ARE SNOW RESOURCES ON THE NORTHERN PLAINS AND PRAIRIES DWINDLING?

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ABSTRACT

Snow across the Northern Great Plains and Canadian Prairies constitutes a very essential natural resource. Although snowfall and snowcover typically vary widely from district to district and from week to week across the region, extended shortages significantly affect the region's environment and economy. A study to determine if northern snow resources have changed in magnitude over the last forty years was initiated. Snow-course data measured in non-irrigated agricultural fields, near Swift Current, Saskatchewan, reflect the large year-to-year and within-year variability typical of wind-swept plains. This variability rendered direct measurement and detection of snow-resource change difficult. However, analyses of a combined set of daily climatological data (Nipher-shielded snowfall water-equivalent and depth of snow-on-the-ground) at Swift Current show a significant reduction within the last twenty years in the frequency of the number of days with snowcover depths exceeding 10 cm. This reduction was accompanied by a 3.6% increase in winter rainfall, a 17.2% decrease in snowfall, and a 48% decrease in the theoretical snowpack water equivalent. Average daily maximum temperature increased by almost 2 °C between the same early and recent decades. If the change in temperature increased snowpack losses by -34.4% and the conversion of snowfall to rainfall by 13.6%, then snow resources on the northern plains and prairies have diminished by 48%. Extrapolating these data throughout the region, one may conclude that snowcovers on the northern plains and prairies are indeed dwindling.

INTRODUCTION

Snow resources on the Northern Great Plains and Canadian Prairies find use in many economic enterprises: (1) by serving irrigation, livestock production, power generation, fisheries, waterfowl, domestic uses, etc.; (2) by accumulating clean snowy substrates in winter recreation areas; (3) by retaining a blanket of snow over winter crops for low temperature protection; and (4) by providing soil water enrichments from melting snow for dryland crops. Snow also possesses environmental importance as flood-waters from meltwater runoff and as snowdrifts over roads, across feedlots, on railways, and in farm yards. Although plains and prairie snowfall and snowcover typically vary widely from district to district and from week to week, extended shortages significantly affect this region. A study to determine if the region's snow resources have changed in magnitude and occurrence over the last forty years was initiated.

Regional snowcovers typically exhibit large areal variation. The ease with which plains and prairie snowpacks can accurately be quantified and their measures areally-extrapolated also varies widely from location to location and from conditions to conditions. This variation results from the vast area within which the region's snowstorms track and the dynamic, wind-swept nature of the region's open environments. The wind can blow an area bare of snow and redistribute the icy crystals into deep drifts located a few meters away. Extremes, ranging from shortfall to paralyzing blizzards, characterize the northern plains and prairies.

THE NORTHERN PLAINS AND PRAIRIES

The Northern Great Plains and Canadian Prairies include a loosely defined area approaching 1,400,000 km^2 (550,000 sq. miles). The region forms part of the North American mid-continental plains, sloping gradually eastward from the Rocky Mountains to Hudson Bay, the Great Lakes, and the Mississippi River Valley. Landforms within the region are generally subdued, reflecting the effects of massive continental glaciation across most of the region. Topographic relief in excess of 80 m is uncommon and usually associated with water courses which currently carry mountain-borne, snowmelt-fed rivers across the region from west to east and with meltwater channels which once drained the receding continental glaciers.

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Although the region's climate is classed as cool semiarid, it is well known for its extremes. The weather may range from hot to cold and from very dry to very wet. Winter air temperatures may drop well below -40°C and reach +35°C during the summer. Mean annual precipitation ranges from 250 to 500 mm with wide fluctuations at all locations within the region. During the summer, potential evaporation greatly exceeds precipitation, owing to ample solar radiation, warm temperatures, and the ever-characteristic wind. Indeed, the wind contributes a major element to the region's dynamic nature

As much as one-third of the annual precipitation falls as snow. Storms which deposit 10 cm or more of snow typically occur only two to five times a season. Although usually wide-spread, these storms do not produce uniform snowfalls. They even miss some districts completely, because the fast-tracking, wind-driven storms rarely cover the entire region. High winds, blowing across the subdued, agricultural terrain, are responsible for considerable areal redistribution and sublimation of snowfall and snowcover. Snowpack accumulations also vary in response to an open-sky radiation and energy advection between shifting air masses. These may initiate thaw and melt at anytime, leading to snowpack losses through evaporation and meltwater releases.

