The Snow Mass Balance of Wolf Creek, Yukon: Effects of Snow Sublimation and Redistribution

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Abstract

Snow cover is not only a major hydrological input to the Wolf Creek Research Basin but provides a habitat for life and sustains important interactions with vegetation and climate. The losses or gains of snow within the basin and to and from the basin are therefore extremely important for the hydrology, biology and climatology of the region. This paper will review a four year record of snow studies in Wolf Creek. The sites are in the alpine, shrub-tundra and boreal forest vegetation bands of the basin and are representative of tundra plateaux, valley shrub-tundra and lowland forest respectively. At the alpine and shrub-tundra sites, wind speed, blowing snow occurrence, snow depth, temperature and humidity were measured half-hourly and snowfall and snow accumulation on the ground measured monthly. These measurements permit a mass balance of snow transformations due to blowing snow on the alpine plateaux and shrub-tundra valleys of Wolf Creek Basin. The measurements show that on average 50% of snowfall is removed from the alpine plateau and 25% is removed from low-lying shrub-tundra by blowing snow storms. Much of this snow is relocated to hillsides where it can triple snow accumulations. However, though some blowing snow is lost to sublimation, the proportion cannot yet be quantified in mountainous terrain. At the forest site, snow surveys under the canopy were compared to snowfall records in order to estimate snow interception storage and eventual sublimation. Snow remains in the canopy for weeks to months in the cold mid-winter. From 38%-45% of annual snowfall is lost to snow sublimation from spruce canopies in the lower elevations of Wolf Creek. The implications of these results are that the snow cover of Wolf Creek is controlled by its vegetation cover, exposure and climate. Changes to land use or climate in the Yukon will therefore have profound changes on the snow cover and then on the water resources, aquatic chemistry, animal populations and vegetation that are influenced by snow.

Introduction

Snow cover has profound implications for the environmental health, habitat and water supply of northern basins. Much of the Wolf Creek basin is covered with snow for eight months, while a few isolated alpine snow patches often survive the summer melt period to form the base for new snow accumulation in the autumn. Peak runoff from the basin normally occurs as a result of the spring snowmelt, however the magnitude of this runoff is not simply related to the amount of snow accumulated in the basin but also to its spatial distribution and to the timing of snowmelt in various elevation and vegetation zones (Janowicz *et al.*, 1997). The change in elevation and vegetation through the basin result in a differing snowfall rates, and strongly differing snow processes which control snow accumulation and ablation[1]. For instance, in low elevation zones covered with evergreen forests, snow is intercepted by the canopy where it is exposed to atmospheric energy and turbulence and can rapidly sublimate[2] before being released to the ground. In sparsely-vegetated tundra, snow is blown by the wind and both redistributed and sublimated in transit. The resulting accumulations of snow differ substantially from snowfall in most environments of Wolf Creek.

On the interior edge of the Coast Mountains, Wolf Creek is felt to represent snow regimes found in the northern boreal cordillera of western Canada in that it falls within a band of relatively low winter precipitation and temperature that extends throughout the Mackenzie, Cassiar and northern Rocky Mountains. In understanding the processes that control snow accumulation in Wolf Creek, a greater perception of the rate and operation of these processes in mountainous northern Canada can be developed. The improved understanding of snow mass balance processes may improve methodologies for estimating the water balance and help to interpret the results of aquatic chemistry studies. The role of vegetation in controlling its snow supply can also be demonstrated. It is the purpose of this paper to:

- describe the processes that cause changes in the snow mass balance,
- discuss the implications for snow mass balance in landscape types of the basin.

This description and discussion will focus on empirical results and a simple analysis of these results.

Processes of Snow Accumulation and Ablation

Two key processes of snow accumulation occur in Wolf Creek basin, interception by vegetation and redistribution by wind. The processes occur in differing vegetation zones with interception dominant in the low elevation zones that are covered with evergreen forests and wind redistribution dominant in the high elevation, exposed alpine zone. An ablation process, sublimation[2], occurs along with the accumulation processes, and is driven by enhanced exchange of energy to and water vapour from intercepted and blowing snow. At other northern sites these processes have been shown to have strong effects on the local snow mass balance and on the variation of this mass balance over a basin.

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[1] *Ablation* is the loss of snow due to evaporation or melt.

[2] *Sublimation* is the direct transformation of snow to water vapour and results in "winter evaporation".

Interception

Evergreen forest canopies collect snowfall and can retain intercepted snow for periods from hours to weeks. This process strongly affects the sequence of snow accumulation and the maximum seasonal snow accumulation. Unloading of intercepted snow to the ground (including melt) occurs with increasing probability over time and is affected by canopy temperature and wind (Hedstrom and Pomeroy, 1998). Snow that does not unload is either relocated by the wind or sublimates (Pomeroy and Gray, 1995). Recent experimental evidence strongly supports sublimation as the primary ablation mechanism for intercepted snow (Schmidt, 1991; Pomeroy *et al.*, 1998).

