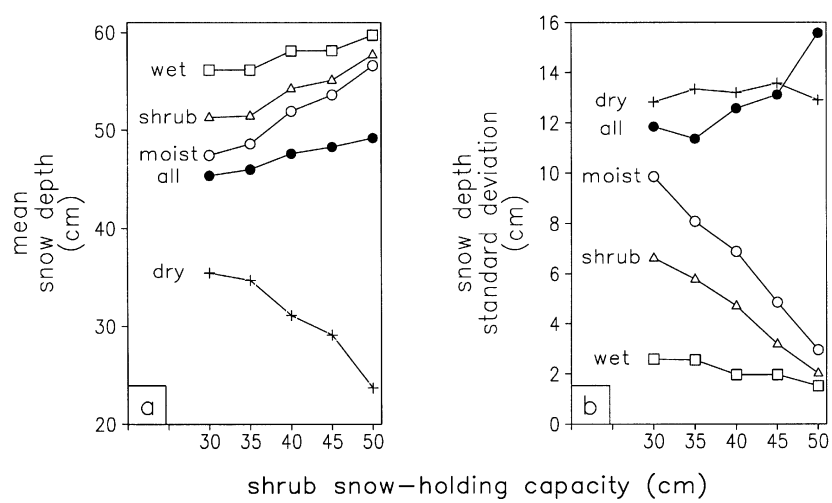


Fig. 4 Same as Fig. 3, but for 1990.

Fig. 5 Model sensitivity simulations for 1987 showing the variation in (a) mean snow depth, and (b) snow depth standard deviation for different choices of shrub snow-holding capacity. Values are plotted for the areas covered by each observed vegetation type (Fig. 1) and for the entire domain (all).



throughout the domain became more highly differentiated as the snow-holding capacity increased (see the 'all' curve in Fig. 5b). At the same time, increasing the snow-holding capacity resulted in decreased snow-depth variability *within* the vegetation types that were converted to shrubs (Fig. 5b). These effects are consistent with the pattern of differences we found between the shrub-enhanced and observed-vegetation simulations, suggesting that another choice of snow-holding capacity would have produced similar results, but with approximately proportional changes in the snow-depth and sublimation values.

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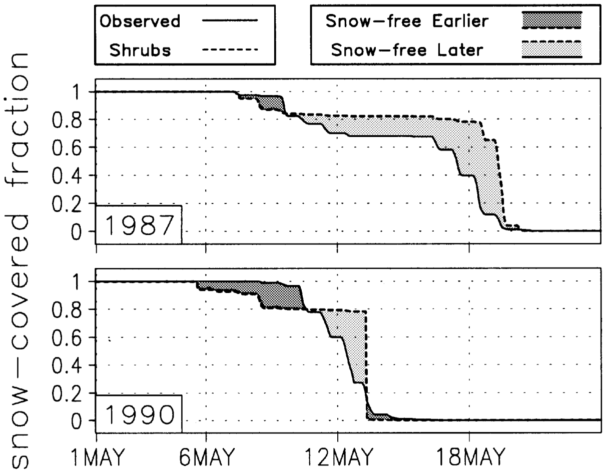

Fig. 6 Time evolution of spring snow disappearance for observed-vegetation and shrub-enhanced snowcover in 1987 (top) and 1990 (bottom). In the shrub-enhanced simulation, ridges became snow-free earlier (dark shading), and shrub-covered areas became snow-free later (light shading), compared to the observed-vegetation simulation.