The dynamic character of the prairie environment is reflected in the degree of snowcover permanency as described by McKay (1964) and depicted in Figure 1. Snowpacks over many districts in the south-southwest areas of the region frequently disappear and reform in response to varying weather and variable winds. East, north and north westward of these districts, snowcover disappears less frequently until at the region's extremities they tend to persist throughout the winter.

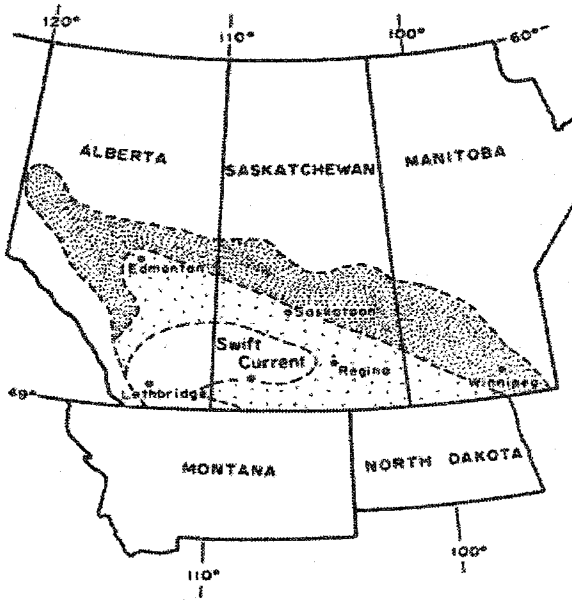

Figure 1. Generalized snowcover permanency during winter over the Canadian Prairies; degree of shading reflects permanency from a zone where snowcovers are frequently lost (white) to where they remain throughout the winter (dark).

ESTIMATING SNOWPACKS ON PLAINS AND PRAIRIES

Snow Surveys

Scientific estimates of snowpack depth, liquid water equivalent and area coverage are needed to effectively manage snow resources. Accurate areal estimates are often difficult to obtain. The traditional snow survey using point measures obtained by weighing vertical snowpack cores encounters enormous sampling problems. If one assumes that each observation accurately describes the absolute water equivalent covering the immediate one square meter of land, a sample size of ten observations for every 1000 km^2 results in a 1/100,000,000 sample (10 m^2 per 1000 km^2).

The snow water equivalent, WE, at a point, i, expressed per unit area is commonly computed as the product of the snow depth, d, and the specific gravity (density), f, of a vertically integrated snow column at the point:

$$WE_i = (f)_i \, (d)_i \qquad [1]$$

The mean areal $\underline{WE}$ for any area of interest can be estimated by using an arithmetic average of n number of sample columns obtained throughout the area sampled:

$$\underline{WE} = \sum_{i=1}^{n} WE_i \qquad [2]$$

The $\underline{WE}$ can also be estimated by using areal mean values for snowpack depth, $\underline{d}$, and specific gravity, $\underline{f}$, obtained from snow survey sampling of the pack to be estimated (Steppuhn, 1975):

$$\underline{WE} = (\underline{f}) \, (\underline{d}) + (r \, s_f \, s_d) \qquad [3]$$

where the correlation coefficient, r, between f and d measurements forms a term together with the sample standard deviations, s, for f and d. Estimating $\underline{WE}$ by this component separation technique, Equation [3], reduces the total sampling effort. The areal variability associated with $\underline{f}$ is much less than it is for $\underline{d}$, permitting a reduction in the number of labor-intensive snow cores required (Steppuhn, 1976). This leaves more time to increase the number of d-values obtained, providing better sampling precision for this more variable component of WE.

The agricultural fields containing the Swift Current Snow Courses surrounding the climate station accumulate snowpacks typical of open plains in a wind-blown prairie environment. The packs were measured for $\underline{f}$ and $\underline{d}$ during the 36 winters from 1966 through 2002. The snow surveys reflected the snowcovers existing on agricultural fields at the time of measurement and were located within 1 km of a Nipher-shielded precipitation gauge. Two types of vegetative covers, wheat stubble and cultivated summerfallow, were sampled and their measurements combined (Figure 2).

Precipitation Gauge Measurements

Most water stored in any seasonal snowpack on the plains and prairies originates as snowfall, accumulating over time under winter conditions. Consequently, measures of precipitation, especially when occurring as snowfall, have been used to estimate snowpack water equivalent. Equations based on the conservation of mass describe the relationship:

$$WE_t = \sum_{j=1}^{t} (W_j + C_j - E_j - I_j - R_j + B_j) \qquad [4]$$

where the snowpack water equivalent, WE_t, at time t equals the algebraic sum of snowfall water, W, condensation, C, evaporation, E, infiltration into the surface litter or soil, I, runoff, R, and the net mass of deposited or eroded wind-blown snow, B, accumulated by time increments j over the period t beginning on the day that the snowcover begins to accumulate.