A simple mass balance of cumulative snowfall and snow accumulation can provide a quantitative estimate of snow interception and sublimation for cold climates where mid-winter melts are not prominent. In this situation for the cold mid-winter period, just after heavy snowfalls and before unloading can occur, the cumulative interception, I_C, is found from cumulative values of snowfall, P_C, and measures of snow water equivalent accumulation on the ground, SWE:

$$I_c = P_c - SWE \quad . \qquad 1)$$

Normally, by the end of winter snow has completely unloaded from the canopy and if melt has been insignificant then seasonal sublimation, S_S, can be estimated from the seasonal snowfall, P_S, and the maximum snow accumulation, SWE_{max} as,

$$S_s = P_s - SWE_{\max} \quad . \qquad 2)$$

These mass balance equations while crude permit an explanation of the effect of intercepted snow processes on SWE development over the season and on the maximum SWE.

Values for Ic and Ss have been derived for other regions of northern Canada but not in the Yukon. Pomeroy *et al.* (1998) found in northern Saskatchewan boreal forests that up to 67% of cumulative seasonal snowfall could be intercepted by dense black spruce canopies in mid-winter (late December). This percentage declines as the season progresses. Over the winter, from 10% to 45% of seasonal snowfall sublimated from intercepted snow, the loss depending on tree species (deciduous versus evergreen) and winter leaf area. Most of the sublimation occurred episodically in late winter when measured sublimation rates reached 3 mm per day.

Blowing Snow

Snow is redistributed by wind from exposed sites with short vegetation to sheltered valley bottoms, lee slopes and/or dense vegetation (shrub or forest). Wind redistribution can therefore manifest as ablation or accumulation, depending on local topography, vegetation and upwind conditions. The process of redistribution, blowing snow transport, can be described in a similar manner to river sediment transport or blowing sand or dust. Eroded snow is entrained in saltation near the surface, lifted above the surface in suspension and eventually either returns to the ground or sublimates. Generally less than 25% of a blowing snow mass saltates near the surface with the rest suspended by turbulence and carried well-above the ground (Pomeroy and Gray, 1990). Wind transport of snow is limited by the supply of snow as blowing snow particles sublimate and are hence removed from that which can be transported (Pomeroy *et al.*, 1993). The sublimation rate of a wind-blown snow particle is primarily controlled by wind speed, air temperature and humidity and because blowing snow is well-ventilated, proceeds several orders of magnitude faster than sublimation from surface snow covers. Sublimation removes snow particles from the air stream, which are replaced from a vertical flux of eroded surface snow particles.

One method used to estimate snow accumulation in wind-swept locations is to divide the landscape into *sources* and *sinks* of blowing snow. Examples of source areas are alpine tundra or short shrub-tundra ridges and plateaux and examples of sinks are tall shrub-tundra, taiga forest, hillsides and stream channels. The mass balance for cumulative snow water equivalent accumulation, SWE, in a source area can be written as:

$$SWE = P_c - T_c - S_c \quad , \qquad 3)$$

where, P_C is the cumulative snowfall, T_C is cumulative net blowing snow transport out of the source area and S_C in this case refers to cumulative sublimation of blowing snow over the source area. Quantities are accumulated over from the beginning of the snow accumulation season (neglecting Autumn snowfalls that were subject to melt). For a sink area the mass balance is easier to construct, as by definition blowing snow only enters a sink and sublimation during transport over the sink area can be considered negligible. The mass balance of snow water equivalent accumulation, SWE, for a sink area can be written as:

$$SWE = P_c + T_c \quad , \qquad 4)$$

where in this case T_C is cumulative snow transport from the source area to the sink.

Despite the cold temperatures of northern Canada, strong winds and dry air promote both blowing snow transport and sublimation. Calculations of blowing snow transport in a rolling arctic basin north of Inuvik, NWT suggest that 28% of seasonal snowfall is sublimated during redistribution from tundra surfaces, while 18% is transported to shrub-tundra and drift areas (Pomeroy *et al*, 1997). Shrub-tundra and drift (steep hillsides and stream channels) areas received windblown snow equivalent to 16% and 182% of seasonal snowfall. Over the basin area 19.5% of snowfall sublimated during blowing snow and the equivalent of 5.8% of seasonal snowfall was blown into the basin. As a result, snow accumulation in the basin varied from 54% to 419% of seasonal snowfall, controlled by topography and particularly vegetation. The results of snow mass balance studies from relatively level terrain in Saskatchewan and the Northwest Territories should not be directly transferred to a Yukon mountain environment, however the magnitude of the snow processes in these other environments guides the search for snow transformations in Wolf Creek.

Study Sites and Experiments

Sites

The snow mass balance experiments were conducted at three sites, an alpine tundra plateau, a shrub-tundra valley bottom and a white spruce forest riparian zone. Vegetation heights are 0.05, 1.1 and 15 m, at elevations of 1615, 1250 and 750 m respectively. The vegetation zones represented by these sites comprise 20%, 58% and 22% of the classified area (Francis, 1997). Photographs showing terrain and vegetation for these zones are shown in Fig. 1. Snowfall data was also collected from the Environment Canada station at Whitehorse Airport, elevation 740 m and 20 km west of the forest site.