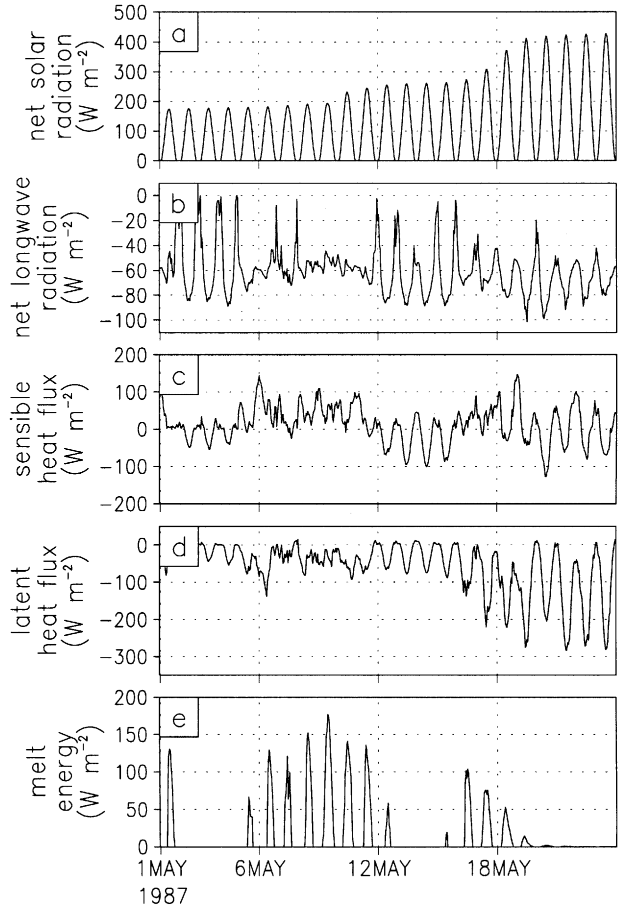

Fig. 7 Domain-averaged, hourly surface energy balance components for the 1987 snowmelt period: (a) net solar radiation, (b) net longwave radiation, (c) sensible heat flux, (d) latent heat flux, and (e) melt energy. Energy fluxes toward the surface are defined to be positive.

Snowmelt simulations

In the 1987 simulation, shrub enhancement caused the snow to melt free earlier over a small part of the domain, but it delayed the time of final melt over most of the domain (Fig. 6). This earlier exposure of vegetation was due to the thinner snowcover on the (dry-tundra) ridges (Table 2), and the later exposure of vegetation is due to the deeper snowcover over the shrub-covered majority of the domain. The snowcover removal by melting in 1989 (not shown) was similar to that in 1987, and the snowcover removal in 1988 (not shown) was similar to 1990.

In 1990, air temperatures were largely above freezing throughout the melt period (Fig. 2). The shrub-enhanced depletion curve (Fig. 6) highlights the initial depletion of the thin, ridge-top snowcover, followed by the abrupt depletion of the uniform shrub-enhanced snowcover late in the melt period. In the simulation, daily melt rates were roughly constant throughout the melt period (not shown), and the observed-vegetation snow distribution was generally uniformly distributed over the snow depth range of 30–50 cm (Fig. 4c). As a result, the observed-vegetation snowcover depletion was quite linear (Liston 1999). For the case of enhanced shrubs, with its relatively uniform snow distribution over the shrub areas of the domain, we expect the snowcover depletion to behave like a step-function, where the majority of the vegetation is exposed as the 50 cm snowcover is finally reduced to zero. As an illustrative example of how this works, if we apply a 5-cm per day melt rate to a 25-cm snowcover, then at the end of day five the area goes from 100% snow-covered to 100% snow-free.

Figure 7 displays the hourly, domain-averaged surface energy balance components computed during the 1987 snowmelt period, for the case of the observed-vegetation simulation. Energy fluxes toward the surface are defined to be positive. The daily averaged, domain-averaged net solar radiation increased by a factor of 2.7 as the domain went from snow-covered (75 W m^{-2}) to snow-free (203 W m^{-2}); where the vegetation and melting-snow albedos were assumed to be 0.15 and 0.6, respectively. A dramatic increase in net solar radiation as snowmelt progresses is commonly observed in the arctic (e.g. Weller *et al*. 1972; Weller & Holmgren 1974; Rouse 1990; Hinzman *et al*. 1996; Eugster *et al*. 2000). The sensible heat flux was positive (downward) during melting periods, and when the domain was snow-free the sensible heat flux was positive at night and negative during the day. The latent heat flux became more negative throughout the simulation, reflecting increased evaporation as the melt progressed. The melt energy was greatest early in the melt period when the domain had the greatest snow-covered fraction. The general characteristics of the surface energy fluxes during the 1987 snowmelt period were typical of the other three simulation years (not shown). In 1987, the melting stopped completely around 14 May when air temperatures dropped below freezing, and then started again around 16 May when air temperatures rose above freezing.

