

## Chapter 6

### **Snowmelt Processes and Runoff at the Arctic Treeline: Ten Years of MAGS Research**

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**Abstract** Under the Mackenzie GEWEX Study, extensive snowmelt and runoff research was carried out at the Trail Valley and Havikpak Creek research basins at the tundra-forest transition zone near Inuvik, Northwest Territories. Process based research concentrated on snow accumulation, the spatial variability of energy fluxes controlling melt, local scale advection of sensible heat from snow-free patches to snow patches, percolation of meltwater through the snowpack, storage of meltwater in stream channels, and hillslope runoff. Building on these studies, process based models were improved, as shown by a better ability to model changes in snow-covered area during the melt period. In addition, various land-surface and hydrologic models were tested, demonstrating an enhanced capability to model melt related runoff. Future research is required to accurately model both snow-covered area and runoff at a variety of scales and to incorporate topographic and vegetation effects correctly in the models.

#### **1 Introduction**

Prior to the Mackenzie GEWEX Study (MAGS), there had been numerous studies of snowmelt and snowmelt runoff in northern Canada. Examples include: the distribution of the spatially variable end-of-winter snow cover (Woo et al. 1983) caused by blowing snow events (Pomeroy et al. 2007); surface energy balance of snow covered terrain (Dunne et al. 1976); water storage in snow choked channels (Woo and Sauriol 1980); and melt water flow through cold snowpacks (Dunne et al. 1976; Marsh and Woo 1984a, 1984b). However, by the start of MAGS in the mid 1990s, many unknowns remained (Marsh 1999) and there was considerable uncertainty in our ability to model snow accumulation, melt and runoff at a range of scales in northern environments. To help address these issues, the National

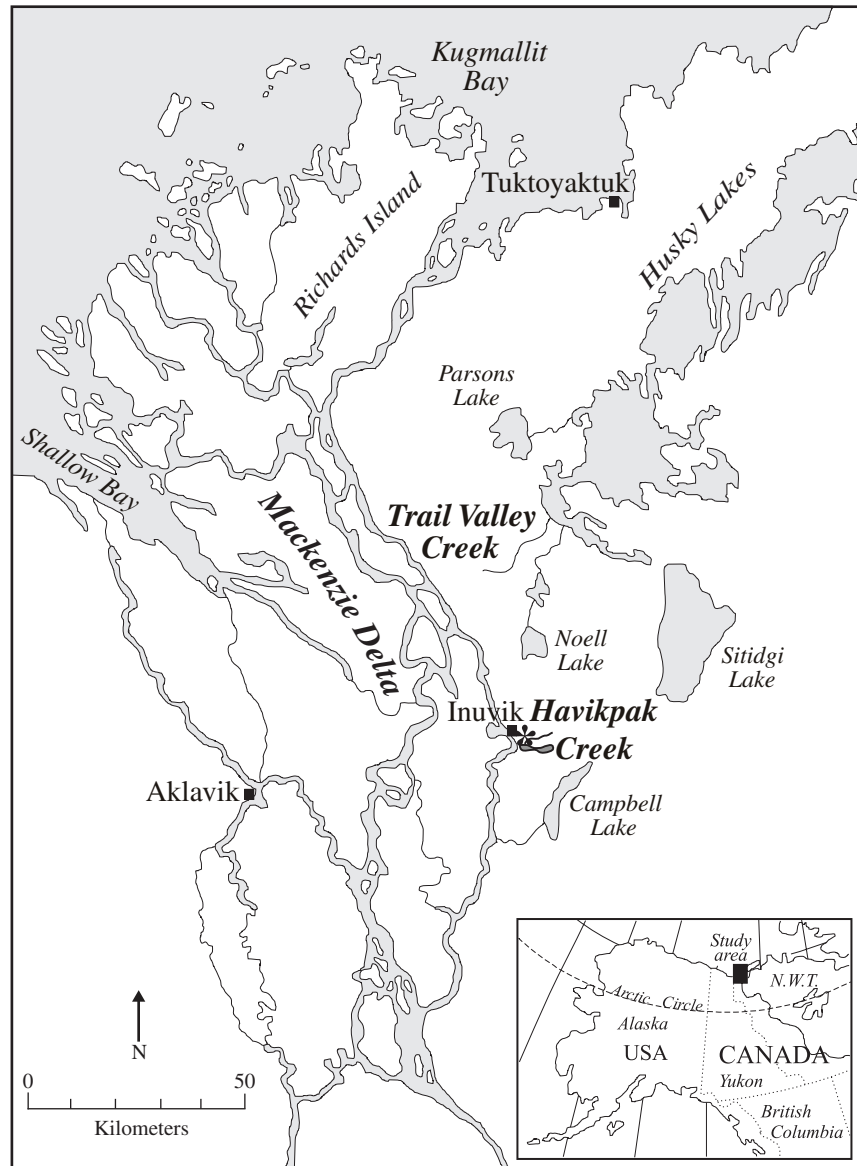
Water Research Institute (NWRI) of Environment Canada conducted research in two basins in the boreal forest–tundra transition zone, in an environment representative of the northern portions of the Mackenzie River Basin (MRB). Although the terrain and vegetation types constitute a small portion of the total Basin area, they are typical of a large area of the circumpolar Arctic.

Under the umbrella of this NWRI research, the topics of investigation included:

- blowing snow and snow accumulation (reported in Pomeroy et al. 2007);
- spatial variability of energy fluxes controlling melt, including: point estimates measured from towers; larger scale variability estimated from aircraft; advection of sensible heat from snow-free to snow covered patches; scale considerations for modeling turbulent fluxes and radiation for a typical modeling grid; and modeling changes in snow-covered area during melt;
- percolation of meltwater through the snowpack;
- storage of meltwater in stream channels prior to the initiation of streamflow in the spring;
- improvement of snowmelt and snowmelt runoff models; and
- incorporation of an appropriate variety of hydrologic and land-surface models for use in northern environments.

## 2 Study Area and Methods

The lower Mackenzie Valley is characterized by a vegetation transition from northern boreal forest to tundra and the occurrence of continuous permafrost with thickness of 100 to 150 m. Hydrologic research has been conducted in two basins in this area since 1992 (Fig. 1). Trail Valley Creek (TVC), located approximately 50 km northeast of Inuvik (68°17'N; 133°24'W), has an elevation range from 48 to 205 m asl, and is dominated by tundra vegetation (Marsh and Pomeroy 1996). The basin area has been reported as 63 km<sup>2</sup> (Marsh and Pomeroy 1996) or 68 km<sup>2</sup>, according to the Water Survey of Canada; but recently obtained LiDAR data indicate that an upper part of this estimated basin area drains into an adjacent basin. Using RiverTools to estimate drainage area covered by the LiDAR data provides an estimated basin area of 55.1 km<sup>2</sup>. Combined with an additional 2 km<sup>2</sup> outside the LiDAR coverage (estimated from DEM), a best estimate of the TVC basin area is 57 km<sup>2</sup>. This example illustrates an often



**Fig. 1.** Location map showing Trail Valley and Havikpak Creeks. The Inuvik MSC (formerly AES) upper air station is indicated by asterisk (\*)

overlooked error associated with the drainage networks on topographic maps. Such an error can render it difficult to compare modeled and measured discharge. With an overestimate of basin area by >10%, an even dis-

tribution of precipitation and evaporation over the entire basin would cause a similar overestimation of discharge by any hydrologic model.

Havikpak Creek (HPC) situated a few kilometers north of the Inuvik airport (Marsh et al. 2002) is 17 km<sup>2</sup> in area, has an elevation range from 73 to 231 m asl, and is predominantly covered by northern boreal forest, with tundra in the higher elevations. The contrasting vegetation between TVC and HPC has significant effects on aspects of their hydrology, including snow accumulation and melt, evaporation and runoff (Russell 2002).

