LOCAL SCALE VARIABILITY IN STORM SNOWFALL AND SEASONAL SNOWPACK DISTRIBUTIONS IN THE BRIDGER RANGE, MONTANA.

by
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ABSTRACT

Synoptic and regional estimation of snow water equivalent often uses a sparse network of elevation-stratified snow measurements. The interpolation of such data on meso- and local scales has seldom been tested. Individual storms and April 1st snowpack were measured during the 1994-95 winter near Bozeman, Montana to assess geographic and meteorologic factors influencing meso- and local scale snowfall and snowpack distribution and its variability. A network of eleven measurement sites was established east of Ross Pass in the central Bridger Range. Results showed that the regional April 1st snow-elevation gradient predicts local scale gradients but a local scale gradient did not predict the regional scale. For storm distributions, elevation was significantly correlated in 50% of storms. Distance east of the ridge was significant in 81% of storms, and was more strongly correlated in six of the eight storms where elevation was also significant. However, because of strong covariance, partitioning these two signals was not possible and thus, either variable is a reasonable linear predictor of snow distributions in this study. Snowfall distributions were classified using hierarchical cluster analysis which identified four storm classes. Snow distributions in the Ross Pass area resemble distributions generated by small-scale barrier models.

INTRODUCTION

Water is one of the most important resources in the western United States and the winter snowpack contributes an estimated 80 percent of the annual runoff and water supplies for the region (SCS 1972). Agricultural, domestic, economic, and recreational activities are strongly influenced by the distribution of snow and computer modeling of its distribution is now an important management tool for forecasters at all scales (Table 1). However, the variability in storm snowfall and seasonal snowpack distribution is least understood at the local scale of individual basins.

Table 1. Hierarchy and definition of meteorological spatial scales.

Scale	Domain	Horizontal Extent	Variables
Global	Planetary	10,000 km	ocean current, pressure cells/winds, insolation
Synoptic	Continental	1,000 km	physiography, pressure cells, jet streams
Regional	Regional	100 km	regional topography, frontal systems, jet streams
Meso	Neighborhood	10 km	wind fields, air mass characteristics, large-scale topography
Local	Basin	1 km	wind fields, air mass characteristics, large-scale topography
Micro	Site	0.1 km	ground cover, forest structure, aspect, slope

(adapted from Linacre 1992)

At the synoptic scale (Figure 1A), numerical models of snow distribution in mountainous areas rely upon data collected from a network of automated and manual snow survey sites. This network is largely managed by the United States Department of Agriculture - Natural Resource Conservation Service (NRCS) Snow Survey. The network contains roughly 560 automated SNOTEL (snow telemetry) stations (J. Beard, NRCS-Snow Survey, Pers. Comm.) with daily or sub-daily sampling intervals and manual snow courses with monthly and bimonthly sampling intervals. The SNOTEL stations (Figure 1) are supplemented with 2,530 snow courses (SCS 1994). The network appears to be comprehensive.

At the regional scale (Figure 1B), however only a few snow survey sites are placed in each individual range (Figure 1C). These are stratified by elevation, such that snow-elevation gradients are determined by the difference in snowpack accumulation between high-low elevation pairs. This gradient is then generally applied across the entire range to estimate snowpack accumulation and distribution (Custer et al. 1996).