Differences in energy-balance components between the shrub-enhanced and observed-vegetation simulations for 1987 are given in Fig. 8. These difference plots highlight the strong control of snowcover in defining the surface energy fluxes. Because shrubs have modified the snow distribution, virtually every component of the surface energy balance has been affected. The net solar radiation was reduced by as much as 125 W m^{-2} in response to the greater snow-covered area during much of the melt period. The sensible and latent heat fluxes were greater (less negative), by as much as 75 and 125 W m^{-2}, respectively, throughout this same period. The melt energy differences were greatest late in the melt period when the deepest snow in the shrub-enhanced simulation was being melted.

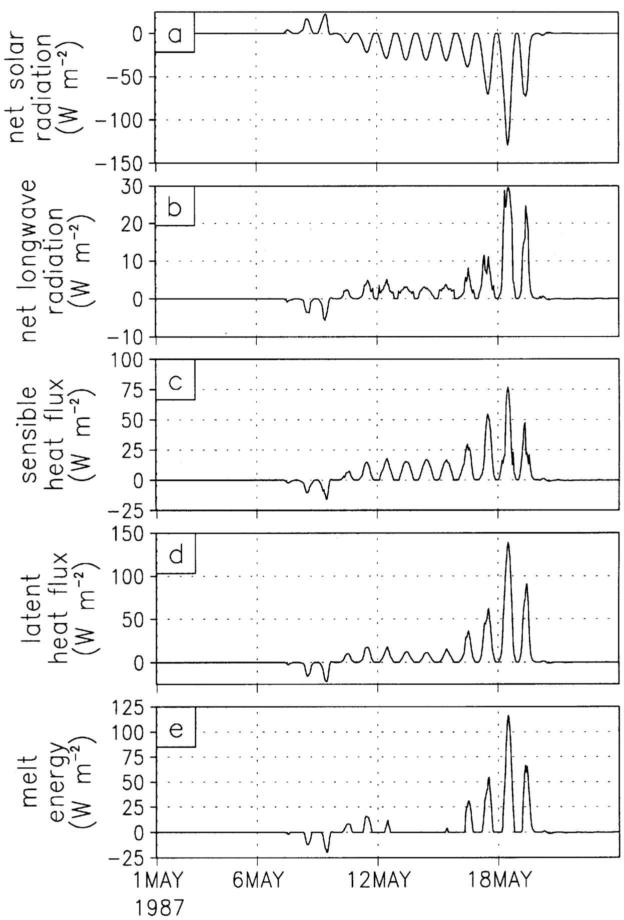

Fig. 8 Differences in domain-averaged, hourly surface energy balance components for the 1987 snowmelt period (the shrub-enhanced variable minus the observed-vegetation variable): (a) net solar radiation, (b) net longwave radiation, (c) sensible heat flux, (d) latent heat flux, and (e) melt energy.

Discussion

Increasing the distribution and height of shrubs in our model simulations had two primary consequences: (i) less snow was redistributed by the wind, and (ii) less snow was lost to sublimation during wind transport. The interactions between snow-precipitation inputs and vegetation height, and the processes of wind redistribution and sublimation are represented schematically in Fig. 9. With increased shrubs, less wind transport resulted in a reduced snowpack over downwind, dry-tundra areas (Figs 3a, b, 4a, b). At the same time, shrubs caused a decrease in sublimation fluxes, which increased the amount of snow remaining on the ground at the end of winter within the shrub-covered area. Shrub enhancement reduced sublimation by 20% or more over much of the domain (Fig. 10). During the four years that we studied, the domain-averaged fraction of total winter precipitation that was returned to the atmosphere by sublimation varied from 2% to 10% with increased shrubs, compared to 10–25% with the observed vegetation (Table 2). Under conditions of higher wind speeds, such as those experienced in the coastal regions of arctic Alaska, domain-averaged sublimation fractions of over 30% of the precipitation input can be expected (Liston & Sturm 1998). This sublimation fraction represents a significant portion of the winter surface moisture budget that is not currently accounted for within regional and global climate models (Pomeroy *et al*. 1998). If the simulation domain was able to support enhanced shrubs over its entire area, such as might be possible for regions without the dry tundra included within the Imnavait domain, then conditions where the shrub snow-holding capacity exceeds the winter precipitation would lead to essentially zero blowing-snow sublimation.