A Meteorological Service of Canada (MSC) upper air station is located near the outlet of HPC, and a MSC weather station is located within the TVC basin. NWRI has also operated meteorological stations at both research basins since 1992, recording air temperature, rainfall, snowfall, net radiation, incoming and outgoing solar radiation, soil moisture and soil temperature, and turbulent fluxes using eddy correlation during periods of intensive measurements. Incoming long-wave radiation measurement was added during the latter stage of MAGS. Although these stations operated throughout the year, they were unattended for much of the winter, with implications to the accuracy of some of the measurements. Snow surveys, stratified by terrain type, were conducted at both TVC and HPC in most years. Water Survey of Canada (WSC) has operated discharge gauging stations at TVC and HPC since 1979 and 1994, respectively. Additional determination of discharge by current metering from a boat or by wading, and by dye injection (Russell et al. 2004) were made by NWRI during the spring to reduce the large errors typical of discharge estimates in snow/ice clogged channels. Routine meteorological and hydrologic measurements by the MSC and WSC are used to fill in missing research basin measurements. These observations have resulted in a consistent, long term data set that is available for many purposes. For example, Marsh et al. (2004) used these data to consider variations in the annual water balance of TVC and HPC for the period 1992 to 2000. Marsh et al. (2002) analyzed the long term MSC and WSC records, to consider the maximum late winter SWE, timing of the winter to summer transition, the date of the onset of runoff from TVC and HPC, and the time of the peak flow at these basins. This analysis demonstrated that the 1994/95 MAGS study year had the earliest winter to summer transition on record, with early spring melt and its attendant runoff.

### 3 Spatial Variability of Snowmelt Processes

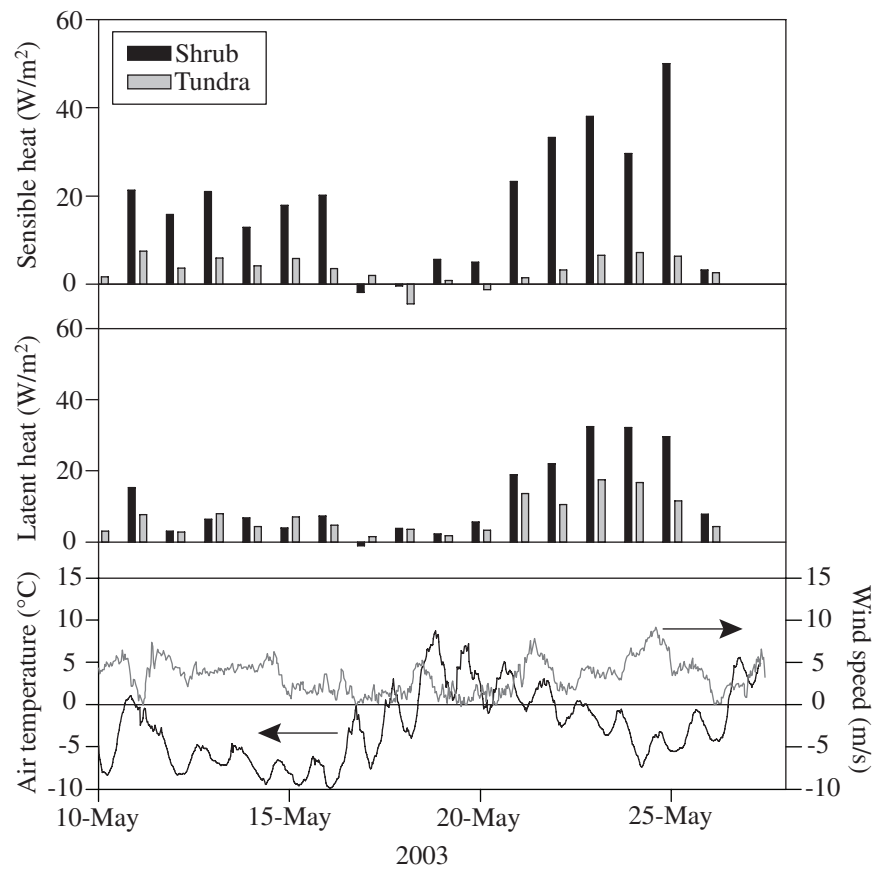
The TVC and HPC land surface is heterogeneous at different scales and in surface patterns due to their irregular topography and vegetation cover. Differences in the vertical transfers of radiation and sensible and latent heat from different portions of the land surface often result in large spatial differences in snowmelt. Combined with a spatially variable end-of-winter snow distribution (Pomeroy et al. 2007), these processes produce a highly variable and patchy snow cover during the melt period. This patchiness significantly affects the fluxes of energy from the land surface to the atmosphere, as well as runoff.

#### 3.1 Measured Variability in Turbulent and Radiative Fluxes

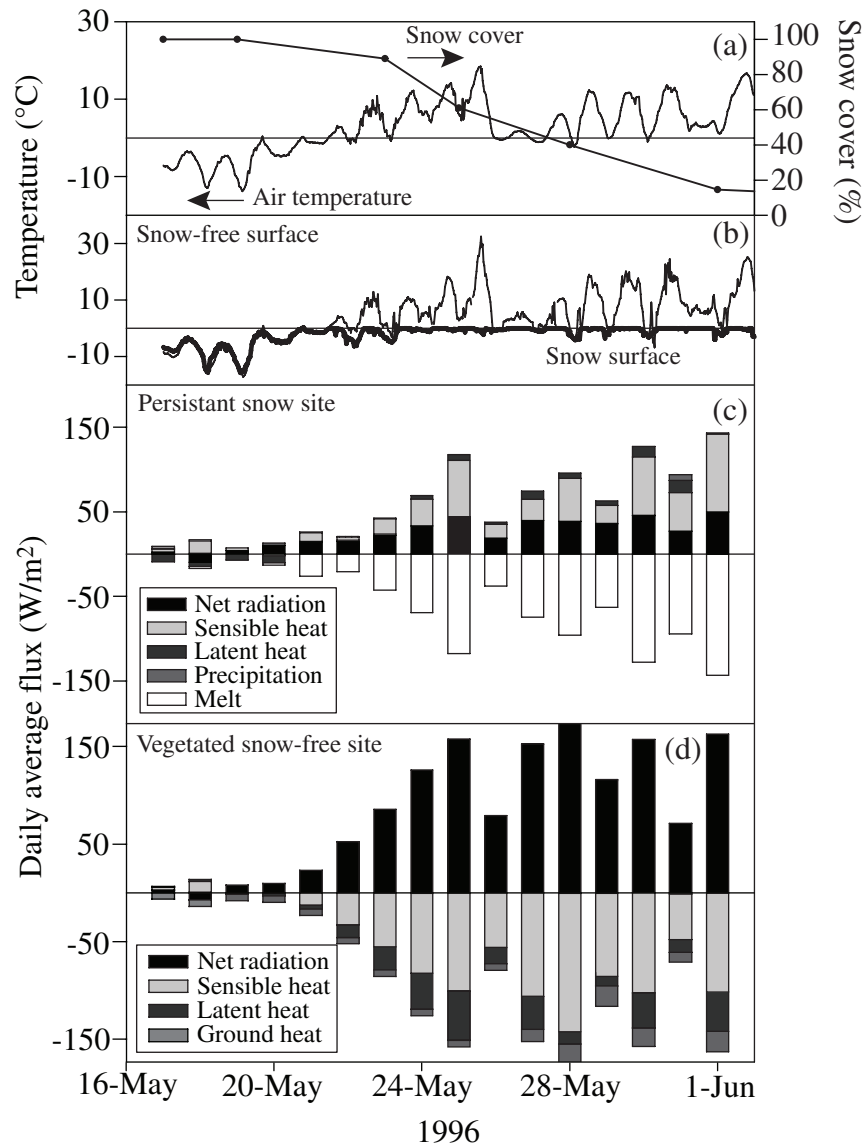
The snowmelt landscapes of open windswept environments typically have patchy snow covers during the melt period (Marsh 1999), with large differences in albedo, surface roughness, and surface temperature between the snow and snow-free patches. Observations of turbulent fluxes and radiation from both towers and aircraft have confirmed such spatial variability. Examples are provided from tower observations. Figure 2 shows the sensible and latent heat fluxes at TVC over a tundra and a shrub site. Although latent heat was similar at both sites early in the melt period, sensible heat flux was typically larger at the shrub site throughout the melt season, while latent heat became larger at the shrub site in the latter parts of the melt period. Figure 3 compares measurements over a persistent snow patch and over a snow-free patch. As expected, net radiation was much smaller at the snow site, while the sensible, latent, and ground heat fluxes were in different directions at the two sites. Such large variations in fluxes clearly indicate that a single point measurement of turbulent fluxes cannot represent an entire basin.