The Agricultural Climatological Station on the Research Farm near Swift Current, Saskatchewan, forms part of the Federal Atmospheric Environment Service's (AES) Canadian network. The station is located 3 km southeast of the city on a wind-swept plain sloping gently (1% or less) to the north. The Nipher-shielded gauge complies with AES site requirements and is read manually at least once each day. The 117-year mean annual precipitation equals 360 mm.

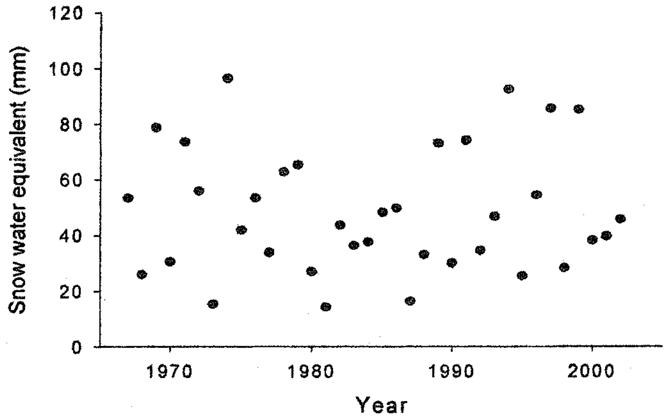

Figure 2. Mean annual snow water equivalent from snowcourse surveys near Swift Current, Saskatchewan, from 1966 through 2002.

Liquid water volumes, W, from daily accumulations of snowfall caught in the Nipher gauge served as point measures of precipitation. These quantities, left uncorrected for wind, were summed by daily increments of j over the snowcover accumulation period, t, from November 1st through April 30th of the snowpack year,

$$\sum_{j=1}^{t} (W_j).$$

A total of 42 years were summarized (Table 1).

Table 1. Annual winter precipitation, rain and snowfall (mm), during the period Nov 1 through Apr 30, Swift Current, Saskatchewan.

Year within the decade	Decade				
	1960's	1970's	1980's	1990's	2000's
	mm				
1	103	94	74	123	60
2	90	88	88	54	55
3	69	116	91	86	
4	80	190	68	93	
5	111	121	94	88	
6	107	116	77	123	
7	170	59	80	164	
8	70	124	42	55	
9	133	99	110	119	
10	96	51	90	101	
Decade average	103	106	81	101	57

ADJUSTING PRECIPITATION GAUGE ESTIMATES

One of the daily observations required at Canadian AES Climatological Stations involves measuring the depth of the snowpack in level areas within and immediately surrounding the site containing the weather instruments. These depths are averaged and reported each day as "Depth-of-Snow-on-the-Ground." If these daily depths increase in tandem with increases in snowfall precipitation, new snow is being added to the pack. If depths decrease after having previously remained constant, the pack is increasing in density and/or losing snow-mass by meltwater runoff, subsurface infiltration, or evaporation as outlined in Equation [4]. Thus, these depth measurements offer an opportunity to adjust the accumulated Nipher gauge data for weather-induced snowpack changes (Steppuhn 2000).

The adjustment procedure requires daily-measured inputs of snowfall, W_j, and depth-of-snow-on-the-ground, h_j. These observations serve the calculation of a daily specific gravity (density) value, f_j, and a daily-adjusted cumulative water equivalent, W'_j of a theoretical snowpack, whose dynamics are based on the actual effects of the weather on the snowcover. Depending on W_j, h_j, and f_j, the theoretical snowpack is adjusted for accumulation, evaporation, and meltwater release. The procedure does not adjust the snowpack WE for condensation nor for net change due to erosion or deposition by wind-borne snow, nor does it separate melt losses into runoff or infiltration. Once the theoretical specific gravity for the day, f, is computed, the adjustment method requires three additional assumptions:

(1) that the maximum f-value for prairie packs equals 0.35 (or any other chosen value),
(2) that no significant change in snowpack mass occurs until the maximum density is reached (thus, evaporation without depth change is ignored), and
(3) that water in excess of maximum f leaves the pack.