The shrub-related snowcover changes also affect the snow distribution's thermal characteristics. By assuming the snowcover consists of two distinct layers, one of depth hoar and one of wind slab (Benson & Sturm 1993),

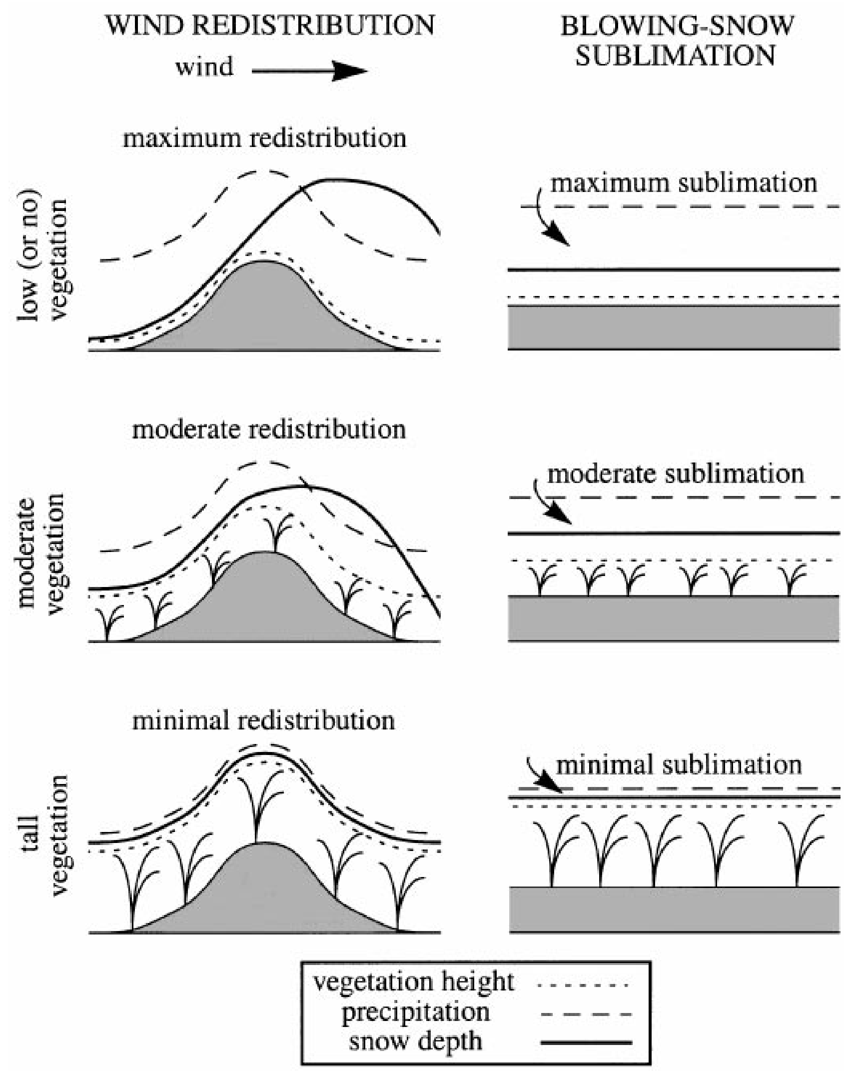

Fig. 9 Schematic illustrating the reduction in wind redistribution and blowing-snow sublimation resulting from increased vegetation heights.