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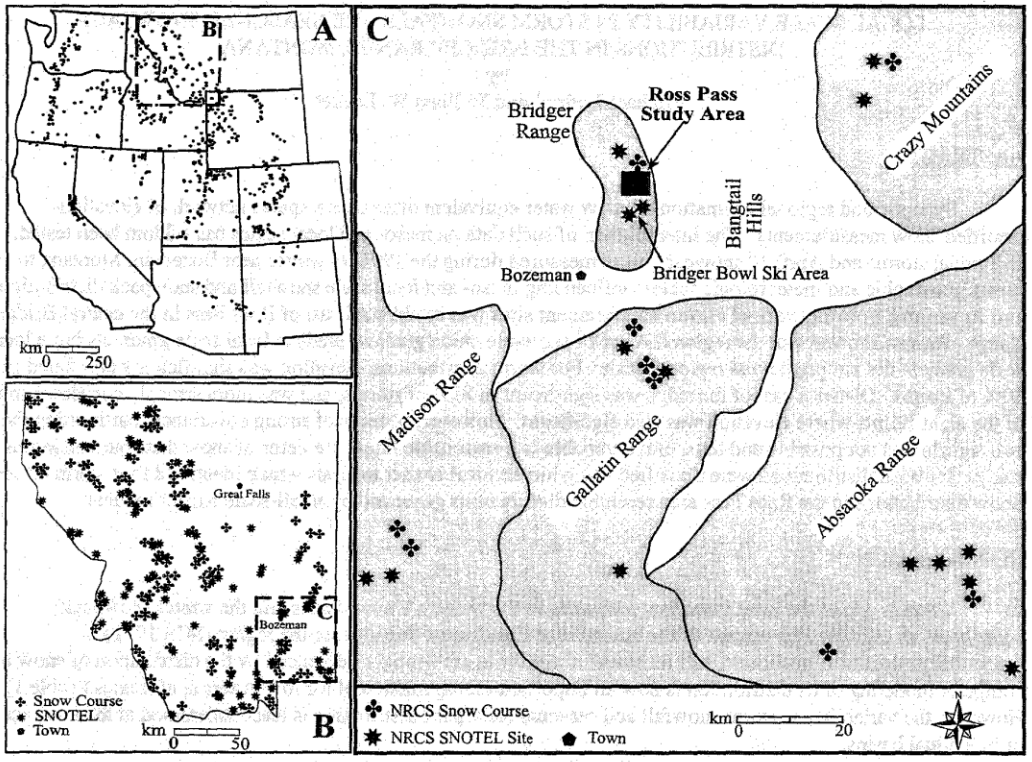


Figure 1A. NRCS SNOTEL network as of 1988 representing the synoptic scale.
Figure 1B. NRCS snow survey network in western Montana as of 1993 representing the regional scale.
Figure 1C. Present NRCS snow survey network in SW Montana representing the meso-scale and location of the Ross Pass Study Area (black square) representing the local scale. Shaded areas are elevations above 1,830 m (6,000 ft) in ranges with summit elevations exceeding 2,500 m (8,200 ft).

An understanding of the variability in snow distribution at the meso- and local scales is important for the calibration and validation of physically based models to improve resolution of water supply forecasting. The existing NRCS snow survey network provides adequate coverage for synoptic scale (Figure 1A) and regional scale (Figure 1B) topographies. However, at meso- (Figure 1C) and local scales, snow distribution variability is not registered by the snow survey network.

The latest generation of high-resolution models operates at a sub-network local scale and the existing measurement network is inadequate for model control (Barros and Lettenmaier 1994). This study documents an example of meso- and local scale snow accumulation patterns. Such measurements are necessary to clarify the nature of local scale variability, thus to calibrate and validate large-scale snow distribution models, and further test whether regional interpolation strategies can be accurately applied at meso- and local scales.

Study Area and Objectives

The specific objective of this study was to evaluate the representativeness of NRCS Snow Survey data in characterizing storm snowfall and seasonal snowpack in a lee-side, meso-scale (<100 km^2) mountain basin. The Brackett Creek basin on the east flank of the Bridger Range (Figure 1C) was selected to maximize the likelihood of measuring recognizable, local scale, topography- and weather-driven perturbations in snowfall and snowpack. The basin is bounded on the west by the nearly level 2,600 m high crest of the Bridger Range, which trends nearly N-S, perpendicular to the prevailing winds. The ridge crest is notched by Ross Pass, about 1 km wide and ½ km deep.

Based on past studies of the complex nature of airflow and precipitation in complex terrain (Hayes 1984; 1986; Daley and Neilson 1992; Barros and Lettenmaier 1993), snow distributions based on three NRCS SNOTEL sites and one snow course on the margins of the study site (Figure 1C), were expected to differ significantly from that measured at eleven monitoring sites within the small (~20 km^2) montane area. Trends in the local scale snow distribution will be explicable, in part, by elevation, wind azimuth, wind velocity, air temperature, relative humidity, and distances from the ridge and pass.