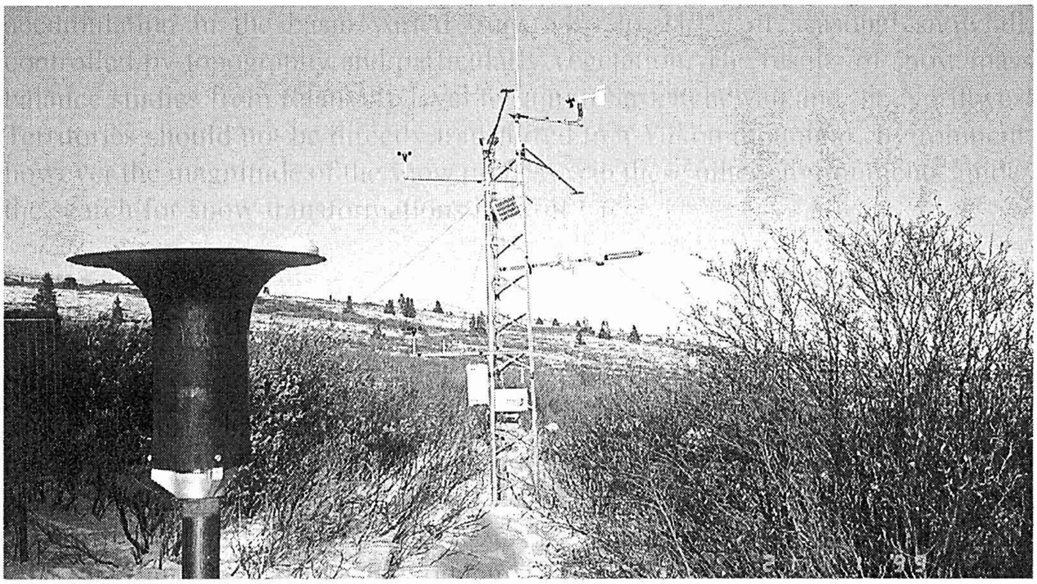

Figure 1.

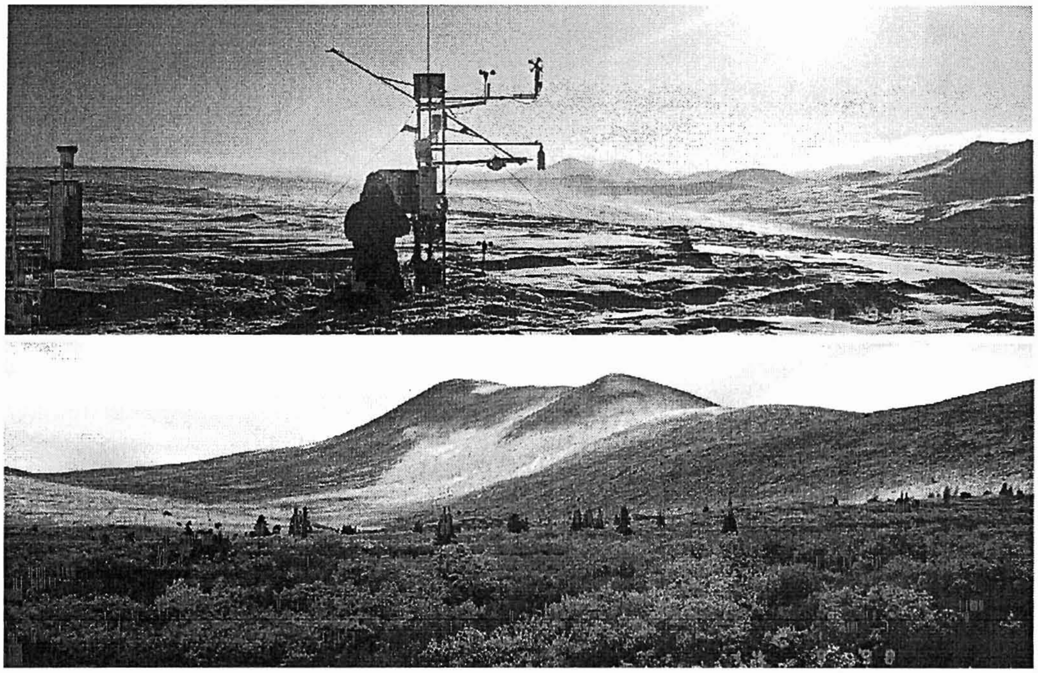

Figure 1. *(cont'd)*

Instrumentation and Measurements

Instrumentation to measure snow processes and mass balance was installed in September 1993 with occasional upgrades and improvements. Figure 1 also shows the towers, locations and some instruments. This instrumentation has been used in a variety of studies (Granger, this volume; Janowicz *et al.*, 1997). At the alpine tundra, shrub-tundra and forest sites, towers 3, 5 and 20 m tall extend well above the local vegetation. On the towers, instrumentation is staged at various heights and includes: NRG cup anemometers, wind vanes, REBS net radiometers, Vaisala hygrothermometers and specialised snow instrumentation: Nipher-shielded snowfall collection gauges - snowfall, measured monthly,

1) Snow particle detectors - blowing snow mass flux (alpine tundra only),
2) Weighed, Hanging Tree - intercepted snow mass and sublimation (forest only),
3) Ultrasonic Depth Sensor - snow depth on ground,
4) Snow Pillow - snow water equivalent at a point (shrub-tundra only),
5) Thermocouples - snowpack temperature.

Some instruments (1, 2, 4, 5) are located above canopy at the shrub-tundra and alpine tundra sites, all other instruments and sites have sub-canopy deployment. The instruments are controlled and interrogated by Campbell Scientific Inc. 21X dataloggers with sampling at least every minute and average values stored half-hourly.