On any day, j, W_j can either equal or exceed zero, and the h_j measured that day will relate to the previous day's measurement, h_{j-1}, depending on one of five conditions existing with respect to the snowfall measured on that day, W_j. If for any day j and the previous day j-1, the theoretical snowpack variables of water equivalent, W', and density, f', and their daily pre-adjusted values, W'' and f'', can be calculated in response to ambient conditions. Each of the five sets of conditions triggers specific equations for calculating the theoretical snowpack W'_j, and f'_j, plus the adjusted daily snowfall (Adj.W_j). Within each of the five sets of conditions, various equations become applicable, reflecting the snowpack physics depending on f'' reaching or exceeding a pre-defined threshold snowpack density (0.35 herein) when W' begins to lose water. The five sets (I-V) of ambient conditions are:

I. If $W_j > 0$ and $h_j > 0$ and $h_j > h_{j-1}$

$$W''_j = W'_{j-1} + W_j \qquad \text{and} \qquad f''_j = W''_j / h_j$$

i) If $f''_j < 0.35$

$$W'_j = W''_j \qquad \text{and} \qquad f'_j = f''_j \qquad \text{and} \qquad \text{Adj.}W_j = W_j \qquad [5]$$

Snowfall occurred, as recorded in the Nipher-shielded gauge, the depth of snow-on-the-ground exceeded that of the day before, and the pre-adjusted density remained below the threshold required for the pack to lose water.

ii) If $f''_j = 0.35$

$$W'_j = W''_j \qquad \text{and} \qquad f'_j = 0.35 \qquad \text{and} \qquad \text{Adj.}W_j = W_j \qquad [6]$$

Snowfall occurred, as recorded in the Nipher-shielded gauge, the depth of snow-on-the-ground exceeded that of the day before, and the pre-adjusted density just reached the threshold required for the pack to lose water.

iii) If $f'_j > 0.35$

$$W'_j = W'_{j-1} + \left\{0.35(h_j - h_{j-1})\left[1 - \frac{(f'_j - 0.35)}{(f'_j - f_{j-1})}\right]\right\} \qquad \text{and} \qquad f_j = 0.35 \qquad \text{and} \qquad Adj.W_j = W_j \qquad [7]$$

Snowfall occurred, as recorded in the Nipher-shielded gauge, the depth of snow-on-the-ground exceeded that of the day before, and the pre-adjusted density exceeded the threshold required for the pack to lose water.

II. If $W_j > 0$ and $h_j > 0$ and $h_j = h_{j-1}$

$$W''_j = W'_{j-1} + W_j \qquad \text{and} \qquad f'_j = W''_j / h_j$$

i) If $f'_j < 0.35$

$$W'_j = W''_j \qquad \text{and} \qquad f_j = f'_j \qquad \text{and} \qquad Adj.W_j = W_j \qquad [8]$$

Snowfall occurred, as recorded in the Nipher-shielded gauge, the depth of snow-on-the-ground equaled that of the day before, and the pre-adjusted density remained below the threshold required for the pack to lose water.

ii) If $f'_j = 0.35$

$$W'_j = W''_j \qquad \text{and} \qquad f_j = 0.35 \qquad \text{and} \qquad Adj.W_j = W_j \qquad [9]$$

Snowfall occurred, as recorded in the Nipher-shielded gauge, the depth of snow-on-the-ground equaled that of the day before, and the pre-adjusted density just reached the threshold required for the pack to lose water.

iii) If $f'_j > 0.35$

$$W'_j = W'_{j-1} + \left\{(W_j)\left[1 - \frac{(f'_j - 0.35)}{(f'_j - f_{j-1})}\right]\right\} \qquad \text{and} \qquad f_j = 0.35 \qquad \text{and} \qquad Adj.W_j = W_j \qquad [10]$$

Snowfall occurred, as recorded in the Nipher-shielded gauge, the depth of snow-on-the-ground equaled that of the day before, and the pre-adjusted density exceeded the threshold required for the pack to lose water.