To obtain a better estimate of the spatial variability of fluxes at both TVC and HPC, the NRC Twin Otter Flux aircraft of the National Research Council was employed during the 1999 Canadian GEWEX Enhanced Study (CAGES) field period in the Inuvik area (Brown-Mitic et al. 2001). The sensible heat, latent heat, and net radiation measured from the aircraft (for a 1 km line centered over the tower) agreed well with the tower data (Fig. 4a), suggesting that the TVC tower is representative of a larger area around it. Figure 4b shows hourly flux data from the TVC tower for the entire melt period, as well as average flux measurements along each of 9 flight lines covering all of TVC. Since the aircraft data were obtained over

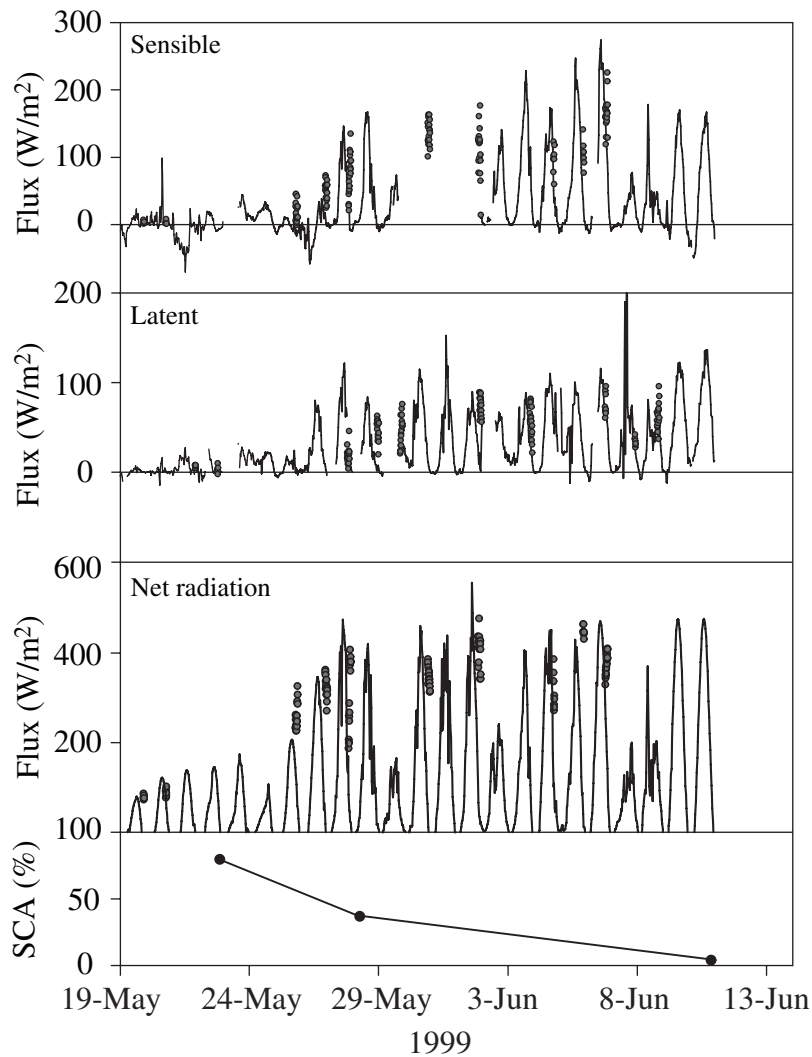
a short period (approximately a 1 hour period each day), they can be considered as “snapshots” of conditions covering the entire basin. Early in the melt period, when the basin was completely snow covered, the fluxes from the aircraft and the tower were in agreement. As the snow covered area (SCA) declined over the melt season, the peak fluxes measured by the



**Fig. 2.** Sensible and latent heat flux for tundra and shrub sites located in the vicinity of TVC. Also shown are air temperature and wind speed at both sites (after Marsh et al. 2003)



**Fig. 3.** Trail Valley Creek: (a) air temperature and fractional snow cover, (b) snow surface temperature and snow-free surface temperature, (c) energy balance terms for a persistent snow site and (d) for a snow-free vegetated site. May 17 to June 1 covers the period immediately before the start of snowmelt until the time with only residual snow covering approximately 10% of the basin area. Snowcover data are from SPOT satellite image and all energy balance terms are considered to be spatially representative averages (after Neumann and Marsh 1998)



**Fig. 4.** Sensible and latent heat flux, and net radiation as measured from both the TVC tower (line), and from the NRC aircraft (circle). Also shown is the basin snow covered area. Data are either average values from a single line passing over the tower, or averages for each of the nine flight lines

tower increased, and the range of fluxes measured by the aircraft also increased, clearly showing an increase in the spatial variability in fluxes. It is believed that these observed spatial variations in fluxes at scales of less than 1 km play an important role in the hydrology of northern areas. As a



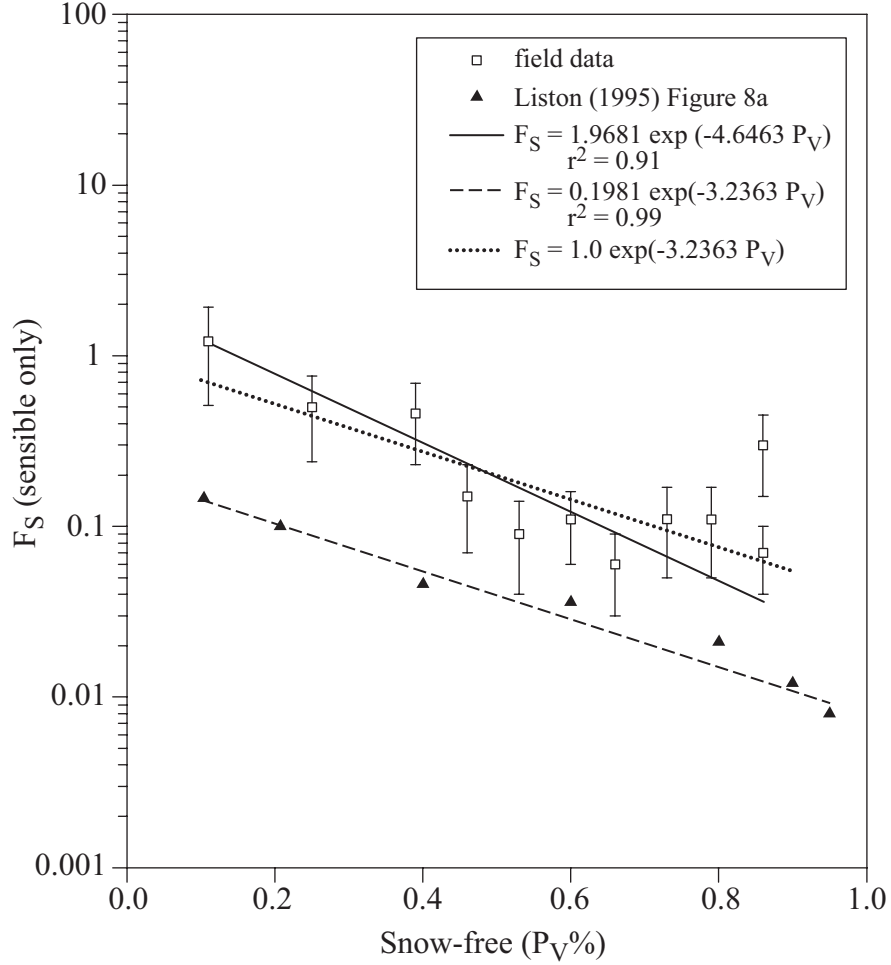
result, the following observations and modeling studies were undertaken in order to better understand the importance of such variations, and to assess the appropriate scale needed for simulating the hydrology of these areas.

### 3.2 Advection of Sensible Heat from Bare Patches to Snow Patches

The primary sources of energy for snowmelt are sensible heat and radiant energy, while local advection of sensible heat from the bare ground can increase the fluxes at the upwind edge of the snow patches (Shook 1995). Local advection is further complicated by the gradually changing area and size distribution of the patches during the snowmelt period. Attempts were made to incorporate advection into simple melt models. Marsh and Pomeroy (1996) showed that the average advection of sensible heat to snow patches can be related to the available sensible heat from the snow-free areas, and suggested that the ratio between the two, termed the advection efficiency factor ( $F_s$ ), varied over the snowmelt period.  $F_s$  varies between 0 and 1, and its determination requires estimates of the spatially averaged sensible heat flux to the snow patches, the sensible heat flux at the downwind edge of a large snow patch where local advection is negligible, the sensible heat over vegetated snow-free area, and the fraction of the basin that is snow-free and snow-covered.