Snow depth and density surveys are conducted at the sites each month to calculate SWE. Snow survey lines of 125 m are followed, with 25 depth and 6 density measurements made. Care was taken in designing the survey lines so that they cross through a variety of vegetation types and densities, near to the observation tower.

Results

Seasonal Snowfall over the Basin

Snowfall was estimated for each vegetation/elevation zone over the four winter seasons of study from monthly measurements of snowfall throughout the basin and four times daily measurements from the Environment Canada weather station at the airport. All stations were corrected for wind-induced undercatch by nipher-shielded snow gauges, using the most recent Environment Canada algorithm and measured wind speeds during snowfall. Recorded snowfall at the Environment Canada station was found to be from 85% to 92% of corrected snowfall. For the high elevation shrub-tundra and tundra stations in Wolf Creek the measured snowfall ranged from 75% to 97% of corrected values. Rainfall events were removed from the airport winter precipitation record. The forest site was slightly sheltered by forest canopy and may have a small undercatch due to gauge position, therefore the corrected airport data is considered a better representation of forest site snowfall. Data quality problems in the 1995-96 season preclude use of snowfall data from the airport and alpine sites, however all other data are shown in Fig. 2.

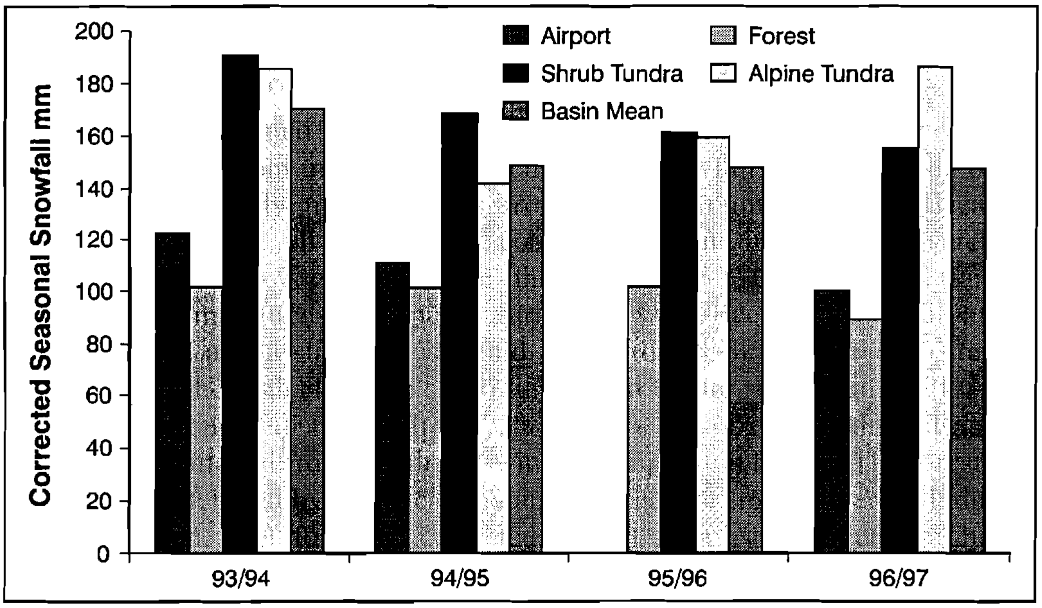

Figure 2. Seasonal measurements of corrected snowfall by elevation/vegetation zone, and corrected, areally-weighted basin snowfall in Wolf Creek Basin.

Mean, areally-weighted snowfall for the basin ranged from 147 mm in 1996-97 to 170 mm in 1993-94. It is evident that the shrub-tundra normally receives the greatest snowfall and the forest the least. Though the upper basin receives more snowfall than the lower basin, there is no consistent relationship between snowfall and elevation such as indicated in standard orographic snowfall calculations used in temperate climates. In most years, the alpine tundra receives less snowfall than the shrub-tundra, despite the greater elevation at the alpine site. In 1996/97 the alpine snowfall exceeded that of the other sites because an early snowfall in the alpine fell as rain at lower elevations. The nearby airport snowfall data clearly is not representative of basin snowfall. Areally-weighted basin snowfall exceeds that measured at the airport by 33% to 47% of the airport measurement.

Snow Accumulation Regimes

Daily snow depth measured with an ultrasonic snow depth gauge and monthly snow densities were used to reconstruct the accumulation and ablation regimes from the three vegetation/elevation zones over the four winters of record (Fig. 3). The regimes display remarkable intersite and interannual variability in accumulation. In one high snowfall year (1993-94) the shrub-tundra accumulated ten times more snow than did the lowest snow accumulation site, alpine tundra, presumably because of wind redistribution. In a later high snowfall year (1996-97) with two large wet snow events, the alpine retained its snowcover near to levels measured in the shrub-tundra and the forest had the lowest snow accumulation. The complex variability in accumulation regimes and differences between maximum accumulation and seasonal snowfall mean that simple guidelines for "adjusting" winter precipitation as commonly employed in hydrological models are not appropriate in this environment and that explicit process-based procedures to simulate snow accumulation may be necessary. The next sections examine the snow accumulation regimes in terms of the processes controlling snow accumulation, as a first step towards developing procedures for calculating snow accumulation.