III. If $W_j > 0$ and $h_j > 0$ and $h_j < h_{j-1}$

$$W''_j = W'_{j-1} + W_j \qquad \text{and} \qquad f'_j = (h_{j-1} / h_j)\, f_{j-1}$$

i) If $f'_j < 0.35$

$$W'_j = W''_j \qquad \text{and} \qquad f_j = f'_j \qquad \text{and} \qquad Adj.W_j = W_j \qquad [11]$$

Snowfall occurred, as recorded in the Nipher-shielded gauge, the depth of snow-on-the-ground measured less than the depth the day before, and the pre-adjusted density remained below the threshold required for the pack to lose water.

ii) If $f'_j = 0.35$

$$W'_j = W''_j \qquad \text{and} \qquad f_j = 0.35 \qquad \text{and} \qquad Adj.W_j = W_j \qquad [12]$$

Snowfall occurred, as recorded in the Nipher-shielded gauge, the depth of snow-on-the-ground measured less than the depth the day before, and the pre-adjusted density just reached the threshold required for the pack to lose water.

iii) If $f''_j > 0.35$

$$W'_j = W'_{j-1} - \{0.35(h_{j-1}-h_j)\left[\frac{(f''_j - 0.35)}{(f''_j - f'_{j-1})}\right]\} \quad \text{and} \quad f'_j = 0.35 \quad \text{and} \quad Adj.W_j = W'_j - W_{j-1} \qquad [13]$$

Snowfall occurred, as recorded in the Nipher-shielded gauge, the depth of snow-on-the-ground measured less than the depth the day before, and the pre-adjusted density exceeded the threshold required for the pack to lose water.

IV. If $W_j = 0$ and $h_{j.}\ h_{j-1}$

$$W'_j = W'_{j-1} \quad \text{and} \quad f'_j = f'_{j-1} \quad \text{and} \quad Adj.W_j = 0 \qquad [14]$$

No new snow fell, the depth of snow-on-the-ground equaled or exceeded the depth the day before, and weather conditions allowed the snowpack density to remain below the threshold required for the pack to lose water.

V. If $W_j = 0$ and $h_j < h_{j-1}$

$$W''_j = W'_{j-1} \quad \text{and} \quad f''_j = (h_{j-1} / h_j)\, f'_{j-1}$$

i) If $f''_j < 0.35$

$$W'_j = W'_{j-1} \quad \text{and} \quad f'_j = f''_j \quad \text{and} \quad Adj.W_j = 0 \qquad [15]$$

No new snow fell, the depth of snow-on-the-ground measured less than the depth the day before, and weather conditions caused the pre-adjusted density to remain below the threshold required for the pack to lose water.

ii) If $f''_j = 0.35$

$$W'_j = W'_{j-1} - [0.35\,(h_{j-1} - h_j)] \quad \text{and} \quad f' = 0.35 \quad \text{and} \quad Adj.W_j = W'_j - W'_{j-1} \qquad [16]$$

No new snow fell, the depth of snow-on-the-ground measured less than the depth the day before, and weather conditions caused the pre-adjusted density to just equal the threshold required for the pack to lose water.

iii) If $f''_j > 0.35$

$$W'_j = W'_{j-1} - \{0.35\,(h_{j-1} - h_j)\left[\frac{(f''_j - 0.35)}{(f''_j - f'_{j-1})}\right]\} \quad \text{and} \quad f' = 0.35 \quad \text{and} \quad Adj.W_j = W'_j - W'_{j-1} \qquad [17]$$

No new snow fell, the depth of snow-on-the-ground measured less than the depth the day before, and weather conditions caused the pre-adjusted snowpack density to exceed the threshold required for the pack to lose water.

The theoretical snowpack density, f'_j, is not allowed to exceed a theoretical maximum, say 0.35, and from Equation [1], the term $0.35\,(h_{j-1} - h_j)$ equals the maximum potential volume of water which could have left the pack based on the measured change in snowpack depth. The term $[(f'_{j-1} - 0.35)/(f'_j - f'_{j-1})]$ represents that fraction of the snowfall water associated with a change in depth in excess of densification to the maximum.

SNOWFALL AND SNOWPACK RESOURCES

Snowfall

Mean annual snowfall (water equivalent) accumulated in the Swift Current Nipher-shielded gauge during the last 42 years (1960-2002) shows deviations ranging from -40 to +80 mm of the period mean (Figure 3). Following visual inspection, deviations were further grouped sequentially into two sub-periods of 16 years (1961-1977) and 26 years (1977-2002). The deviation in water equivalent averaged +15.2 mm in the 1961-77 period and -9.3 mm during the 1977-2002 period. This represents a decrease of 24.5 mm or about 25% of the annual winter precipitation (Table 1). A closer view of these data also suggests that winter precipitation (snowfall plus rain) in the 1960's and 1970's compared to that in the 1980's and 1990's has decreased less than snowfall water equivalent alone, -13.6% and -17.2%, respectively (Figure 4). The difference equals 3.6% reflecting an increase in rainfall from the early to the recent decades.