Marsh et al. (1997, 1999) and Neumann and Marsh (1998) used field observations and a boundary layer model to show that  $F_s$  decreases with increasing snow-free area (Fig. 5), but increases with wind speed and decreasing snow patch size. Neumann and Marsh (1998) suggested that the relationship between  $F_s$  and the snow-free fraction ( $P_v$ ) can be described as:  $F_s = 1.0 \exp(-3.2 P_v)$ . Differences in the relationship between  $F_s$  and  $P_v$  from field and modeling studies could be attributed to differences in patch size between the observations and model.

Pohl and Marsh (2006) incorporated  $F_s$  into a snowmelt model. This improved the accuracy of the estimate of the snow cover area during the melt period when snow coverage decreased from 40% to 5% of the basin area. Since the usage of  $F_s$  has only been tested in limited conditions, further work is needed to better understand how the relationship changes between the magnitude of local scale advection and such factors as terrain condition, patch geometry, and patch size.



**Fig. 5.** Advection efficiency term ( $F_S$ ) vs. snow-free fraction. Dashed line represents the best fit to the model output from Liston (1995) for model runs with a single snow patch of varying size. Solid line is the best fit for  $F_S$  estimated from measurements at TVC, with error bars for the case of a  $\pm 40\%$  error in  $\hat{Q}_{H_S}$  (i.e., sensible heat flux at 1.8 km downwind of the leading edge of a large snowpack, as estimated from Eq. 3). Dotted line has an intercept of 1 and the same slope as the best fit line through Liston model data (after Neumann and Marsh 1998)

### 3.3 Variability in Turbulent Fluxes and Incident Solar Radiation

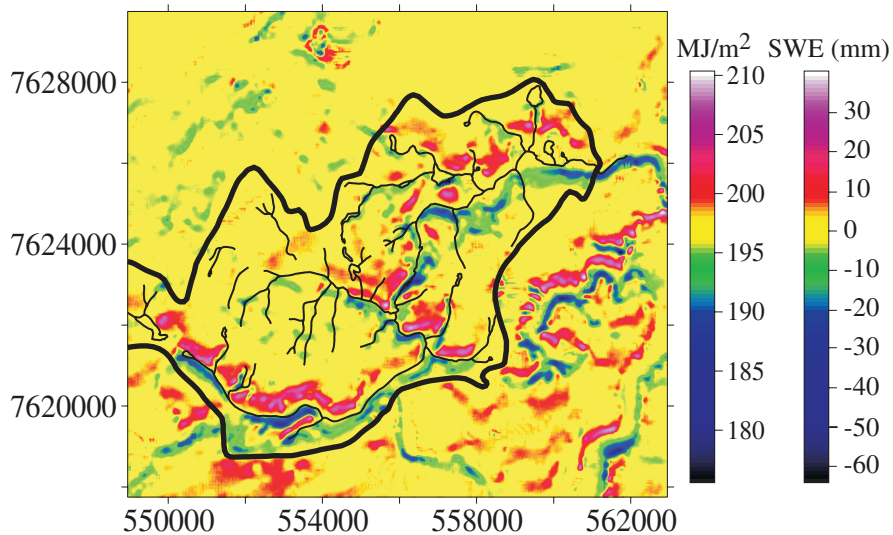
It is well known that incident solar radiation varies with slope angle and aspect in areas of high relief. However, Pohl et al. (2006b) demonstrated that even in relatively low relief areas such as TVC, spatial variability in incident solar radiation is important in controlling snowmelt. They modelled incident solar radiation by calculating clear sky horizontal plane radiation and cloudy sky radiation, and then using standard methods for determining the topographic effects on incident short-wave radiation at a scale of 40 m. Direct beam and diffuse radiation were evaluated by a combination of estimated and measured global short-wave to obtain a cloudiness index. Model runs compared well to observed direct and diffuse radiation. Accumulated net solar radiation over the entire melt period showed large variations over the study area, with notable effects on snowmelt. One indication of the importance is that the difference in absorbed solar radiation was equivalent to about 53 mm of melt potential. Since open tundra areas within TVC typically have a SWE of 50 to 120 mm, such differences in solar radiation have considerable implications for the development of a patchy snow cover.

There can be also large spatial variability of turbulent fluxes due to topographically induced wind speed variations. Pohl et al. (2006a) implemented a simple wind model to simulate topographic effects on the surface wind field at a scale of 40 m. Hourly wind observations were distributed by the model and used to calculate spatially variable sensible and latent turbulent heat fluxes for TVC. Simulations showed that, even though the study area is characterized by relatively low relief, the small-scale sensible and latent heat fluxes varied considerably. Overall, turbulent fluxes within the research area varied by as much as 20% from the mean, leading to differences in potential snowmelt of up to 70 mm SWE over the entire melt period. Such potential variations in snowmelt rates further contribute to the development of a patchy snow cover.

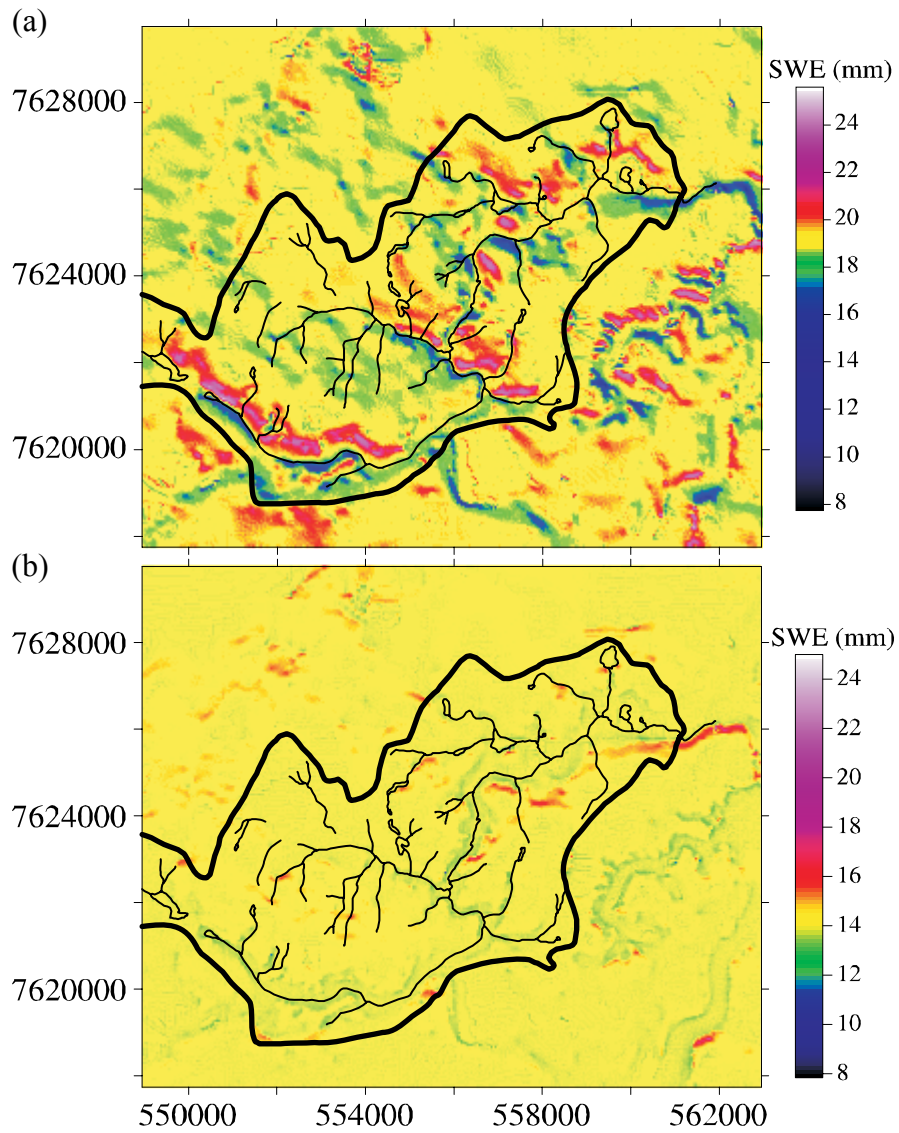
### 3.4 Variability in Snowmelt and Snow-covered Area

Pohl and Marsh (2006) combined model results of spatial variability in incident solar radiation and turbulent fluxes with estimates of local scale advection and a spatially variable end-of-winter snow cover to demonstrate the relative importance of each. This study also illustrated appropriate methods to model snowcover melt, depletion, and runoff at a variety of scales.