Forest Snow Accumulation

Accumulation of seasonal snowfall in the spruce forest is dominated by the interception process and sublimation of intercepted snow as discussed earlier in this paper. In the cold mid-winter period, snow is intercepted and mostly retained in the canopy; whilst intercepted, it sublimates. Sublimation rates in extremely cold weather are small. Warmer weather and higher net radiation arrive in late winter, increasing the sublimation rate substantially but also increasing the likelihood of unloading to the ground. Figure 4 shows an example of the forest snow accumulation regime and the monthly snowfall for the winter 1994-95 which had the best record. As described in Eq. 1, the difference between snowfall and snow accumulation in late December is due to interception of snow in the canopy. The difference at the beginning of snowmelt in late March (when the canopy is free of intercepted snow) is due to sublimation (Eq. 2). As evident from the figure, no significant snowmelt occurred until the end of March.

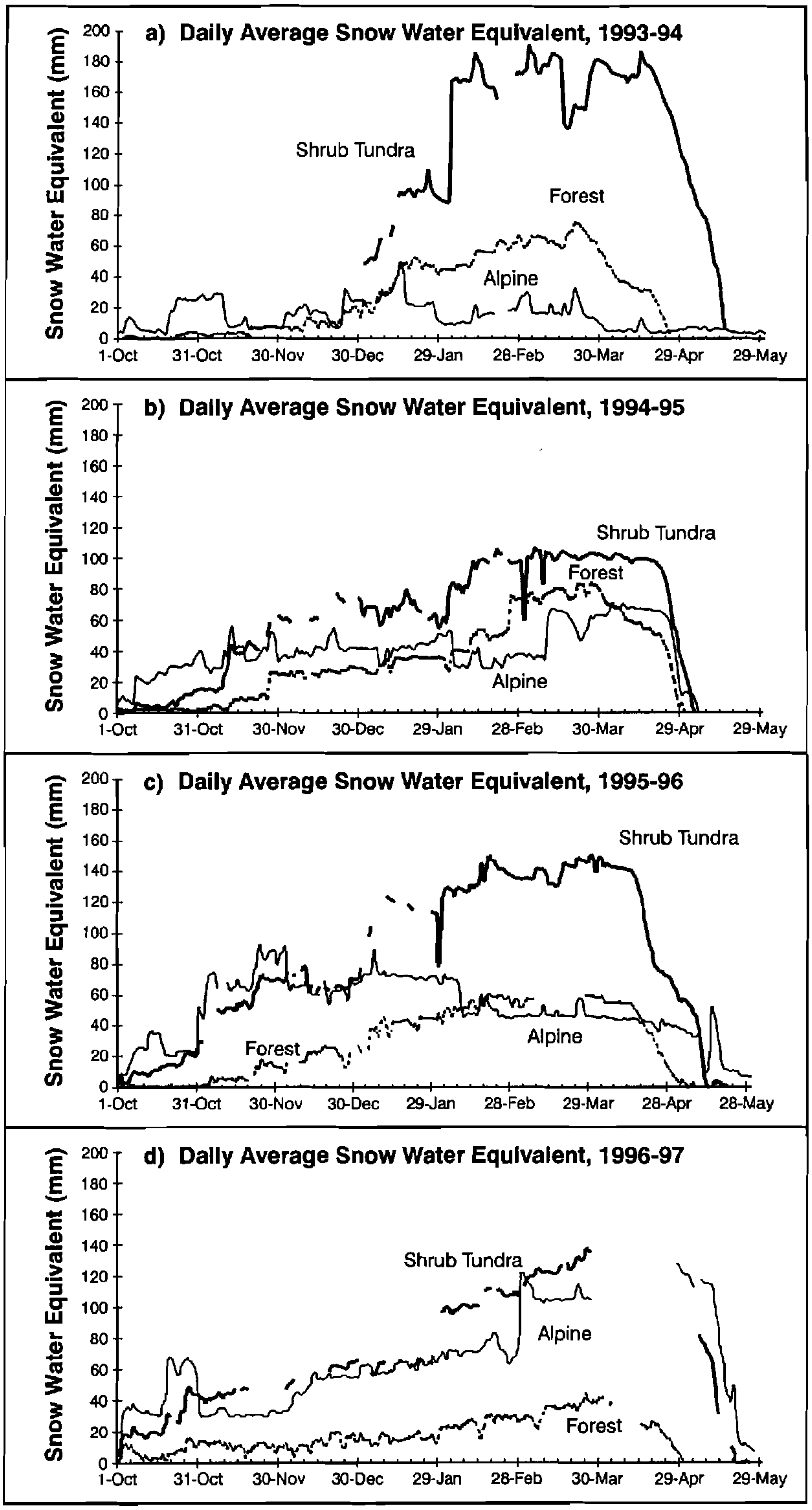

Figure 3. *Snow Accumulation regimes estimated from monthly density and daily snow depth measurements for the three elevation/vegetation zones in Wolf Creek: **a)** 1993-94, **b)** 1994-95, **c)** 1995-96, **d)** 1996-97.*