Snowpack

A decrease over time in the annual theoretical snowpack water equivalent based on the Nipher gauge and snow-on-the-ground measurements at Swift Current reflects the variability in snowfall (Figure 5). Since 1979, the number of years with snowpack water equivalent below the 42-year mean equaled 20 years out or 23 or 87%. The mean annual water equivalent of the theoretical snowpack ($\underline{W'}_j$) calculated daily over the 181-day winter and averaged by decade resulted in an obvious decline in the 1980's, 1990's, and in the first two years of the 2000's compared to the 1960's and 1970's (Figure 6). The decrease in the average water equivalent of the calculated (theoretical) annual snowpack between the early and recent decades is 48%, of which 17.2% appears to be a drop in snowfall magnitude. What processes account for the remaining 30.8%?

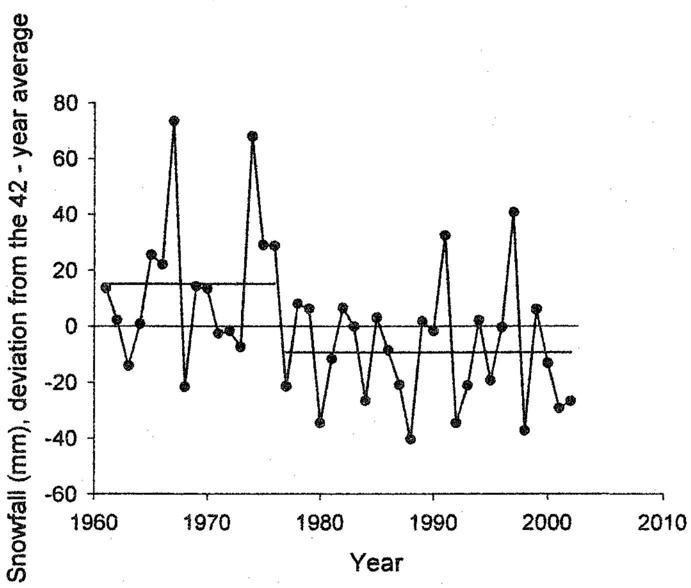

Figure 3. Deviation of the accumulated annual snowfall water equivalent (mm), from the 42-year mean with average deviations for 1961-1977 and 1977-2002, near Swift Current, Saskatchewan.

If the numbers of days per winter (Nov 1 through Apr 30) when the mean theoretical snowpack ($\underline{W'}_j$) exceeds 10 mm are averaged by decade, a large decrease emerges (Figure 7), which is in agreement with the drop in mean annual snowpack water equivalent observed in Figure 6. When these numbers are compared to the number of days per winter with no snow on the ground ($\underline{W'}_j = 0$), averaged by decade, an opposite trend results (Figure 8). Those decades exhibiting fewer days with snowcovers greater than 10 mm also record more days with no snowcover.

Temperature

Records from the AES climatological station near Swift Current also provide daily temperature data. The average daily maximum temperature during the winter season is physically related to the percentage of precipitation falling as rain and to the potential for snowpack melt and evaporation. A comparison of the maximum daily temperature, averaged by decades, viewed as deviations from the 42-year mean reveal a 1-2 °C increase from the 1960's and 1970's to the 1980's, 1990's and 2000's (Figure 9). Viewed together with the decrease in the theoretical snowpack, this suggests that snowpacks over the recent decades have been more affected by ambient temperature than by at

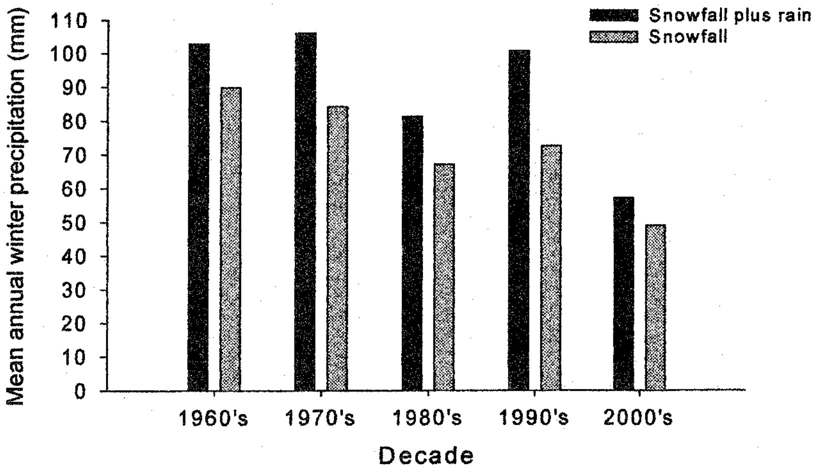

Figure 4. Mean annual winter (November 1 through April 30) precipitation (mm), snowfall and snowfall plus rain, averaged by decade near Swift Current, Saskatchewan.

