ABLATION RATES OF SNOW FENCE DRIFTS AT 2300-METERS ELEVATION IN WYOMING

768-85

BY

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INTRODUCTION

Knowledge of the melt rate and water balance of snowdrifts is necessary to design water augmentation projects using snow fences, as well as to evaluate the hydrologic effects of fences built for other purposes. If seasonal ablation rates can be predicted, for example, snowmelt discharge rates can be estimated and erosion potential can be assessed. The melting of drifts formed by snow fences is complicated by the influence of the fence on the energy balance of the drift, and by the fact that these drifts are usually islands of snow surrounded by snow-free ground. Few studies have been done on isolated snowdrifts in prairie environments compared to the numerous references to mountain snowpacks, snowfields, and glaciers. Fisher (1968) studied the melting of an immature drift behind a 3.7-m-tall snow fence at 2500 m elevation in southeastern Wyoming, and Rechard and associates (Rechard and Raffelson, 1974; Rechard, 1975; and Fletcher and Rechard, 1976) also studied the water balance of drifts behind 2.4-m fences in the same general location. Zuzel and Cox (1978) and Cooley et al. (1981) have reported on the ablation and hydrologic effects of a snowdrift behind a 2.4-m fence on a ridge at 2100 m in Idaho. Although other authors have reported studies of the water balance of drifts behind fences (Saulmon, 1973), published data have not included ablation rates or temperature indices.

Measurements of drift ablation reported here were an extension of a study to determine how different widths of openings (bottom-gaps) under snow fences affect snow trapping efficiency and drift geometry. The 1983-84 winter brought unusually heavy precipitation to southeastern Wyoming, resulting in the study fences being filled nearly to capacity by the end of the drifting season. This provided an opportunity to trace the ablation of fully developed drifts behind 3.8-m fences.

Objectives of this study were to monitor ablation of several snow fence drifts throughout the melt season, and to relate ablation rates and changes in drift geometry to air temperatures.

STUDY SITES, MEASUREMENTS, and COMPUTATIONAL PROCEDURES

The snow fences are standard 3.8-m-tall Wyoming Highway Department wood fences, as described by Tabler (1974), having 15-cm-wide horizontal boards and 50% porosity. Various modifications were made in the standard bottom-gap of 35 cm for this study. The study fences comprise part of the 52 km of snow fence protecting Interstate Highway 80 between Laramie and Walcott Junction in southeastern Wyoming. The fences are straight and perpendicular to the prevailing WSW winds.

Ablation measurements were initially duplicated at two sites having different weather conditions. The "Cooper Cove" site (at I-80 Mile 280) is located at 41°33' N., 106°05'W., elevation 2335 m, on shortgrass rangeland sloping downward 2% towards the north. Two measurement transects were established behind a single 556-m-long fence. One transect was in the center of a 110-m-long section of the fence having a 15-cm bottom gap, and the other was in the center of an adjacent 110-m section having a 55-cm bottom-gap.

The "Elk Mountain" fence at I-80 Mile 255, is 346 m long and is located at 41°44' N., 106°29' W., elevation 2220 m, on shortgrass rangeland sloping downward to the southwest at 1%. Two transects were measured behind this fence also, with one located in the center of a 110-m-long section of fence having a 15-cm bottom-gap, and the other in the center of an adjacent 110-m section having a 90-cm gap.

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Measurements at both the Cooper Cove and Elk Mountain sites continued through the melt season (April 10 - June 14, 1984). After the snow had disappeared from these locations, ablation measurements were begun at the "Wagonhound" site at I-80 Mile 268, and continued until snow disappearance on July 6. The snow fence at this site (41°37' N., 106°15' W., elevation 2390 m) is located on a gentle ridge which causes the lee drift to be exceptionally deep and to persist later into the summer. Terrain behind the fence slopes downward toward the northeast at about 15%. The Wagonhound fence is 370 m long and has a uniform standard bottom-gap of about 35 cm. The single measurement transect was located near the center of the fence, coinciding with the deepest part of the drift.

On most measurement dates, snow depths were probed at 3-m intervals along each permanent transect. On a few dates early in the melt season, snow depths were measured at a single permanent reference point in the center of the drift to provide supplemental ablation data while minimizing disturbance to the drift surface. Snow ablation between measurement dates was computed as the mean change in snow depth at all measurement points having snow on both dates.

Snow density samples were taken with a standard Federal sampler on May 3 and June 13, 18, 22, and 30, to allow ablation to be converted into water-equivalent. Because of the dense snow, samples deeper than about 50 cm could only be obtained by driving the tube down with a hammer, and no samples were obtained below 300 cm.

To test the hypothesis that the usual 10% over-measurement by the Federal sampler (Farnes et al., 1982) applied to these melting drifts, twelve bulk density samples having depths 30-50 cm were excavated using a 30- by 30-cm steel template. Some of these samples included the entire snow depth, and some were at the surface of snow much deeper than the sample taken. These samples were placed in plastic bags and weighed on a standard dairy scale.

At each study fence, a recording hygrothermograph was installed in an instrument shelter attached at 2 m height to the rear braces of the snow fences. Thus, the fences shaded the shelters during the afternoons. Because these instruments were not installed until April 10, the degree-days reported here do not include any accumulated before that date. A National Weather Service cooperative-observer station in the town of Elk Mountain, near the fence site of the same name, reported 1.7 degree-days in March, and 0.6 from April 1 to April 10 as computed from daily mean temperatures.