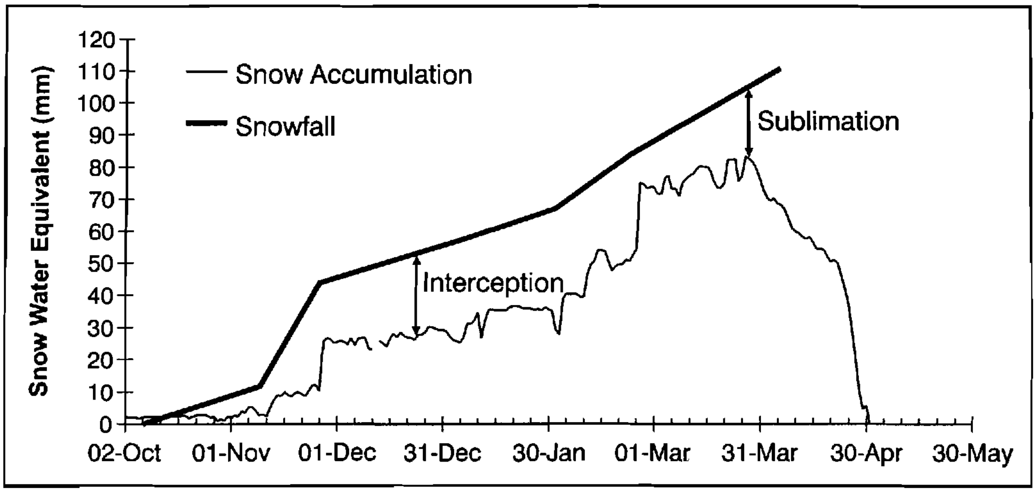

Figure 4. *Snowfall and snow accumulation in the winter 1994-95 for the spruce forest site. Snowfall is corrected from nipher shielded snow gauges and snow accumulation is determined from a transect of depth and density measurements in the forest.*

Using Eq. 1 and 2, mid-winter interception and seasonal sublimation values were calculated using monthly snowfall and snow survey measurements and are shown in Table 1. Mid-winter interception was normally the maximum as a percentage of cumulative snowfall and occurred in late December or early January. Seasonal sublimation was normally calculated from the premelt snow accumulation at the end of March. Mid-winter interception was large, ranging from 46% to 69% of cumulative snowfall or from 21 to 39 mm. Sublimation loss as a percentage of seasonal snowfall was smaller, ranging from 38% to 45% with most values near 40%. This sublimation loss range was 28 to 45 mm, a substantial abstraction of potential meltwater. Losses of this magnitude to sublimation demonstrate the importance of forest cover in controlling basin water balance through influence on the interception process.

Table 1. *Mid-winter (maximum) interception expressed as a percentage of cumulative snowfall and as mm and seasonal sublimation (pre-melt period) expressed as a percentage of seasonal snowfall and as mm. All values are for the spruce forest site in Wolf Creek Basin.*

Season	Mid-winter Interception %	Mid-winter Interception mm	Seasonal Sublimation %	Seasonal Sublimation mm
1993-94	46%	39	39%	45
1994-95	70%	30	41%	45
1995-96	61%	26	38%	28
1996-97	69%	21	45%	34

Tundra Snow Accumulation

Snow accumulation above treeline is also influenced by vegetation, however here the influence is conveyed by the aerodynamic roughness that vegetation presents to the atmosphere and the effect of this roughness on the flow of blowing snow across the landscape. Snow is blown from exposed, short-vegetation sites to areas with sharp slopes or tall vegetation. As snow is blown some of it sublimates and never reaches a site where it may accumulate.

The tundra snow accumulation regime can be divided into sink and source phases. When vegetation extends above the snowcover, then the site tends to trap more blowing snow than is eroded and is therefore a sink of windblown snow. When snow buries the vegetation, then further accumulations can be more easily eroded and transported to a more sheltered or vegetated site. Sites in sharp gullies or hillsides in the lee of dominant windflows may be sheltered such that local wind speeds are insufficient to erode or transport blowing snow, these sites are sinks throughout the year and develop into characteristic snow drifts that may remain in Wolf Creek until late summer. The ecological effects of snow drifts can be significant. Near the crest of Mt. Granger a prominent permanent snowpatch is apparently sustained because it is a sink of wind blown snow. This snowpatch has been frequented by caribou herds for several millennia.

An example of a predominately sink snow regime is shown in Fig. 5 with data from the shrub-tundra site in the winter 1994-95. Through the first two-thirds of the winter, snowfall and snow accumulation are well matched, suggesting that the site traps all falling snow, even if accompanied by strong winds. After March 1 (SWE=100 mm) the site switches to a source of snow, as it does not accumulate any more snow despite an additional 70 mm of snowfall. Snowmelt occurs rapidly in late April and is excluded from this analysis.