METHODS

Sampling Design

Three transects were measured and analyzed to determine snow distribution in the Ross Pass Study Area (RPSA) and to test the influence of pass topography. Transect one (T1) was below Ross Pass to measure downwind influence. Transect two (T2) was between one and two kilometers south of T1 and established to measure eddying effects generated by westerly airflow through Ross Pass. Transect three (T3) was between two and three kilometers south of T1 to measure snow distribution influenced by the Bridger Range crest.

Selection criteria for measurement sites followed NRCS standard guidelines for SNOTEL locations (Farnes 1967; 1971). Sites were located in small forested openings with negligible canopy influence in a 30° cone from vertical above the measurement point and covered as wide a range of elevation and distance from the ridge crest as possible.

Sampling sites consisted of three storm boards placed such that a third of the opening was represented by each board. Snowfall was measured from 40 x 40 cm (16 x 16 in) storm boards using bulk samplers (USGS 1977) constructed from #10 coffee cans. A 2-kg hand-held spring was used to weigh snow core samples with a scale accuracy of ± five grams.

Snow distributions were measured for individual storms and on a seasonal basis. Individual storms were measured from early November 1994 through March 1995. Storm sampling occurred when first possible after the cessation of snowfall. April 1st snowpack was used to characterize seasonal snow distribution. Seasonal snowpack at RPSA sites were measured using a standard Federal Snow Sampler and double sampling procedure (Rovansek et al. 1993). Snow core measurements were adjusted for over sampling (Farnes et al. 1982).

Geographic and Meteorological Variables

Elevation and spatial coordinates for each site were determined off the Saddle Peak quadrangle. Local baselines were established with the origin set at Ross Pass and rotated N25°W aligning the Y baseline with the ridge crest in the Ross Pass Study Area. Three coordinate sets were determined: polar coordinates (theta and phi) and easting and "southing" using the baselines set in Ross Pass, and ridge and pass distance, measured respectively, due east of the ridge crest and N-S of an E-W line through Ross Pass (Pipp 1997).

Upper air data was collected from the nearest NWS rawinsonde station at Great Falls, MT, located approximately 187 km (116 mi) north of Bozeman (Figure 1B). Based on reported correlations of upper air measurements between Great Falls and the Bridger Range (Super et al. 1972), 700 and 500 Mb azimuths, air temperatures, and relative humidities and 500 Mb velocities were used.

Surface weather was recorded using a data logger located 6 km (4 mi) south of Ross Pass on the ridge above the Bridger Bowl Ski Area (Figure 1C). Data included wind azimuth, velocity, air temperature, and snowfall recorded at one-hour intervals. Wind velocity and air temperature was used from this data set. Azimuths were dropped because topographic forcing created a dominant westerly airflow with little variation during the winter. Snowfall data from Bridger Bowl was not used because it contained no density measure.

Storm boundaries were defined based on local observations of snowfall at locations east and west of the range. Measurements contained within these boundaries, to the nearest atmospheric sounding time, were compiled into the meteorological data set. Wind azimuth was averaged as *unit vector wind directions* where vectors are obtained by averaging the north-south and east-west components of individual samples (Thuillier 1995). Averaged vectors were then classified as one of eight cardinal wind directions. Wind velocity, air temperature, and relative humidity was calculated as the arithmetic mean for the storm.

RESULTS

Storm Snowfall

The winter of 1994-95 had 23 storms through April 1. Seven storms were dropped from analysis because melt was observed on storm boards prior to sampling (two events) or storms were not sampled individually (five events). The sixteen storms included in the analysis contained 76% of the total seasonal snowfall recorded.