Degree-days (0° C base) were computed from the sum of 2-hour temperatures exceeding 0° C, in order to provide the resolution required for short intervals between ablation measurements. A comparison showed cumulative degree-days computed in this manner were within 2% of values calculated from mean daily temperature, (maximum + minimum)/2.

RESULTS

Chronology.

Heavy early winter snowfall and cold temperatures compensated for below-normal wind run so that by February 22, 1984, the study fences averaged more than 90% of the equilibrium capacity reported by Tabler (1980). Characteristics of the drifts at the two primary study sites on this date are given in Table 1. Drifting after February 24 was only sufficient to compensate for settlement and evaporation. Temperatures remained cold until April 5 when active surface melting began. Minimum snow temperatures measured in cores obtained with a Federal sampler on April 10 were -0.6° C at 230 cm depth at Elk Mountain, and -1.0° C at 230 cm depth at Cooper Cove, with essentially uniform temperature gradients to 0° C at both the surface and bottom of the drifts. By April 10, drift depths at both sites were within a few centimeters of those measured on February 22. Ablation continued without interruption through the rest of the spring, but rates were low until May 2, when the drifts were "ripe" and active melting began.

From May 2 until the disappearance of snow at the Elk Mountain and Cooper Cove sites on June 14, an average of only 3.0 cm of rain was recorded at precipitation gages located a few kilometers from each site. The largest 24-h rainstorm was 0.6 cm. Seasonal temperatures continued until July 6, the date of snow disappearance from the Wagonhound site.

Table 1. Characteristics of snowdrifts at peak accumulation (February 22-24, 1984).

Drift characteristic	Cooper Cove fence (3.76-m fence height)		Elk Mountain fence (3.79-m fence height)	
	15-cm gap	55-cm gap	15-cm gap	90-cm gap
Leeward Drift:				
Distance to beginning of drift (m)	0	1.4	0	10.4
Depth at fence (m)	1.13	0	1.25	0
Maximum depth (m)	4.47	4.51	4.63	4.23
Distance to maximum depth (m)	21.3	24.4	22.9	32.0
Distance to end of drift (m)	104	102	107	110
Cross-sectional area (m^2)	238	247	269	258
Windward Drift:				
Distance to beginning of drift (m)	0	0	0	0
Maximum depth (m)	1.69	1.32	2.05	1.13
Distance to maximum depth (m)	0.6	3.0	1.2	2.9
Distance to end of drift (m)	52	52	55	52
Cross-sectional area (m^2)	36	26	43	25

Drift Ablation.

For simplicity, analyses reported here have been restricted to leeward drifts. Results can be applied to windward drifts with reasonable accuracy for engineering purposes.

Drift dimensions, snow ablation, and degree-days for each measurement date are presented in Tables 2-4. Plots of cumulative ablation versus cumulative degree-days (Figure 1) show relatively uniform relationships over the season. Ablation rate factors and confidence intervals are also shown in the figure. Wind speed near the snow surface is higher for wider bottom-gaps, which tends to increase the ablation rate. Melt rate behind the fence having a 90-cm gap was about 11% greater than that for the adjacent 15-cm-gap section. Presumably, the ablation rate at Wagonhound was less than that at the other sites because the drift was in a relatively sheltered location on the lee side of a ridge. Although there was no obvious tendency for ablation rates to diminish with time at the other sites, this might be expected at Wagonhound because terrain sheltering would increase as the drift melted.

The best estimate for ablation rate of drifts behind snow fences having moderate bottom-gaps (i.e., less than 15% of the total height) and located on level terrain, would be 0.98 ± 0.02 $cm \cdot deg^{-1} \cdot day^{-1}$ (0.95 confidence interval), derived by combining the two fence sections at Cooper Cove and the 15 cm gap-section at Elk Mountain. The author computed about the same value for the 1968 spring (1.02 $cm \cdot deg^{-1} \cdot day^{-1}$) for the much smaller drift described by Fisher (1968). These rates also compare closely with those the

Table 2. Lee drift dimensions, ablation, and degree-days for all measurement dates at the Cooper Cove fence.

	15-cm bottom-gap					55-cm bottom-gap				
Date (1984)	Elapsed time	Cross-sect. area	Drift length	Degree-days	Ablation	Elapsed time	Cross-sect. area	Drift length	Degree-days	Ablation
	(h)	(m^2)	(m)		(cm)	(h)	(m^2)	(m)		(cm)
02/24	-	237.5	104.2	-	0	-	247.1	100.4	-	0
03/09	-	-	-	-	-	336	244.2	102.1	-	0
04/12	-	-	-	-	-	814	236.4	102.4	2.4	2.76
04/23	-	-	-	-	-	261	-	-	30.2	15.2
04/28	-	-	-	-	-	128	-	-	6.1	7.6
04/30	-	-	-	-	-	43	-	-	0.2	0.0
05/02	1620	209.3	100.6	44.9	27.2	51	220.5	99.1	6.0	7.6
05/15	310	116.8	64.3	108.7	110.5	310	123.6	66.1	108.7	119.1
05/21	143	81.0	54.6	69.1	59.8	143	-	-	69.1	63.6
05/29	187	42.4	37.5	76.3	76.9	187	40.3	39.3	76.3	80.2
06/01	76	29.4	33.1	47.8	35.8	76	25.8	32.9	47.8	38.4
06/05	95	18.5	28.0	39.0	34.2	95	13.7	27.2	39.0	39.4
06/06	24	17.2	27.4	7.5	4.1	24	12.1	25.6	7.5	5.4
06/08	48	13.2	23.5	14.3	14.9	48	7.9	22.4	14.3	17.1
06/11	71	6.5	18.9	19.7	30.1	71	1.7	13.1	19.7	29.2
06/13	47	2.6	15.1	24.1	23.6	47	0	0	24.1	22.9
06/14	24	0	0	15.6	27.9					

Table 3. Lee drift dimensions, ablation, and degree-days for all measurement dates at the Elk Mountain fence.