When mapped over the TVC domain, combined radiation, turbulent fluxes and local advection yielded large spatial differences in total accumulated energy balance (Fig. 6), with melt energy varying from +30 to -60 mm SWE over the entire domain. Pohl and Marsh (2006) provided similar maps for the radiation and turbulent flux components comprising the accumulated energy balance distribution in Fig. 6, and described the major forcing factors controlling their distribution. In addition, the melt magnitude is greatly influenced by wind direction (Fig. 7). At this treeline site, spatial variability increases considerably on days with a southerly wind as turbulent fluxes and radiant fluxes are both largest on south-facing slopes. In contrast, days with a north wind have a much more uniform melt, with larger turbulent fluxes on north-facing slopes and the largest radiative fluxes on south-facing slopes.



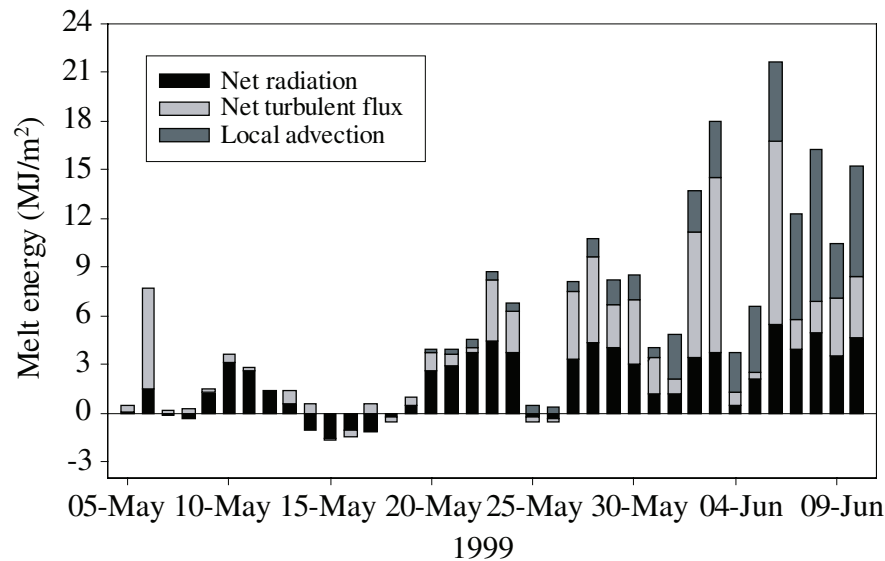
**Fig. 6.** Total energy balance over entire study period and as potential snowmelt amount (expressed as difference from the mean potential snowmelt) (after Pohl and Marsh 2006)

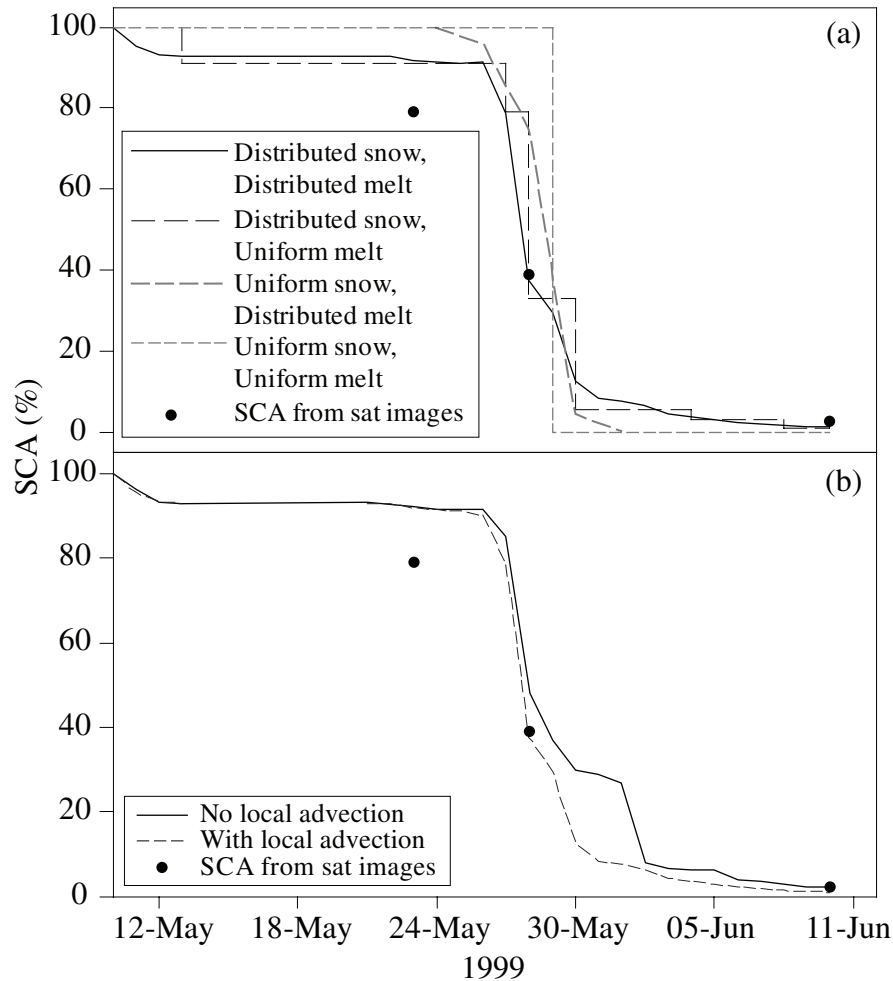


**Fig.7.** Influence of wind direction on daily melt rates for consecutive days with similar snowcover, air temperature, and wind speed. (a) 23 May (southerly winds, mean melt 19 mm,  $S=28 \text{ MJ m}^{-2}$  or 0.9 mm) and (b) 24 May (northerly winds, mean melt 14 mm,  $S = 0.11 \text{ MJ m}^{-2}$  or 0.3 mm) (after Pohl and Marsh 2006)

The basin average for each component (radiation, turbulent flux, and local advection) over the entire TVC basin is shown in Fig. 8. Note that early in the melt period net radiation tends to dominate melt, but as the snow becomes increasingly fragmented, the relative importance of turbulent fluxes and local advection increases.

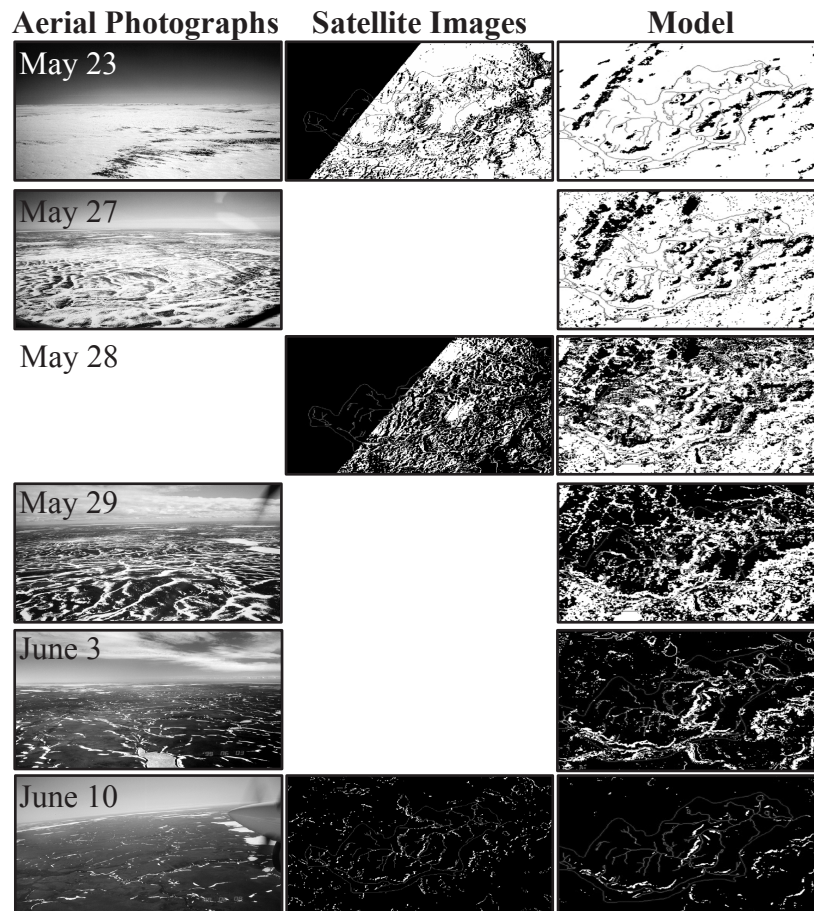
Pohl and Marsh (2006) carried out a variety of model runs to compare the relative importance of distributed snow, distributed melt, and advection on modeled changes in snow covered area during melt at TVC (Fig. 9). With uniform snow and uniform melt, the SCA obviously is a step function with the SCA changing instantly from completely snow-covered to completely snow-free. In contrast, distributed snow/distributed melt provides a gradual decrease in SCA that is similar to observed.