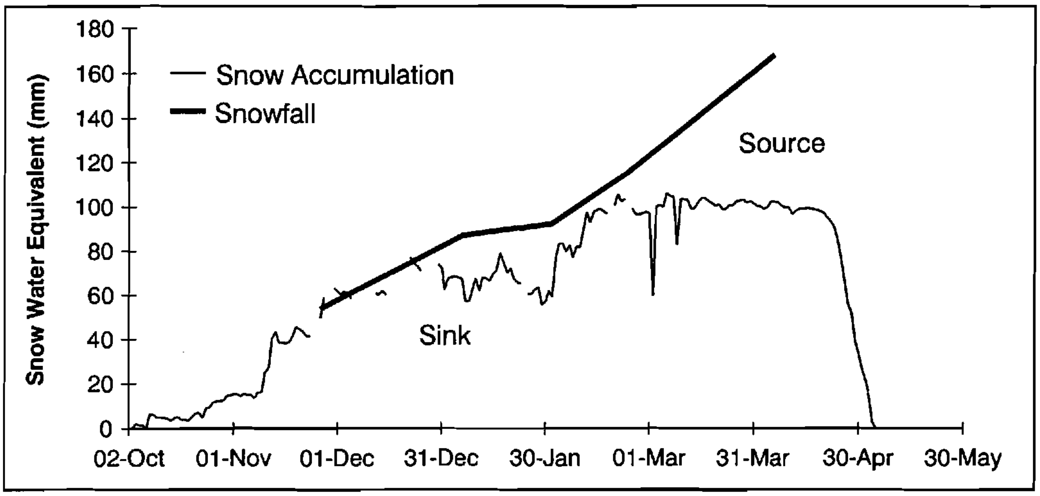

Figure 5. *Shrub-tundra snow accumulation regime, 1994-95. Snowfall is corrected from monthly readings, snow accumulation is measured as a daily snowdepth with monthly updates to snow density.*

At the alpine tundra site, the blowing snow source regime develops earlier due to short vegetation, strong winds and frequent blowing snow. An example of the regime is shown in Fig. 6 for the same year as Fig. 5. By early December snowfall begins to exceed snow accumulation, and by late in the year is more than twice the accumulation. The excess snow (approximately 70 mm SWE) is removed from the site by blowing snow, some being deposited in drifts and shrub-tundra and some being sublimated.

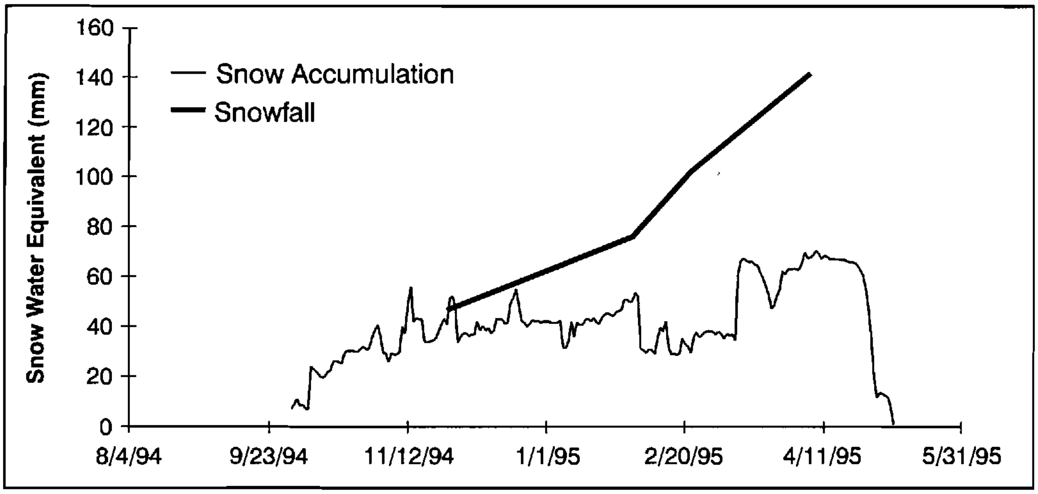

Figure 6. Alpine tundra snow accumulation regime, 1994-95. Snowfall is corrected from monthly readings, snow accumulation is measured as a daily snowdepth with monthly updates to snow density.

Blowing Snow Fluxes

The occurrence of blowing snow was measured with an opto-electronic blowing snow particle detector at the three measurement sites in Wolf Creek. If the daily snow particle flux exceeded 10 particle counts per second over several half-hour periods then blowing snow was assumed to have occurred. These days were summed to seasonal values which are shown in Table 2 (a season is about 180 days for the shrub-tundra site and 210 days at the alpine site). The alpine tundra site recorded the highest frequency of blowing snow with from 32 to 42 days per season with blowing snow (roughly up to 20% of winter days). The occurrence of blowing snow at the shrub-tundra site was much less at between 8 and 13 days per season (roughly up to 7% of winter days). The greater number of blowing snow days at the alpine site are due to greater exposure to wind (on a hillcrest), higher wind speeds and a longer snow-covered season. Blowing snow did not occur at the forest site, but at the tundra sites it is a meteorological phenomenon for which the hydrological consequences should be considered.

Table 2. *Frequency of occurrence of blowing snow days in Wolf Creek Basin. Numbers shown are days per winter with significant blowing snow as measured by a snow particle detector.*

Season	Alpine Tundra	Shrub-tundra	Spruce Forest
1993/94	37		0
1994/95	32	13	0
1995/96	42	11	0
1996/97	32	8	0

Fluxes of blowing snow from or to tundra vegetation types (T_c-S_c) can be calculated using a mass balance (Eq. 3) of snowfall and snow accumulation for cold months in which melt and direct surface evaporation are insignificant. Fluxes estimated from monthly snowfall measurements and snow surveys are shown in Fig. 7 for the shrub-tundra site. Most fluxes were small, less than 0.5 mm/day gain or loss, and slightly negative, except for events in at the end of two winters that resulted in a losses of greater than 1.2 mm/day over March. The season progression of fluxes suggests that the shrub-tundra acts as a small source of blowing snow until late winter when it may become a major source of snow. The year with the most extreme monthly fluxes (1994-95) had a sequence of blowing snow losses following gains, suggesting that whatever wind-blown snow was trapped was subsequently lost. Blowing snow fluxes from the alpine tundra site are shown in Fig. 8 and provide a contrast to the smaller shrub-tundra fluxes. Fluxes from the alpine almost always indicate a loss of snow equal or less than 1 mm/day. The exceptions were events in November and March during which snow was transported to the alpine tundra (up to 0.3 mm/day in 1995).