	15-cm bottom-gap					90-cm bottom-gap				
Date (1984)	Elapsed time	Cross-sect. area	Drift length	Degree-days	Ablation	Elapsed time	Cross-sect. area	Drift length	Degree-days	Ablation
	(h)	(m^2)	(m)		(cm)	(h)	(m^2)	(m)		(cm)
02/22	-	268.8	106.7	-	0	-	257.9	107.0	0	0
03/07	336	275.0	112.8	-	0	336	266.9	108.2	0	0
03/30	552	282.5	109.7	-	0	552	273.7	110.3	0	0
04/09	240	-	-	-	16.1	240	259.5	109.7	0	16.1
04/10	24	-	-	0	0	24	-	-	0	0
04/13	72	-	-	0	0	72	-	-	0	0
04/23	235	-	-	27.1	35.6	-	-	-	-	-
04/28	125	-	-	6.1	0	432	229.4	108.5	33.6	27.3
04/30	45	-	-	0.1	0	-	-	-	-	-
05/03	74	234.9	103.7	4.3	10.2	118	212.0	101.2	4.4	16.0
05/15	287	137.3	71.3	97.6	110.5	287	105.3	67.0	97.6	128.7
05/21	143	94.8	64.3	70.9	66.2	-	-	-	-	-
05/29	191	48.9	46.8	74.4	83.0	335	14.0	35.7	146.8	172.3
06/01	73	33.2	36.6	42.8	35.1	73	2.6	16.9	42.8	40.6
06/05	95	19.6	29.6	37.9	40.6	95	0	0	37.9	30.0
06/06	29	17.0	29.0	8.1	8.8					
06/08	43	12.8	25.9	11.4	14.6					
06/11	72	6.3	21.3	17.6	27.1					
06/13	48	2.2	15.4	24.9	21.8					
06/14	26	0.2	4.0	20.0	12.7					

Table 4. Lee drift dimensions, ablation, and degree-days for all measurement dates at the Wagonhound fence.

	35-cm bottom-gap				
Date (1984)	Elapsed time	Cross-sect. area	Drift length	Degree-days	Ablation
	(h)	(m^2)	(m)		(cm)
03/16	-	372.0	83.2	-	-
06/13	2136	99.7	46.6	451.4	418.4
06/18	115	73.3	42.4	74.9	59.0
06/22	94	50.2	37.9	65.2	56.1
06/25	70	35.0	34.4	46.1	41.9
06/30	120	15.3	24.9	95.1	66.3
07/03	74	4.4	16.8	48.9	48.8
07/06	72	0	0	56.9	48.3

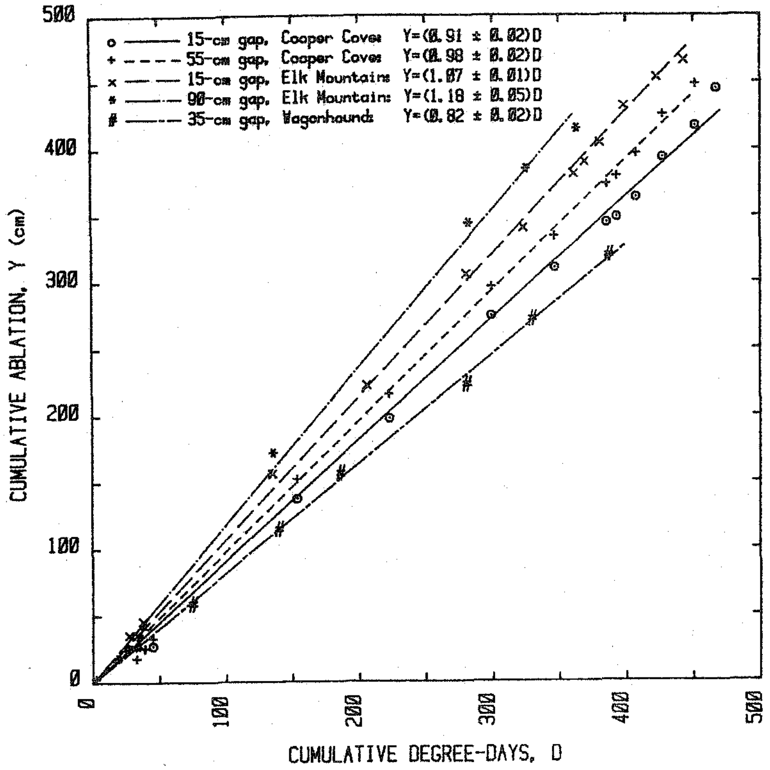

Figure 1. Cumulative ablation rates versus cumulative degree-days for lee drifts behind the 3.8-m-tall fences. Summations at the Wagonhound site do not include values prior to June 13.

author has calculated from Martinelli's (1959) data for alpine snowfields in the Colorado Front Range. At a 3810-m site, ablation rates were 1.01 and 1.11 cm$\cdot$deg$^{-1}\cdot$day^{-1} over the 1955 and 1956 summers. At another site at 3505-m elevation, ablation rates for those years were 1.03 and 1.08. The drift studied by Fletcher and Rechard (1976) had a mean rate of 1.24 cm$\cdot$deg$^{-1}\cdot$day^{-1} in 1973, but this higher rate could be explained by the presence of an underlying black rubber mat used to collect the meltwater for measurement.