**Fig. 9.** Snowcovered area (SCA) for various combinations of (a) uniform/distributed snow and melt, and (b) for local scale advection. In all cases, observed SCA is obtained from satellite images (after Pohl and Marsh 2006)

with the highest air temperatures and a ripe snow cover that has recovered from any energy deficit that might have been incurred during the previous night. The model predicted that the bulk of the open upland tundra areas would become snow free between 27 and 29 May, as was verified by aerial photography (Fig. 10). Most of the north-facing open tundra slopes and shrub tundra areas were predicted to become snow-free over the next two days (30–31 May). Satellite images indicate that shrub tundra areas showed a higher variability, and melting earlier than or simultaneously



**Fig. 10.** Comparison of modeled melt patterns with satellite images and aerial photographs (after Pohl and Marsh 2006)

with the open tundra. This discrepancy was not unexpected, since the model was set up for open, vegetation-free areas (especially through assumptions made about albedo and surface roughness) that were not corrected for vegetation influence. By 3 June the simulation showed residual snow only in drift areas along the sides of river valleys, around lake margins, and in the channels themselves. This result was validated by aerial photography for that day. These late-lying snow patches are attributed to a combination of higher than average end-of-winter snow accumulation and below-average snowmelt energy, especially on steep, north-facing slopes and in the valley bottoms.



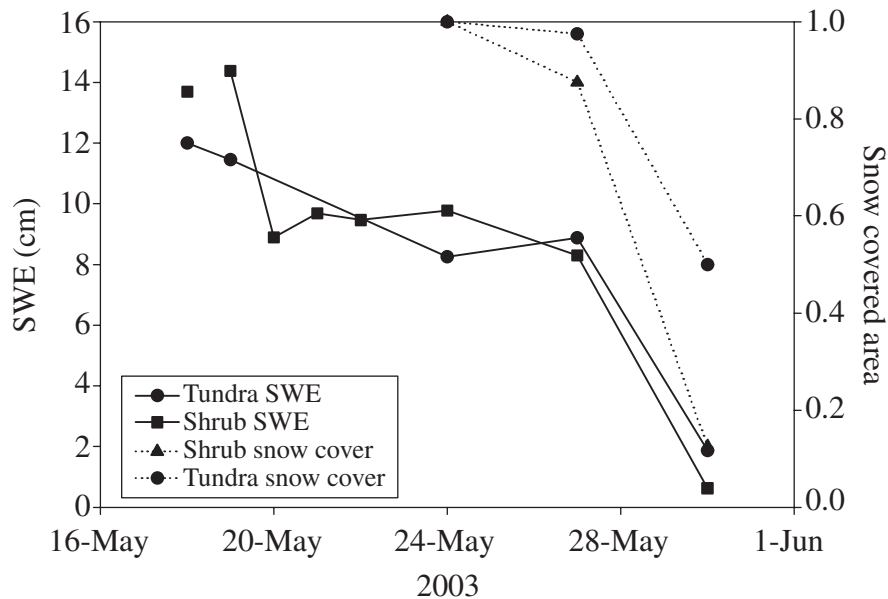
### 3.5 Effects of Shrubs on Snowmelt

As suggested previously, shrubs can significantly affect snowmelt in the study area. To consider this effect, Marsh et al. (2003) carried out a study of snow accumulation and melt at a large shrub area in the vicinity of TVC. End-of-winter snow surveys showed that in late winter 2003, the SWE varied from 98 mm for tundra sites, to 141 mm for shrub sites, 499 mm for drift locations, and 155 mm at forested sites, with a basin average of 142 mm. Although the shrub site had a pre-melt SWE approximately 40% higher than at the tundra site, the SWE and the SCA at the shrub site decreased faster than at the tundra site (Fig. 11), suggesting a higher melt rate at the shrub site compared to the tundra site (cf., Pomeroy et al. 2006). Ongoing work will produce results for implementation in the Pohl and Marsh (2006) melt model to improve the ability to simulate snowmelt, changes in SCA, and snowmelt runoff. This will be especially important when considering runoff scenarios, as the shrub areas may increase rapidly in the coming decades due to climate warming.

## 4 Processes Controlling Lag Between Melt and Runoff

Percolation of surface melt through a snowpack is controlled by both the requirement to wet the dry snow to satisfy its irreducible water content, and to warm the snow to 0°C. Marsh and Pomeroy (1996) applied the Marsh and Woo (1984b) percolation model to consider the effect of melt-water percolation on the timing and volume of water availability for runoff. This model includes a variable flow path and meltwater percolation algorithm, with the melt flux applied to mean snow-cover depth and density in each landscape type in TVC.

Model results indicate that the initial release of meltwater first occurred on the shallow upland tundra sites, with meltwater released nearly two weeks later from the deep snow drifts. The delay between the initiation of melt and arrival of meltwater at the base of the snowpack varied from 6 days for 0.45 m deep snow at tundra sites, to 10 days for 1.85 m deep snow at drift sites. During the beginning of the melt season, not all meltwater is available for runoff. Instead, some snowpacks contribute partially to runoff, and the spatial variation of runoff contribution corresponds to landscape type. At the tundra and drift sites, it was not until 9 days and 16 days respectively that all of the melt water was available for runoff. At TVC, shrub tundra sites were intermediate between the tundra and drift sites in terms of the delay between start of melt and start of runoff.



**Fig. 11.** Change in snow water equivalent and snow covered area during the 2003 melt season at TVC for both tundra and alder shrub sites (after Marsh et al. 2003)

Combining model results with the distribution of landscape types in TVC, Marsh and Pomeroy (1996) were able to map the contributing areas of meltwater runoff on a daily basis. On May 19, 1993 for example, when the tundra areas (70% of the basin) were fully contributing meltwater to runoff, the shrub tundra areas (22% of the basin) were partially contributing meltwater, while the drift areas (8% of the basin) were not contributing any meltwater. Such daily calculations of the contributing areas throughout the melt period could be used to drive a distributed hydrologic model. This large spatial and temporal variability of meltwater release has significant implications for predicting runoff in these environments.

Water balance of TVC and HPC shows that streamflow begins well after the start of melt, indicative of rapid rises in liquid water storage in the snow that reaches a peak near the start of discharge (Fig. 12). The development of large meltwater ponds in the stream channels suggested that the main channels of TVC and HPC may be a major storage area of meltwater prior to discharge commencement. However, field observations of the liquid water stored in TVC stream channels showed that it was only a minor component of total storage, holding only about 1 mm (averaged over the entire basin) of the approximately 100 mm of basin storage at the beginning of melt. This result clearly demonstrates that the largest portion of

meltwater storage must include the following: liquid water in the snow-pack and in numerous meltwater ponds (not in the stream channels) distributed around the basin, and infiltration into the frozen soils,. Further work is required to assess the relative importance of these stores.