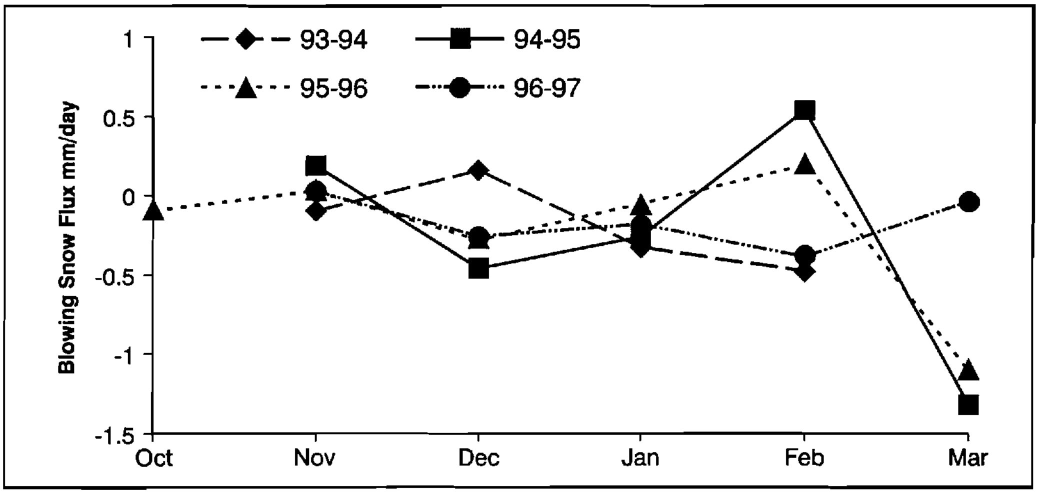

Figure 7. *Daily blowing snow fluxes (mm SWE) expressed as negative when a loss from snowpack, calculated from a mass balance of snowfall and snow accumulation at the shrub-tundra site for various months and years.*

Annual blowing snow mass balances were calculated using Eq. 3 for the alpine and shrub-tundra sites and Eq. 4 for a drift site, downhill from the alpine site that was surveyed in late winter 1996. The drift site was presumed to have the same snowfall input as the alpine site. The results are shown in Table 3 and suggest that the alpine tundra loses roughly one-half of its seasonal snowfall to blowing snow, over twice as much as is lost from the shrub-tundra. In contrast to all other sites, the hillside is a strong sink of blowing snow, gaining almost twice its seasonal snowfall from wind-blown snow.

Table 3. *Net seasonal blowing snow fluxes (mm SWE, % of seasonal snowfall) at three sites in Wolf Creek Basin.*

Season	Alpine Tundra	Shrub-tundra	Hillside
1993/94	-147 mm, -79%	-32 mm, -19%	
1994/95	-62 mm, -51%	-68 mm, -46%	
1995/96	-67 mm, -44%	-28 mm, -17%	+307 mm, +191%
1996/97	-73 mm, -39%	-26 mm, -18%	
Average	-87 mm, -53%	-39 mm, -25%	

It is clear from the net seasonal analysis that snow transported from alpine areas does not cause the shrub-tundra site to become a net sink of wind-blown snow. However it is unlikely that all blowing snow sublimates. The accumulation at the hillside drift site in 1996 (468 mm SWE) is substantially greater than that contributed by snowfall and suggests that hillside drifts are substantial sinks of transported blowing snow. However, until such time as an analysis of fetch distances, hillside drift areas and complex terrain windflow can be conducted in Wolf Creek, it will be impossible to differentiate blowing snow losses due to sublimation from those due to transport.

Conclusions

Several key conclusions can be drawn from the observations presented in this paper. The conclusions are important in anticipating research directions for northern snow hydrology and in evaluating attempts to apply temperate-zone hydrological principles to the North. In Wolf Creek Research Basin over the four years of study:

- Snow accumulation varied strongly with vegetation cover and exposure, this was strongly related to changes in snowfall with elevation.
- A forest snow accumulation regime identified in the dense spruce woodland lost 38% to 45% of annual snowfall to sublimation.
- An alpine snow accumulation regime identified in the alpine tundra lost from 39% to 79% of annual snowfall to blowing snow transport and sublimation and experienced blowing snow on 1/5 of all winter days.

- A shrub accumulation regime identified in the shrub-tundra lost from 17% to 46% of annual snowfall to blowing snow transport and sublimation and experienced blowing snow on 1/15 of all winter days.
- A drift accumulation regime identified on a hillside drift gained 191% of annual snowfall due to blowing snow transport.
- It is therefore not appropriate in northern hydrology to assume that snow accumulation equals snowfall. Further research is necessary to develop procedures that can be used to predict the snow accumulation regimes identified here from standard meteorological measurements.

Acknowledgements

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