Mean daily ablations from April 10 to June 14 were 7.1 and 7.4 cm at Cooper Cove and Elk Mountain, respectively. Maximum observed rates were 12.1 and 11.5 cm. From June 14 to July 3 at the Wagonhound site, mean daily ablation was 13.3 cm, with a peak rate of 16.1 cm$\cdot$day^{-1} for a 3-day period when maximum air temperatures averaged 25.6° C. For comparison, mean daily ablation rate in the alpine snowfield studied by Bartos and Rechard (1974) was 6.00 $\pm$ 0.5 cm$\cdot$day^{-1}.

For the three fence sections having moderate bottom-gaps on level terrain, ablation over the downwind half of the drifts averaged 96% of that over the windward half (Fig. 2). A slightly greater ablation rate over windward portions would be expected because of changes in temperature and humidity that must occur in the boundary layer as wind flows across the drift from the prevailing direction. This effect would be expected to increase with bottom-gap, and could explain the slightly greater ablation over the nose of the drift behind the 90-cm gap section. For the more sheltered location at Wagonhound, ablation was more rapid over the tail of the drift. Although the reason for this is unknown, it may be due to the reverse wind direction associated with flow separation on the lee side of the ridge.

Because these differences between the nose and tail ablation rates are relatively small, it is concluded that for fences with moderate bottom-gaps on level terrain, ablation is essentially uniform over the drift, making it possible to predict changes in the drift shape as the melt season progresses. An empirical equation presented by Tabler (1980) to describe the shape of equilibrium drifts formed by Wyoming snow fences is

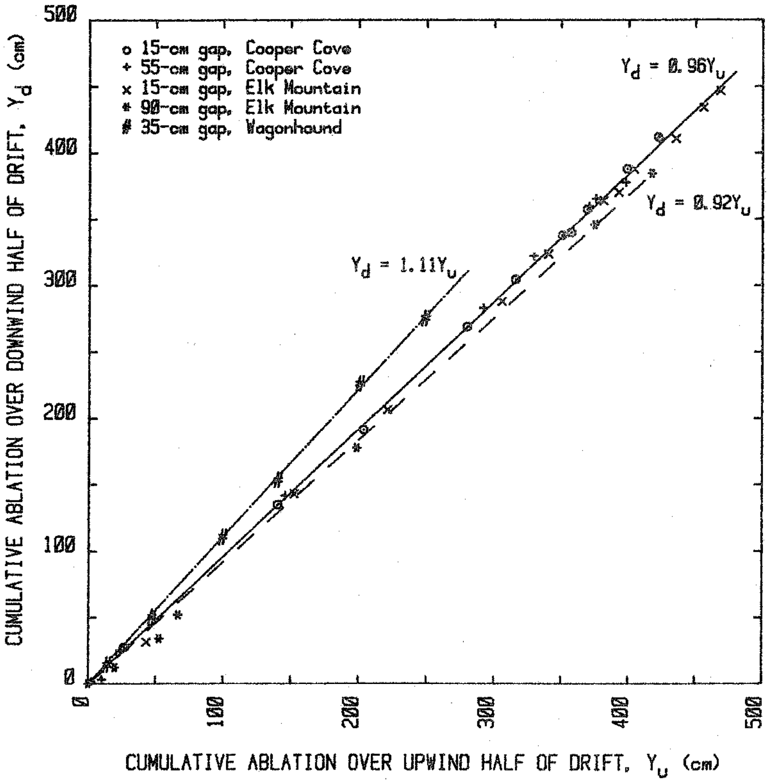

Figure 2. Comparison of ablation over upwind and downwind halves of the lee drifts.

$$\frac{Z}{H} = 0.20 + 0.377\left(\frac{X}{H}\right) - 0.0472\left(\frac{X}{H}\right)^2 + 0.002329\left(\frac{X}{H}\right)^3 - 5.392\cdot10^{-5}\left(\frac{X}{H}\right)^4 + 4.840\cdot10^{-7}\left(\frac{X}{H}\right)^5, \quad X \leq 30H \tag{1}$$

where Z is snow depth at distance X from the fence, and H is total vertical fence height. Using this equation as a starting point, it is possible to compute cross-sectional area, surface length, and drift length for uniform incremental changes in the snow depth, using a numerical computer analysis. Results of this theoretical analysis, assuming an ablation rate of 1.00 $\text{cm}\cdot\text{deg}^{-1}\cdot\text{day}^{-1}$, are shown as curves in Figure 3, where drift length, cross-sectional area and accumulated melt are plotted as functions of accumulated degree-days expressed as a fraction of the total degree-days required for complete melting. Validity of the assumptions about uniform ablation rate in space and time are supported by observed values for drift length and cross-sectional area, which are also plotted in Figure 3. An equation approximating the theoretical curve for drift length, L, is