the vertically integrated thermal resistance, R_{th}, (K W^{-1}) is given by

$$R_{th} = \frac{L_{dh}}{k_{dh} A} + \frac{L_{ws}}{k_{ws} A}$$

where A is a unit area (1 m^2), L_{dh} and L_{ws} are the thicknesses (in metres) of the depth hoar and wind slab layers, respectively, and the thermal conductivity of depth hoar (k_{dh}) and wind slab (k_{ws}) are 0.05 W m K^{-1} and 0.15 W m K^{-1}, respectively (Sturm *et al*. 1997). In the following analysis the depth hoar is assumed to extend from the base of the snowcover to the lesser of the vegetation snow-holding capacity or to 30 cm, and the wind slab extends from the top of the depth hoar layer to the top of the snowcover (Benson & Sturm 1993). This approach provides a conservative estimate of the thickness of the depth hoar layer and takes into account the reduction in the snowcover's vertical temperature gradient (that governs depth hoar formation) as the snow depth increases. Applying Equation 3 to the simulated snow distributions yields the change in thermal resistance resulting from shrub enhancement. For 1987, these changes are plotted in Fig. 11. There are two ways that the thermal resistance is modified as part of these simulations: (i) through changes in snow depth, and (ii) through changes in depth-hoar and wind-slab layer thicknesses as a result of modifying the vegetation snow-holding capacity. In Fig. 11, reductions in thermal resistance occur where the snow depth was reduced, such as in the dry-tundra areas on ridge tops (Tables 2 and 3). Places with increased snow depths led to greater bulk thermal resistance from both increased depth and the lower thermal conductivity of the depth-hoar layer.

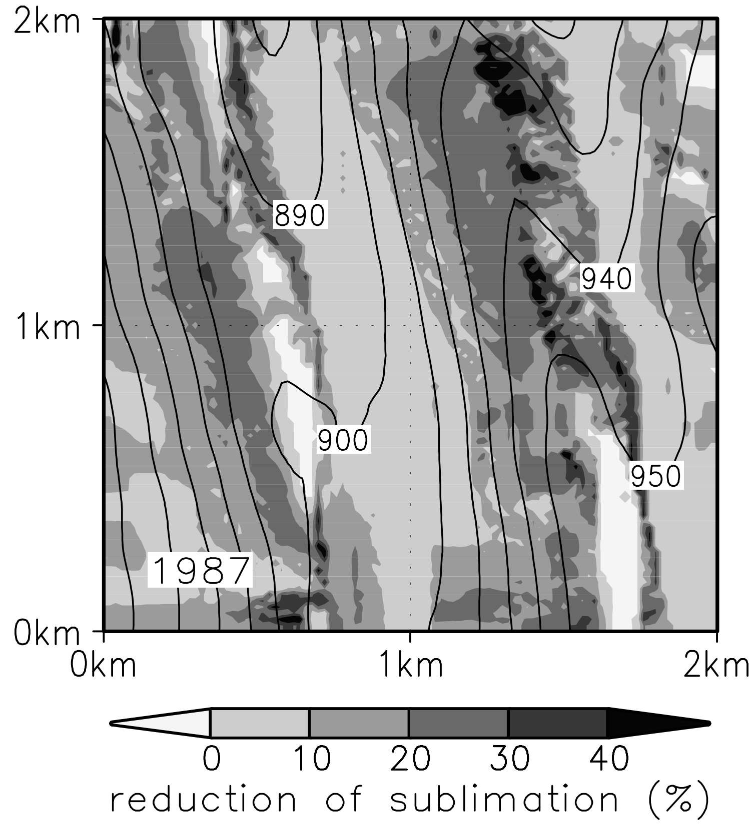

Fig. 10 Reduction of blowing-snow sublimation resulting from shrub enhancement for 1987. Plotted are the differences between the fraction of precipitation that sublimated with shrub enhancement, minus the fraction that sublimated with observed vegetation.