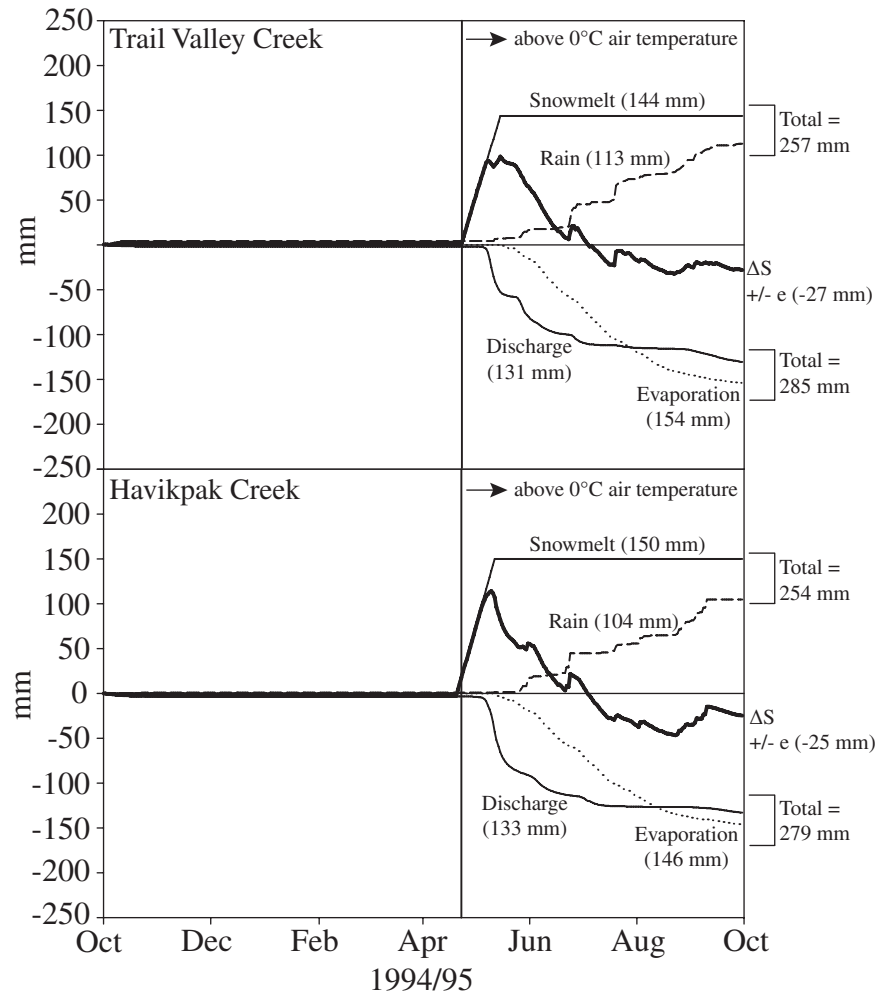
The relative travel times of water through the major components (melt-water percolation through snow, infiltration into the ground, surface and subsurface flows, and stream flow) of the overall flow system, from the surface of melting snowpacks to the basin outlet, as well as the temporal variations in these relative rates were investigated by Quinton and Marsh (1998a). They reported that about 90% of the overall travel time to outlet was spent in the snowmelt percolation pathway. During the middle of the melt period, the hillslope runoff segment dominated (ca. 80%) the overall travel time. Later in the melt-runoff period, the critical factor controlling the overall travel time was whether or not an ephemeral stream was active.

## **5 Snowmelt Runoff**

### **5.1 Processes**

The tundra basins have extensive hummocky permafrost terrain (Fig. 6, Woo and Rouse 2007). Quinton and Marsh (1998b) and Quinton et al. (2000) reported that the combination of mineral earth hummocks and inter-hummock pathways (dominated by peat of about 0.3 m thick) significantly affects slope runoff. Mineral earth hummocks have low permeability while the inter-hummock peat areas have a permeability that is typically three orders of magnitude larger than the hummocks, with the near surface portions of the peat having a permeability up to six orders of magnitude higher than the hummocks. In these inter-hummock zones the physical properties of the peat change abruptly with depth, with bulk density increasing fourfold and the active porosity decreasing from approximately 0.85 near the surface to approximately 0.50 in the basal peat; and the permeability decreasing by two to three orders of magnitude over a 20 cm increase in depth. Mineral earth hummocks influence hillslope runoff by: (1) concentrating flow through the inter-hummock zone, (2) obstructing flow from following a direct path to the stream banks, (3) attenuating flow by interacting with the saturated layer of the inter-hummock zone, and (4) raising the water table in the inter-hummock area by displacement.

Quinton and Marsh (1999) subsequently showed that subsurface flow is the dominant mechanism of runoff to the stream channel, that this flow is



**Fig. 12.** Cumulative daily water balance for both TVC and HPC during the 1994/95 water year. Note that snowmelt occurs well before the start of discharge from both streams and as a result, the storage term rises rapidly, reaching a maximum at approximately the time when discharge begins (after Marsh et al. 2002)

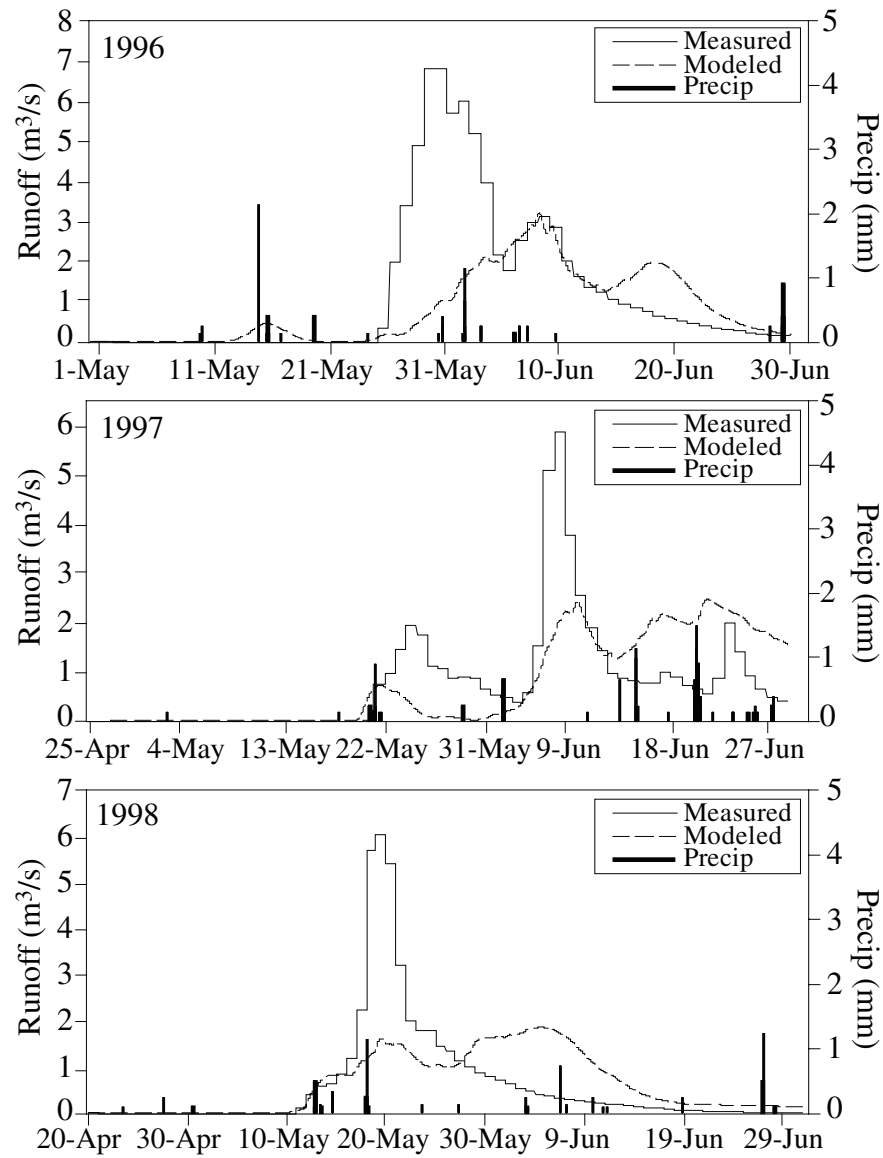
conveyed predominately through the peat of the inter-hummock areas, and that subsurface flow through highly conductive upper peat layer and soil pipes is as rapid as surface flow. They also suggested that TVC can be distinguished into three hydrologic units (viz., stream channel, near-stream area, and uplands), and that the hydrologic response of each unit varies greatly depending on subsurface water levels. For example, when the wa-

ter table is close to the ground surface, flow is rapid and the source area for the production of storm flow is relatively large as the source area extends away from the channels to include the upland areas. However, when the water table is in the lower peat layer, the source area is reduced (typically just the near-stream area), and flows are slow due to slow seepage flow in the lower peat layers.