$$\frac{L}{L_i} = 1.00 - 1.274\left(\frac{D}{D_t}\right) + 1.328\left(\frac{D}{D_t}\right)^2 - 2.814\left(\frac{D}{D_t}\right)^3 + 3.834\left(\frac{D}{D_t}\right)^4 - 2.021\left(\frac{D}{D_t}\right)^5 \tag{2}$$

where L_i is initial drift length before melting (typically 30H for equilibrium drifts), D is cumulative degree-days, and D_t is total degree-days required to melt the drift completely. Assuming an ablation rate of 1.00 $\text{cm}\cdot\text{deg}^{-1}\cdot\text{day}^{-1}$, D_t would equal the maximum snow depth, which for fully developed drifts behind Wyoming fences is 1.2H.

An expression approximating the theoretical curve for cross-sectional area of the lee drift in Figure 3 is

$$\frac{A}{A_i} = 1.00 - 1.866\left(\frac{D}{D_t}\right) + 1.011\left(\frac{D}{D_t}\right)^2 + 0.054\left(\frac{D}{D_t}\right)^3 - 0.540\left(\frac{D}{D_t}\right)^4 + 0.339\left(\frac{D}{D_t}\right)^5 \tag{3}$$

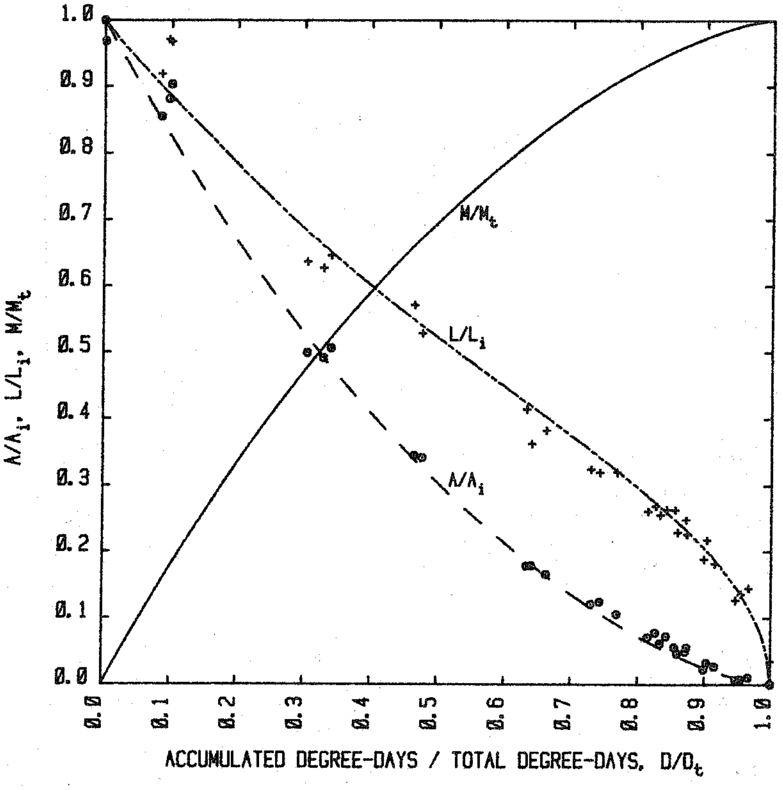

Figure 3. Drift Dimensions (expressed relative to their initial values) versus degree-days expressed as a fraction of the total required for complete melting. Curves are theoretical values computed by assuming uniform ablation of an intitial drift profile described by equation (1) at a rate of 1.0 cm•deg^{-1}•day^{-1}. Plotted points are values measured at the 15- and 55-cm bottom-gap fences at Cooper Cove, and the 15-cm gap fence at Elk Mountain.

Cumulative melt, M, expressed as a proportion of the total melt volume, M_t, is

$$\frac{M}{M_t} = 1 - \left(\frac{A}{A_i}\right) \tag{4}$$

Drift length can also be expressed in relation to the cross-sectional area of the drift, A, as shown in Figure 4. An approximation to the theoretical curve is

$$\frac{L}{L_i} \doteq \left(\frac{A}{A_i}\right)^{0.5} \tag{5}$$

where A_i is the initial cross-sectional area prior to melting (typically $19.3H^2$ for equilibrium drifts formed by Wyoming fences). Although equation (5) overestimates drift length for intermediate values of A/A_i, it provides better estimates than a polynomial expression for the more important lower values.

The above relationships for drift length may be considered to apply also to surface length, S (the curve distance measured parallel to the snow surface). Using equation (1), it is easily shown that the ratio S/L is 1.012 at maximum accumulation. But after the melting is sufficient to reduce snow depth to zero at the fence, the ratio averages less than 1.005 over the remainder of the melt season.