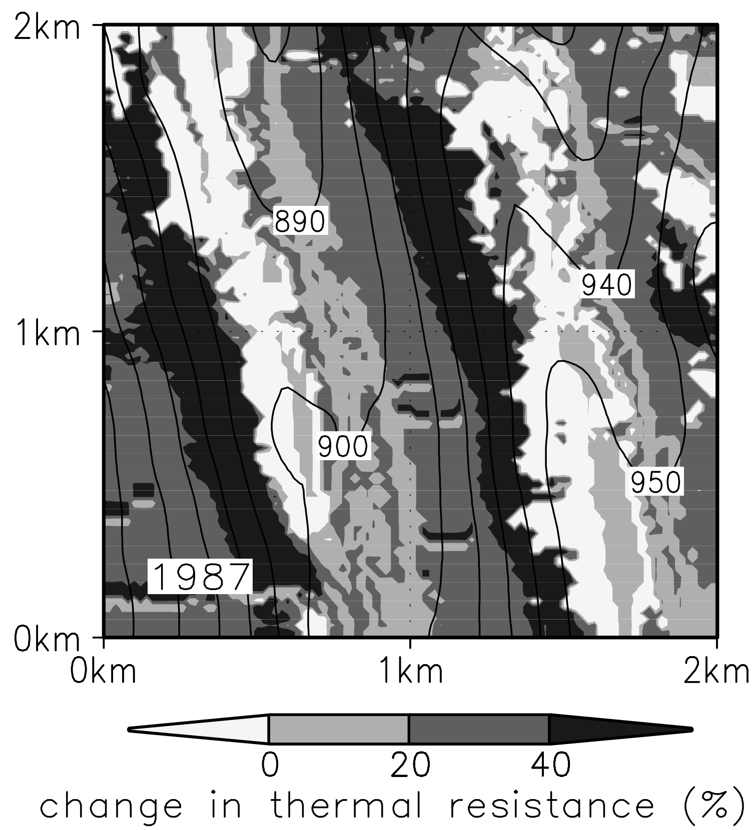

Fig. 11 Change in thermal resistance resulting from shrub enhancement for 1987.

Table 3 Domain-averaged end-of-winter thermal resistance (R_{th}) of the snowcover for observed- and shrub-enhanced vegetation, and the percentage change in R_{th} resulting from shrub enhancement. The lower section presents the breakdown of R_{th} averaged over the portion of the domain covered by each of the different types in the observed vegetation distribution (Fig. 1).

	1987		1988		1989		1990	
	Observed	Shrubs	Observed	Shrubs	Observed	Shrubs	Observed	Shrubs
R_{th} (K W^{-1})	5.1	6.1	4.5	5.4	6.3	7.0	5.1	5.6
Change (%)		+20		+20		+11		+10
Dry tundra								
R_{th} (K W^{-1})	3.7	2.9	3.1	2.4	5.7	4.2	4.0	2.7
Change (%)		–22		–23		–26		–33
Moist tundra								
R_{th} (K W^{-1})	5.4	7.8	4.8	6.9	6.3	8.5	5.3	7.2
Change (%)		+44		+44		+35		+36
Wet tundra								
R_{th} (K W^{-1})	7.7	8.0	6.7	7.0	8.6	8.8	7.2	7.2
Change (%)		+4		+4		+2		0
Shrub tundra								
R_{th} (K W^{-1})	7.5	7.8	6.7	7.0	8.1	8.6	7.0	7.2
Change (%)		+4		+4		+6		+3