Geographic variables that correlated strongly with storm SWE (snow water equivalent) were elevation and measures of distance from the ridge crest: easting and ridge distance. Elevation was significant in eight of 16 storms with correlation coefficients (R) ranging from 0.61 to 0.87. Easting and ridge distance were the most important geographic variables, with significance in 13 of 16 storms with correlation coefficients ranging from -0.63 to -0.93 for easting and -0.61 to -0.91 for ridge distance. Moreover, distance east of the ridge was more strongly correlated in six of the eight storms where elevation was also significantly correlated.

Linear regression of storm SWE against site elevation showed a large variability in elevational control of snowfall, with coefficients of determination (r^2) ranging from 0.00 to 0.76. Regression residuals failed to correlate with geographic variables in any consistent trend suggesting other variables may be important in snowfall distributions.

Storm snowfall patterns were assessed with hierarchical cluster analysis using a Complete Linkage (furthest neighbor) method and Pearson's correlation distance measure (Norušis 1994). The clustering algorithm was run on storm SWE measurements for each site and the ratio of low to high elevation SWE accumulation for each of the three transects (n = 14 for each storm). Storms classified into four clusters by slicing the dendogram between five and ten on the dendogram distance scale (Figure 2).

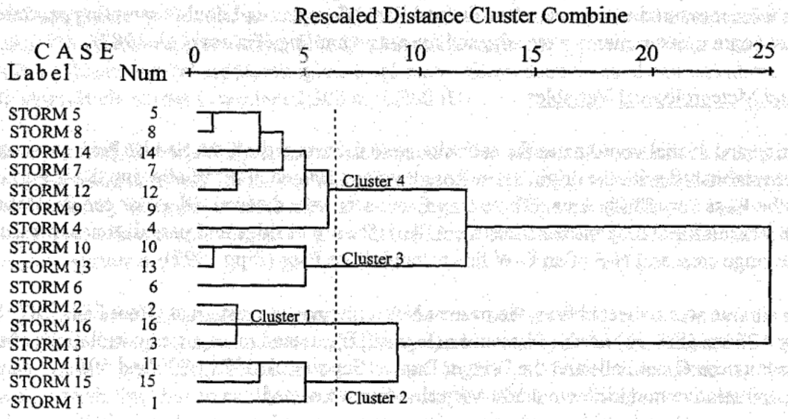


Figure 2. Dendrogram of storm snowfall distributions using a complete linkage (furthest neighbor) algorithm and Pearson's correlation distance measure.

Storm snowfall distributions were regressed against site elevation and graphed with inverse interpolated mesh surfaces using sampling site northing and easting as XY data and storm SWE as Z data (Figure 3). Figure 3A shows the study area's topographic surface and outline of the ridge crest west of the study area. Storm classes 1 and 2 (Figures 3B and 3C) display snowfall augmentation on transect 1 (T1) and snowfall depletion on transect 2 (T2)