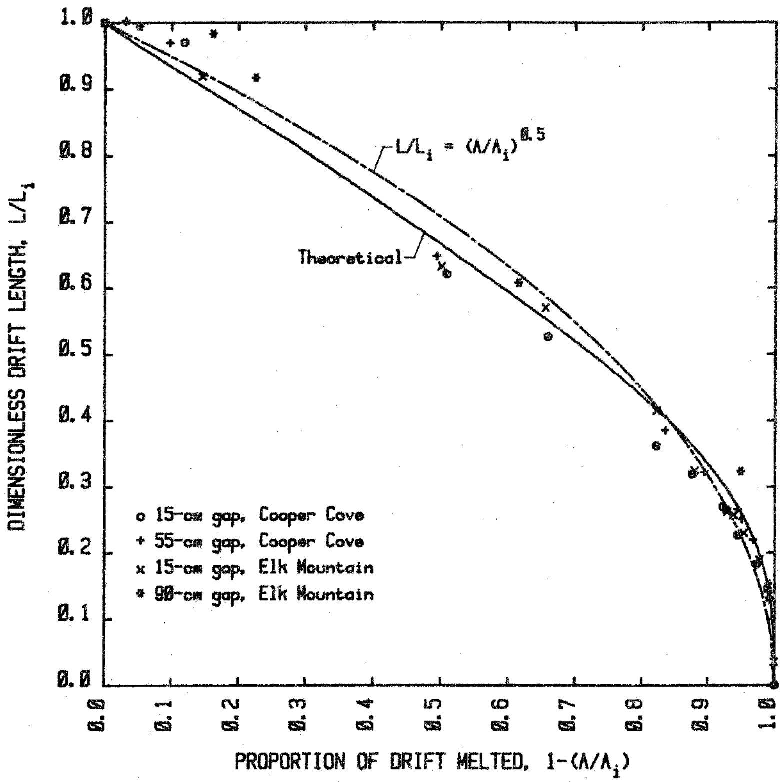

Figure 4. Relative drift length as a function of proportion of drift melted. The solid curve gives theoretical values computed by assuming uniform ablation of an initial drift profile described by equation (1). Plotted points are measured values, and the dashed curve shows the recommended approximation given by equation 5.

Snow Density.

The preceding equations allow volumetric melt rates to be calculated if snow densities are known. Federal sampler densities are compared with the excavated samples in Figure 5, which also shows previously published data. The same correction factor seems to apply to the actively melting drifts as that reported for lower density snow; i.e., true density is approximately 91% of the Federal sampler value (Farnes et al., 1982). The relationship previously proposed by Peterson and Brown (1975), also plotted in Figure 5, would provide an excessive correction for melting drifts.

Corrected densities obtained in this study for melting drifts are plotted against depth in Figure 6. The density of actively melting snow is obviously much more uniform with depth, compared to snow density prior to melting. The slight curvature in the melting snow relationship can be explained by the presence of an ice layer, averaging 2.5 cm thick, which persisted at the bottom of all three snowdrifts throughout the melt season. It is likely that the decreasing density with increasing depth reflects the contribution of this ice layer. If ρ_s represents a uniform snow density without the ice layer, ρ_i is the ice density, ρ is the combined density over depth Z, and the ice layer thickness is $(\Delta Z)_i$, then

$$\rho = \Big(\rho_i(\Delta Z)_i + \rho_s(Z - (\Delta Z)_i)\Big) / Z \tag{6a}$$

Taking $\rho_i = 920\ \text{kg}\cdot\text{m}^{-3}$, $\rho_s = 600\ \text{kg}\cdot\text{m}^{-3}$, and $(\Delta Z)_i = 0.025$ m, then

$$\rho = \Big(23 + 600\ (Z - 0.025)\Big) / Z \tag{6b}$$

provides a reasonable fit to the data in Figure 6, suggesting that the density of actively melting snow, without the ice layer, is about 600 $\text{kg}\cdot\text{m}^{-3}$. This is comparable to the melt season average of 593 $\text{kg}\cdot\text{m}^{-3}$ reported by Fisher (1968), the 590 $\text{kg}\cdot\text{m}^{-3}$ average for the melting 2.4-m fence drift reported by Rechard and Raffelson (1974), and the 600-650 $\text{kg}\cdot\text{m}^{-3}$

range reported by Bartos and Rechard (1974) for the alpine snowfield. Although Martinelli (1959) reported higher densities (600-700 $kg \cdot m^{-3}$), this may have been due to a combination of rainy weather and a different method for correcting snow tube densities.

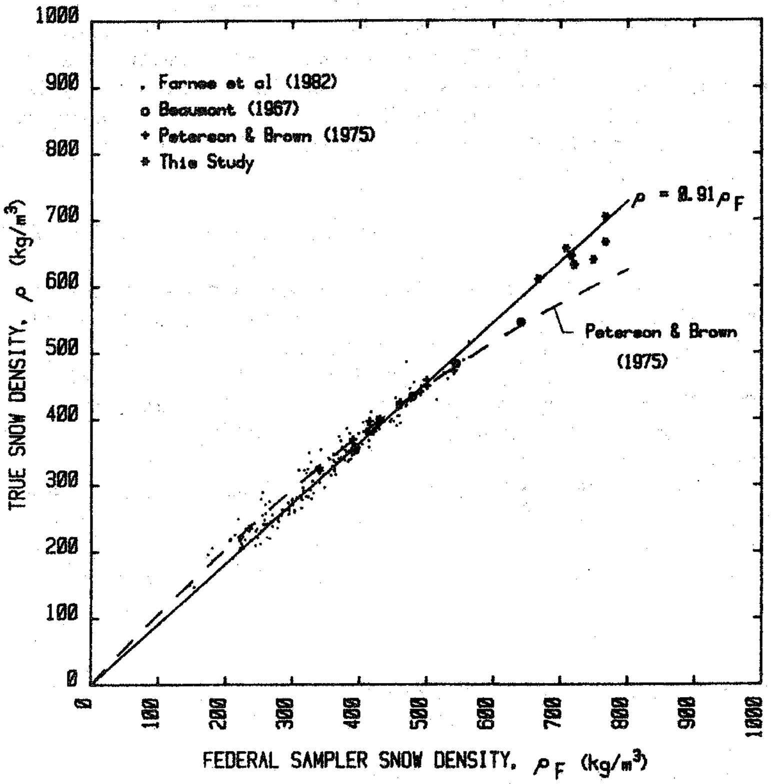

Figure 5. Comparison of true snow density with that measured by the Federal snow sampler.