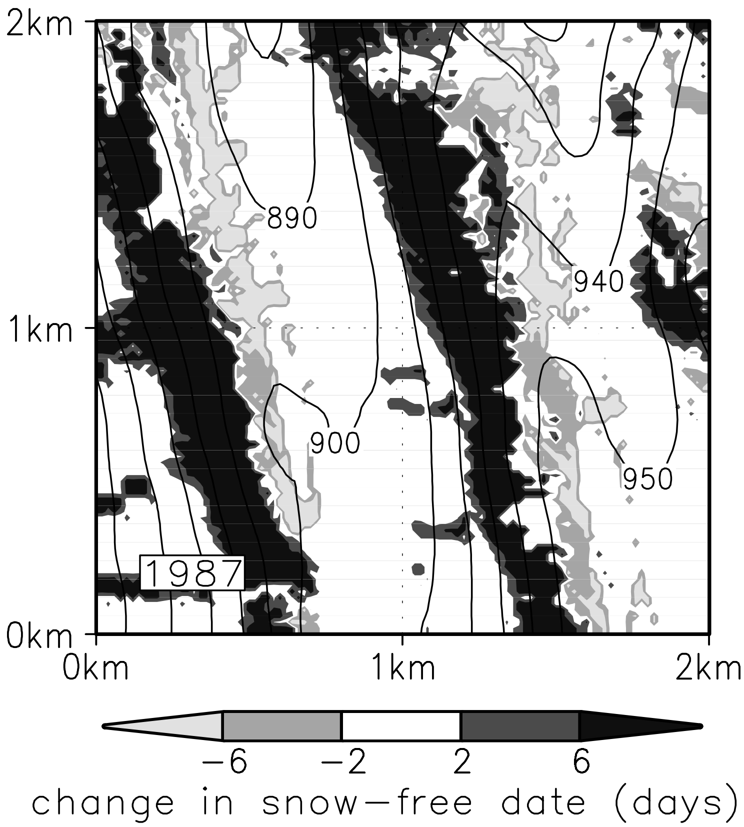

Fig. 12 Difference in snow-free date resulting from shrub enhancement for 1987. Positive (negative) numbers indicate the number of days longer (shorter) the vegetation surface remained snow-covered when shrubs were enhanced.

Table 3 summarizes the decreased thermal resistance over dry tundra, and the increases over the moist, wet and shrub areas. Averaged over the four simulation years, the domain-averaged thermal resistance increased by 15% (Table 3). These changes are expected to directly affect winter soil temperatures, which strongly control

Table 4 Difference in snow-covered-season length between the observed-vegetation and shrub-enhanced simulations. These data include the mean and (range) for the change in snow-covered period length, in days, for the areas covered by each vegetation-type distribution (Fig. 1). Negative (positive) numbers indicate a decrease (increase) in snow-covered period.

	1987	1988	1989	1990
Dry tundra	–4 (–13, 9)	–3 (–7, 1)	–3 (–10, 4)	–4 (–13, 3)
Moist tundra	4 (–7, 10)	1 (–5, 1)	2 (–5, 5)	1 (–8, 4)
Wet tundra	0 (–1, 2)	0 (–1, 1)	0 (–1, 4)	0 (–2, 2)
Shrub tundra	1 (–1, 8)	0 (0, 1)	1 (0, 4)	0 (0, 3)

microbial activity and winter CO_2 efflux (Kelley *et al*. 1968; Zimov *et al*. 1993a, 1993b; Oechel *et al*. 1997; Fahnestock *et al*. 1998; Grogan & Chapin 1999).

Figure 6 shows that the snow-covered fraction goes to zero on approximately the same date for the original-vegetation and the shrub-enhanced simulations, for each of the four years. This is because the maximum snow depths have not greatly increased, even though with enhanced shrubs there is more area covered by deep snow. While the domain-averaged increase in snow-covered period for each of the four years is within a couple of days of zero, the snow-free date of individual model grid cells can vary considerably over the melt period. Figure 12 displays the difference in snow-free date resulting from shrub enhancement. In shrub-free (dry-tundra) areas of the domain, the snow depth was reduced and the snow-free date occurs earlier (Table 4). In shrub-enhanced areas, the snow depth was increased and the snow-free date occurs later. For the four simulation years, the maximum decreased and increased snow-covered period averaged 11 and 5 days, respectively (Table 4).

Changes in snow distribution resulting from shrub enhancement also modified the melt-energy flux timing (Figs 7 and 8). This relates directly to the timing and magnitudes of snowmelt-runoff production. Figure 13 displays the 1987 daily snowmelt under shrub-enhanced and observed-vegetation conditions. For the other three simulation years there was also additional meltwater produced late in the melt period (not shown). In addition to modifying the timing of meltwater production, this additional meltwater corresponded to the increased snow depths resulting from shrub enhancement (Table 2). Such changes are expected to influence soil temperatures and moisture conditions, as well as stream and river discharge characteristics.