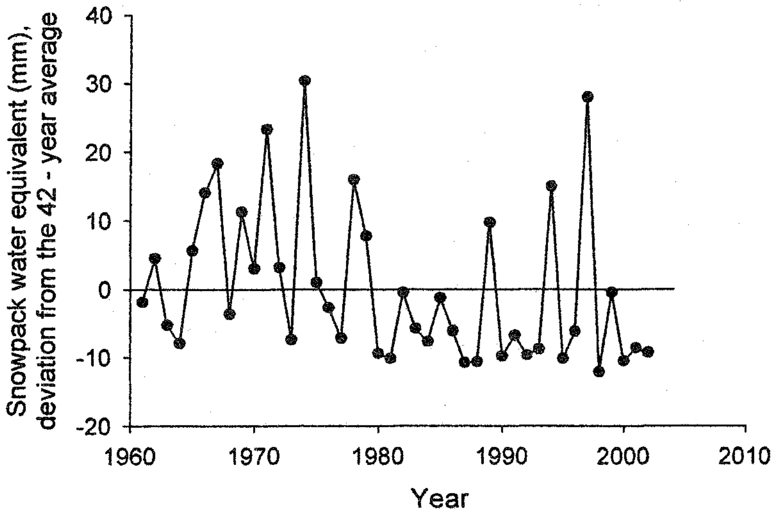

Figure 5. Deviation in the theoretical annual snowpack water equivalent (mm), from the 42-year average, near Swift Current, Saskatchewan.

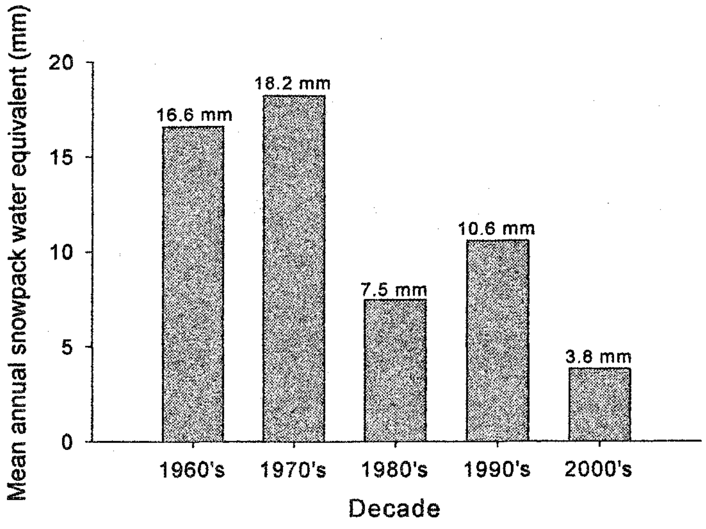

Figure 6. Mean annual theoretical snowpack water equivalent, W’j, (mm) for the 181-day winter averaged by decade, near Swift Current, Saskatchewan.

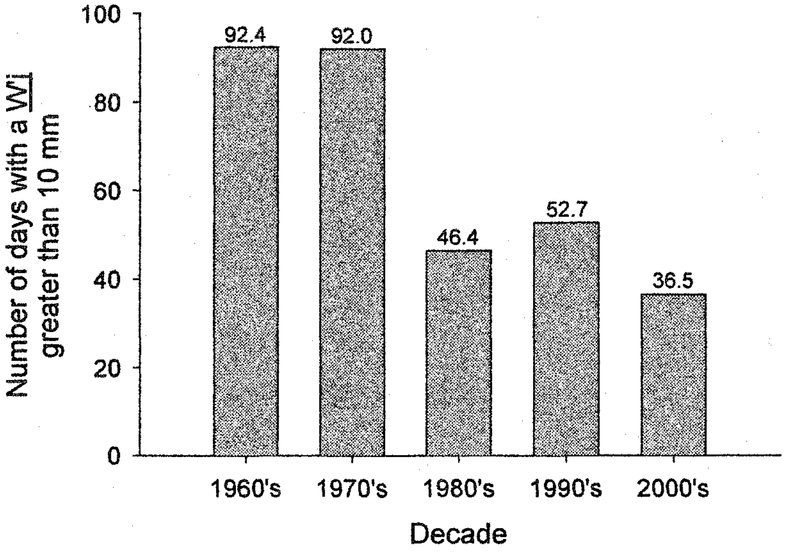

Figure 7. Number of days per winter (November 1 through April 30), with a mean theoretical snowpack W’j greater than 10 mm, averaged by decade, near Swift Current, Saskatchewan.