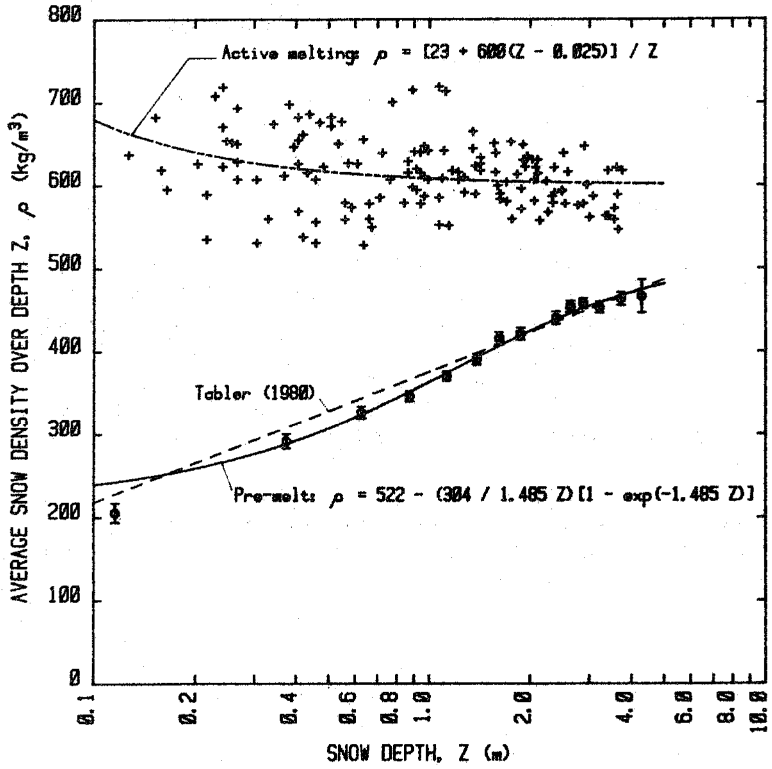

Figure 6. Average snow density in relation to depth for snow fence drifts before and during melting. Bars on points for pre-melt densities correspond to 0.95 confidence intervals.

Fourteen years of pre-melt snowdrift density data (n = 1424) are also shown in Figure 6 for comparison. These data were previously reported by Tabler (1980), but in that publication they were corrected for sampler overmeasurement using the Peterson and Brown (1975) results. The recent report by the Metrication Committee of the Western Snow Conference (Farnes et al., 1982), and the results of this study, prompted the author to reanalyze the data using the standard 91% correction. The results (Fig. 6) are best described by the growth curve function

$$\text{Before melting:} \quad \rho = 522 - (304 / 1.485\ Z)\left(1 - \exp(-1.485\ Z)\right) \tag{7}$$

This type of function has been used to describe the depth/density relationship in deep (>10 m) perennial snow fields, where the asymptotic density limit is taken to be that of ice (Benson, 1962). The 522 $kg \cdot m^{-3}$ asymptotic value fitted to this data by a least-squares method, apparently reflects some plateau in the densification process, such as the closest possible packing attainable by compressive loading with limited metamorphism. Benson (1962) states that the maximum density that can be attained experimentally by packing alone is about 550 $kg \cdot m^{-3}$ which corresponds to the "critical density" where densification rate abruptly decreases. If 13% (by weight) free water were added to dry snow at 522 $kg \cdot m^{-3}$, the resulting density would be 600 $kg \cdot m^{-3}$. This order of free water content has been measured in melting dense snow (Ellerbruch et al., 1977; Bartos and Rechard, 1974), suggesting a possible connection between the densities of dry snow and melting snow.

Melting Rate.

A potential melting rate can be defined as the volume of meltwater, per degree-day, that would be released from a drift without evaporation loss or water retention within the drift. Because melt rate is proportional to drift length, which in turn is proportional to fence height (for equilibrium drifts), a height-independent melting rate, M/WH, can be defined, where M is potential meltwater volume per degree-day, W is fence length, and H is fence height. Equations (2) and (3) can be converted to potential melting rate if the density of the melting snow is known. The results of this calculation, taking snow density to be 600 $kg \cdot m^{-3}$, are shown in Figure 7. The curves can be approximated by

$$\frac{M}{WH} = 0.183 - 0.2279\left(\frac{D}{D_t}\right) + 0.2208\left(\frac{D}{D_t}\right)^2 - 0.4464\left(\frac{D}{D_t}\right)^3 + 0.6120\left(\frac{D}{D_t}\right)^4 - 0.3279\left(\frac{D}{D_t}\right)^5 \tag{8}$$

$$\frac{M}{WH} = 0.1803\left(\frac{A}{A_i}\right)^{0.5} \tag{9}$$

The maximum potential melt rate for an equilibrium lee drift behind a 3.8-m-tall snow fence would therefore be 0.678 m^3 of water per meter of fence length, per degree-day. If initial maximum drift depth were 1.2H, 456 degree-days would be required for total melting. Using this value for D_t, potential melt rate could be predicted for any date if accumulated degree-days were known. At the midpoint of the ablation season ($D/D_t = 0.5$), potential rate would be about 52% of the initial value. When half of the drift volume had melted ($A/A_i = 0.5$), the rate would be approximately 70% of the initial value.