In the natural system there are important interactions and feedbacks that have not been accounted for in this study. In particular, as the snow-covered area is replaced

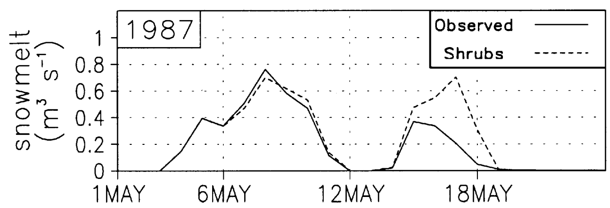

Fig. 13 Domain-averaged snowmelt production for 1987, under conditions of observed vegetation and shrub enhancement.

by exposed vegetation, the air temperatures and humidities will be modified in response to the changing surface conditions. These changes feed back and accelerate the melt of the remaining snowcover (Liston 1995, 1999; Essery 1997; Neumann & Marsh 1998). Within the context of this study, we expect that such feedbacks would reduce the snowmelt rates late in the melt period for the shrub-enhanced case because of the greater snow-covered area at that time (Fig. 6). This would, in turn, create further differences in surface energy fluxes, and further delay the snow-free dates. On much longer time scales, responses of the vegetation itself can be expected. For example, the shrub-induced changes in thermal and moisture conditions would be expected to influence vegetation distribution and abundance (Scott & Rouse 1995; Walker *et al*. 1999).

A transient vegetation change scenario, compared to the step-change or equilibrium condition we modelled, would depend on the numerous atmospheric, vegetation and snowcover interactions that exist within the system. Field experiments suggest that higher summer air temperatures could increase shrub abundance in the region we studied (Hobbie & Chapin 1998). However, under some conditions a warmer environment could lead to a decrease in shrub abundance, such as if tundra is converted to grassland-steppe under hot, dry summers with increased fire frequency (Chapin & Starfield 1997). In addition to air temperature, other factors, such as below-surface thermal and moisture conditions, play important but largely unknown roles in defining shrub growth.

Conclusions

Palaeoecological and experimental field studies indicate that a key response of arctic vegetation to warmer and/or nutrient-enhanced environments could be an expansion of deciduous shrubs. A modelling system that accounts for the interactions between vegetation, snowcover and the atmosphere was used to address the consequences of increased arctic shrubs for snow-distribution characteristics and surface energy and moisture fluxes during the autumn, winter and spring. In response to the shrub-enhanced condition, domain-averaged snow depths increased by 14%, averaged over the four simulation years. Because shrubs hold the snow precipitation, only precipitation that exceeds the vegetation's snow-holding capacity is available to be redistributed and sublimated during wind-transport events. Averaged over the four simulation years, the domain-averaged blowing-snow sublimation fluxes decreased by 68%.

The shrub enhancement led to bimodal snow distributions, in contrast to the unimodal snow distributions that exist under current vegetation conditions. The shrubs caused a larger area to be covered by snow of maximum depth, and the ridges had less snow than without the shrub enhancement. Increasing shrubs in one place caused important changes in adjacent areas where the vegetation was not modified. For example, the presence of shrubs upwind of dry-tundra areas reduced the upwind blowing-snow fluxes to the extent that the snow depth was reduced (less blowing-snow deposition) in the unmodified areas. Blowing-snow sublimation fluxes, the snowcover's thermal resistance and the snow-free dates at those locations were also modified.

The bimodal snow distributions also modified snowmelt timing and magnitudes, where the deeper portions of the snowcover melted late in the melt season, leading to greater runoff at this time. Greater runoff could increase the transport of nutrients (Chapin *et al*. 1988) and dissolved carbon (Kling *et al*. 1991) from terrestrial to aquatic ecosystems. The increased shrubs also caused changes in the snowcover's thermal characteristics and snow-free dates. Averaged over the four simulation years, the domain-averaged thermal resistances increased by 15%. Enhancing shrubs decreased the snow-covered period by an average of 11 days in some areas of the domain, but increased the snow-covered period by 5 days in other areas. For a region that has an annual snow-free period of approximately 90 days, these represent significant changes in growing season length for different ecosystems within the domain.

In addition to shrub increases in one place causing important changes in adjacent areas where the vegetation was not modified, this study has demonstrated that a change in shrub distribution and abundance can reduce winter surface moisture sublimation losses, and make that same moisture available to the land surface at the end of the spring snowmelt period. Thus, we have found that increases in arctic shrub coverage can affect both the spatial and temporal coupling of climatically important snow, energy and moisture interactions.

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