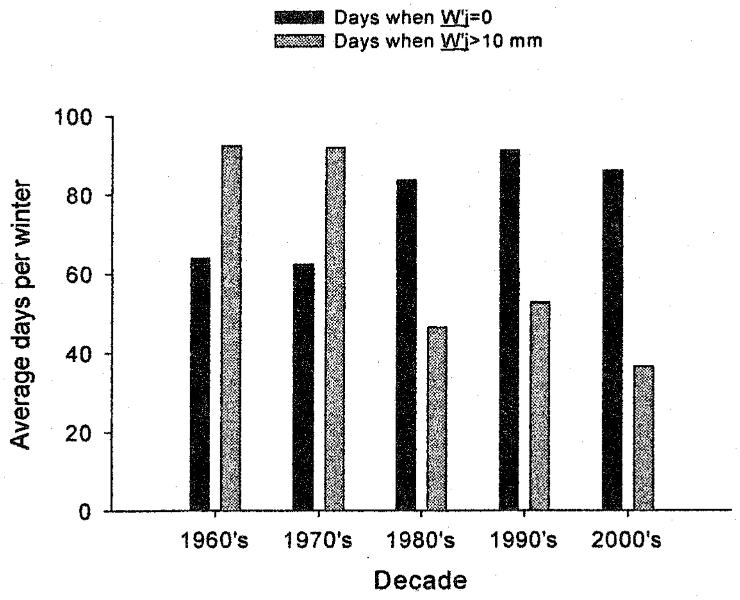

Figure 8. Average number of days per winter (Nov 1 thru. Apr 30), with no theoretical snowpack, W'j, and number of days with a snowpack greater than 10 mm, averaged by decade, near Swift Current, Saskatchewan.

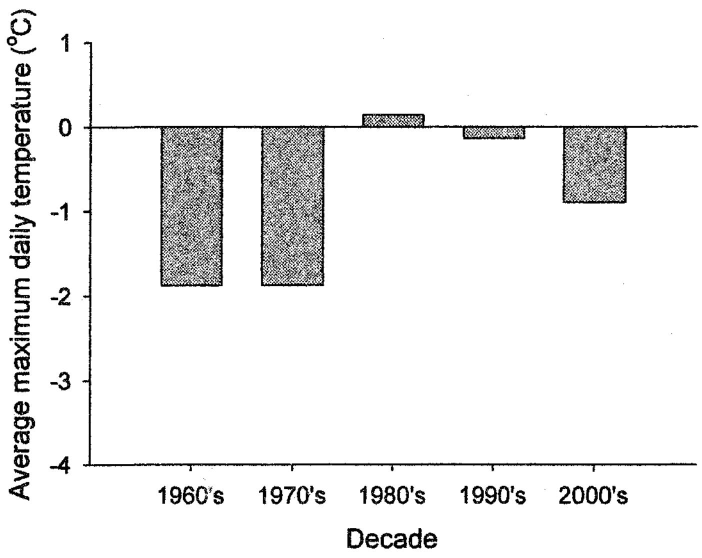

Figure 9. Average daily maximum temperature (°C), for the period (November 1 through April 30), averaged by decade, near Swift Current, Saskatchewan.

CONCLUSIONS

Changes in regional snow resources of the Northern Great Plains and Canadian Prairies stem from changes in the magnitudes of rainfall, snowfall, snowpack accumulation, and snowcover loss (Equ. [4]). Between the early decades (1960's plus 1970's) and the recent decades (1980's and 1990's), data collected at Swift Current, Saskatchewan, from 1961 through 2002, show a 3.6% increase in winter rainfall, a 17.2% decrease in snowfall, and a 48% decrease in the theoretical snowpack water equivalent. This leaves over half of the drop in the magnitude of the theoretical snowpack as having been reduced by elements of the ambient environment. Average daily maximum temperature increased by almost 2 °C between the same early and recent decades. If the change in temperature increased snowpack losses by -34.4% and the conversion of snowfall to rainfall by 13.6%, then snow resources on the northern plains and prairies have diminished by 48%. Of course, this includes snowpack meltwater which leaves the pack during the winter and provides some soil water enrichment and runoff.

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