The mean melt rate (the product of ablation rate and snow density) of 0.60 $cm \cdot deg^{-1} \cdot day^{-1}$ determined in this study is the same as has been reported for "maximum point-melt stations" at the Central Sierra Snow Laboratory in California, and the Upper Columbia Snow Laboratory in Montana (U.S. Army, 1956).

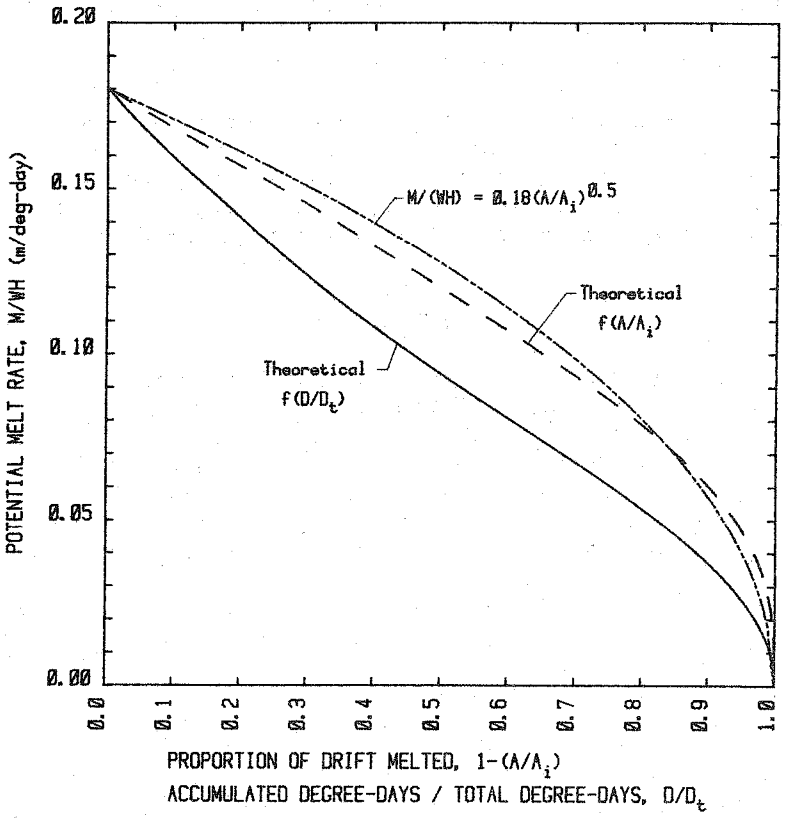

Figure 7. Potential melting rate for snow fence drifts in relation to cumulative degree-days and proportion of drift melted, assuming 600 kg•m^{-3} snow density. The "theoretical" curves are computed by assuming uniform ablation of an initial drift profile described by equation (1).

SUMMARY AND DISCUSSION

To summarize,

1. The seasonal mean ablation rate of lee drifts behind snow fences having moderate bottom-gaps on level terrain averaged 0.98 cm per degree-day. This rate is nearly the same as that found from other snow fence studies, as well as for summer-long ablation of alpine snow fields.
2. Mean ablation rate was 11% greater for a fence having a 90-cm bottom-gap than for an adjacent fence having a 15-cm gap.
3. Ablation rate averaged about 5% more over the windward half of lee drifts as compared to the downwind half.
4. The Federal snow sampler overmeasured the density of melting drifts by about 10%.
5. A layer of solid ice, 2-3 cm thick, was present at the bottom of the snowdrifts throughout the melting season. The snow overlying this ice layer had a uniform density of about 600 kg•m^{-3}.
6. Density of a snowdrift before melt is approximated by equation (7).
7. For equilibrium drifts, the ratio of surface length to horizontal drift length is about 1.012. Over most of the melting season, the ratio averages 1.005. For all practical purposes, surface length may be taken equal to horizontal drift length.
8. Drift length, cross-sectional area, and potential melt rate over the melt season are approximated by equations (2-5, 8, 9).

Although temperature index methods cannot be expected to yield consistently accurate estimates of snowmelt on a daily basis (Huber, 1983), they can provide much better estimates than process-based models for engineering applications. This is because the course of mean daily temperature can be predicted more easily and with better accuracy than is possible when all of the energy balance components (vapor pressure, wind run, net radiation, precipitation, and air temperature) must be predicted. Seasonal mean ablation rates for deep drifts should be relatively constant from year to year.

The relationships presented here should be useful for designing water augmentation projects, hydraulic structures, conveyance systems, and culverts; for predicting snowmelt duration for both ecological and hydrological analyses; for assessing erosion potential; and for estimating evaporation losses. They also provide insight into how snow fence design and placement affect melt rates, and the critical snow depth needed to initiate perennial snow fields.

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