## 5.2 Modeling

A major limitation in hydrologic modeling at large scales is the availability of appropriate input data including, for example, precipitation, temperature, and radiation (cf., Thorne et al. 2007). Russell (2002) compared field observations at TVC and HPC to the Canadian Meteorological Centre Global Environmental Multiscale Model (GEM) weather prediction output and found that pressure, specific humidity and air temperature compared well, but that GEM precipitation was typically lower than measured. These results demonstrate that numerical weather prediction data are potentially a suitable source of input data for hydrologic models in northern Canada.

Pohl et al. (2005) utilized the fully distributed hydrology land-surface scheme WATCLASS (Soulis and Seglenieks 2007) to model changes in snow covered area and spring snowmelt runoff in TVC. WATCLASS was able to predict satisfactorily the runoff volumes (on average within 15% over five years of modeling) and mean SWE, as well as timing of snowmelt and meltwater runoff for open tundra (Fig. 13). Melt was underestimated in the energetically more complex shrub tundra areas of the basin. Furthermore, the observed high spatial variability of the SCA at a 1-km resolution was not captured well (Fig. 14). Several recommendations are made to improve model performance in Arctic basins, including a more realistic implementation of the gradual deepening of the thawed layer during the spring, and the use of topographic information in the definition of land cover classes for the GRU approach. Davison et al. (2006), for example, attempted to improve the sub-grid variability of the snow cover and the subsequent melt in TVC by including wind-swept tundra and drift classes based on topography rather than the traditionally used vegetation land classes. This approach improved the ability of WATCLASS to simulate the variability in snow covered area during the melt period.



**Fig. 13.** Observed vs WATCLASS simulated hydrographs for spring melt periods in TVC. 1997 and 1998 were model calibration periods (after Pohl et al. 2006)

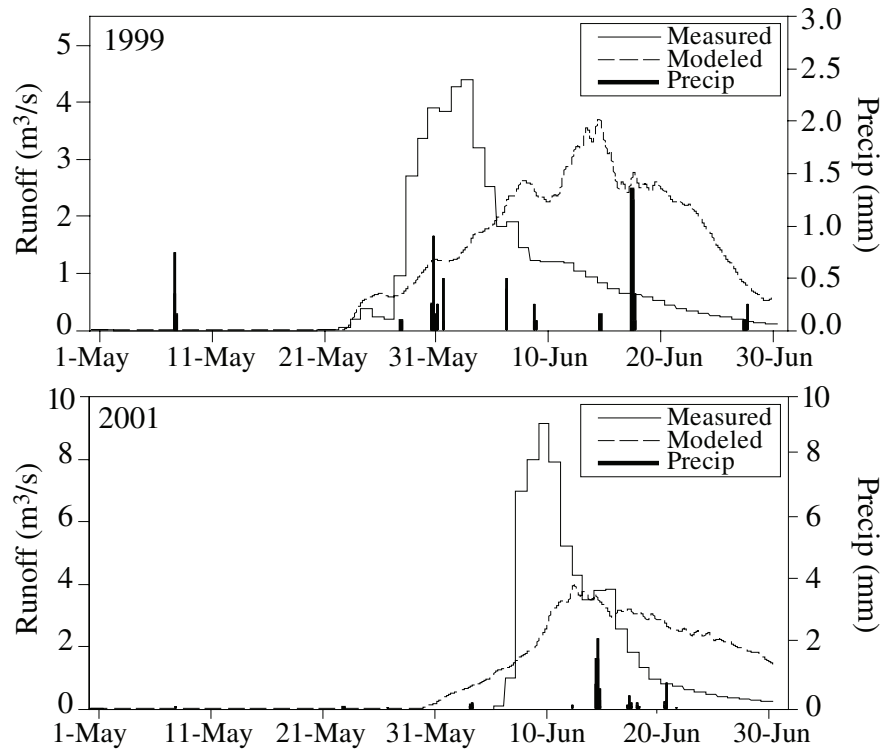
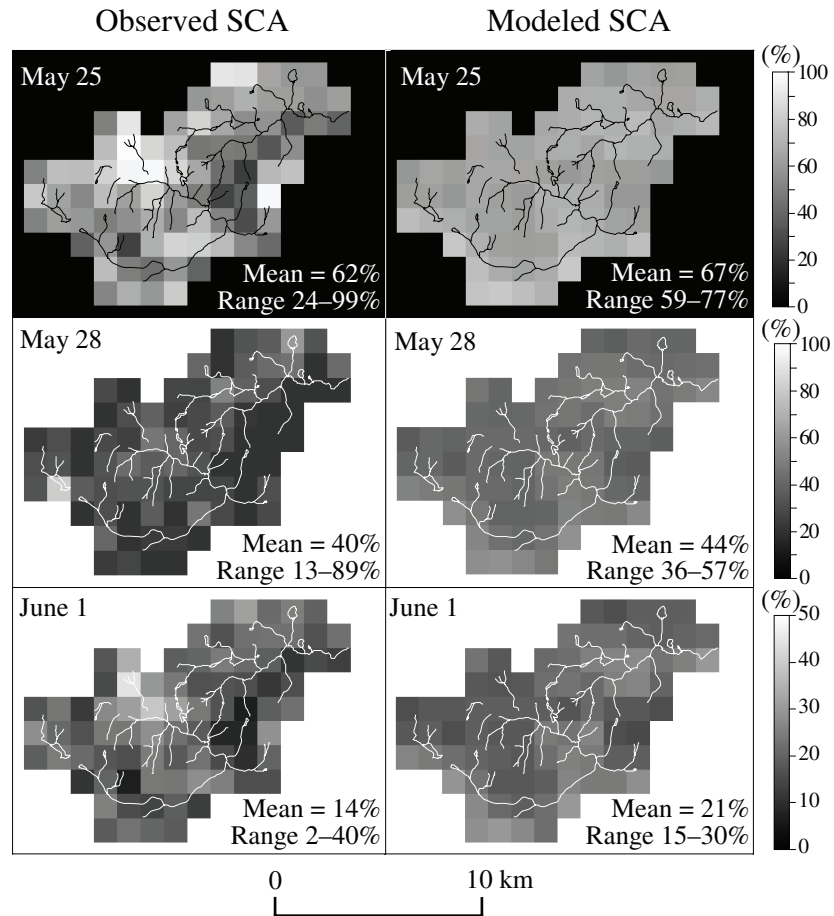


Fig. 13. (cont.)

## 6 Conclusion

Field investigations in two small basins at the treeline have advanced knowledge of understanding of snowmelt and runoff processes in the northern environment. A combination of tower and aircraft flux measurements have demonstrated conclusively that the fluxes of sensible and latent heat, and radiation vary significantly over typical  $10 \times 10$  km grids. Combined with a spatially variable snow distribution at the end of winter, this results in a patchy snow cover during the melt period, with implications on the fluxes of energy and water to the atmosphere and for runoff. Implementation of these processes in a model allowed the simulation of spatially variable fluxes, and produced realistic changes in the snow cover pattern over the study area. These studies demonstrated the importance of a variable snow cover, variable energy fluxes, and local scale advection in con-



**Fig. 14.** Observed vs. WATCLASS simulated spatially distributed snow covered area for TVC in 1996

trolling the snowmelt process at small scales. In addition, runoff studies showed that meltwater storage in the snowpack and flow pathways of meltwater as influenced by such features as earth hummocks and peat terrain, have major impacts on hillslope runoff and therefore basin discharge. The combined land-surface/hydrology model WATCLASS was tested for the TVC basin. Although this model has produced improvements in combining hydrology with detailed surface energy balance, comparison with detailed datasets has revealed areas where future efforts should focus, including the ability to represent properly the spatial variability in melt. Ongoing studies continue to use detailed observations, process studies, and



parameterizations from TVC and HPC to further improve the models to simulate the hydrology of northern Canada at a variety of scales.

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