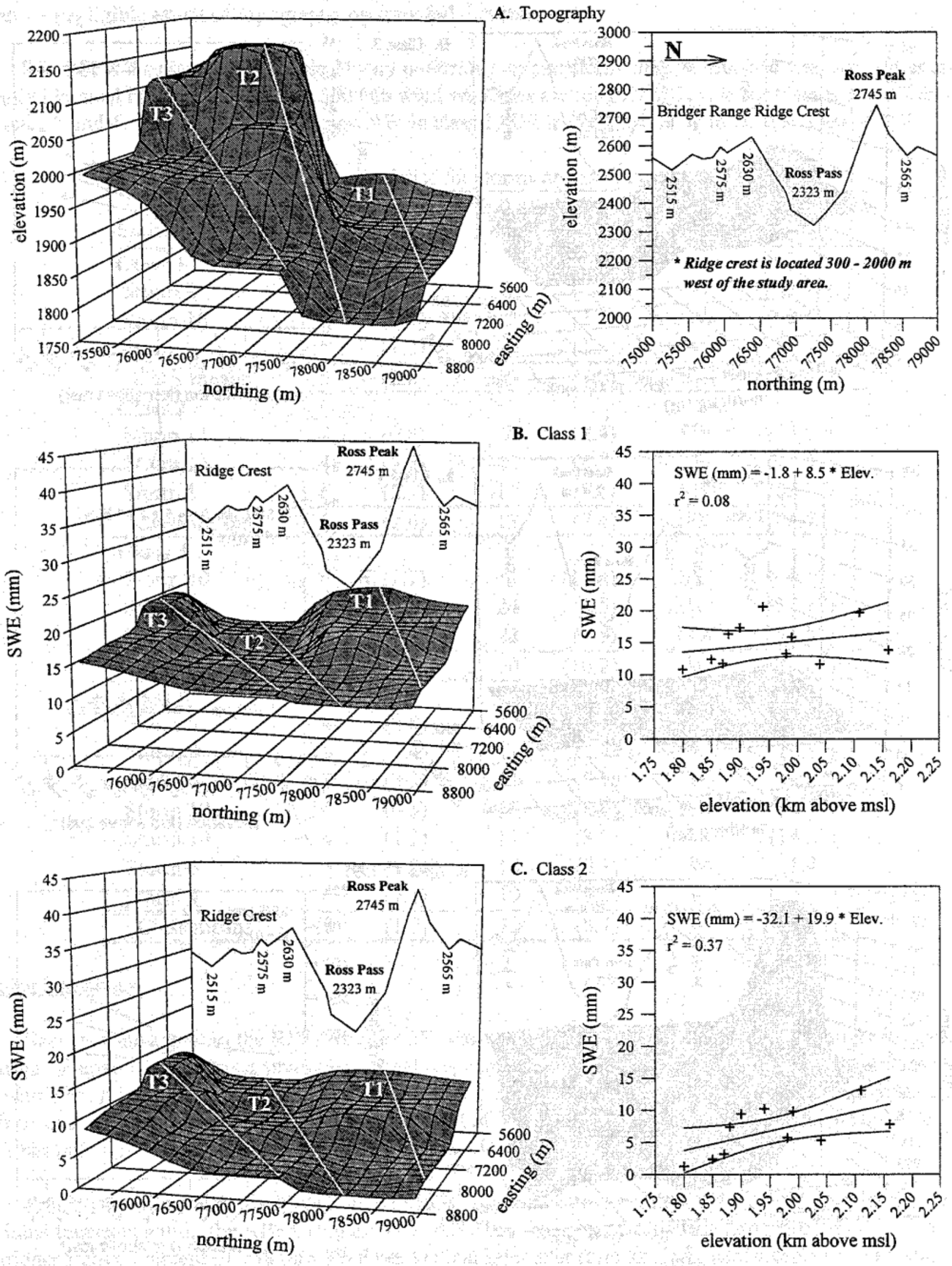
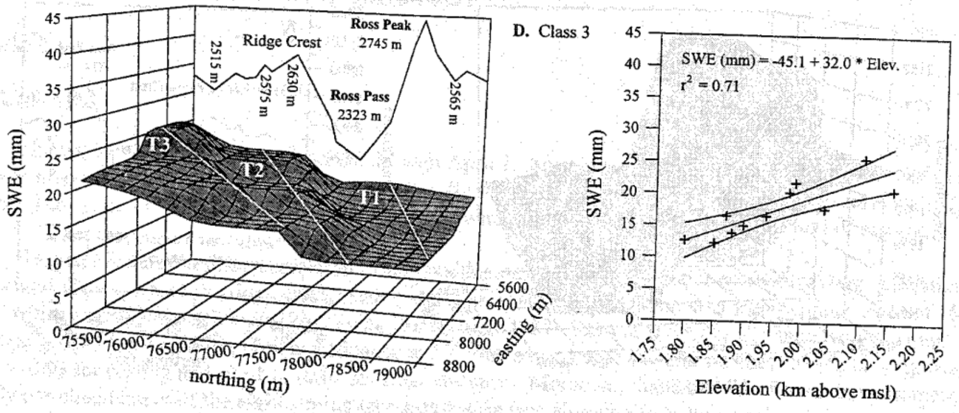
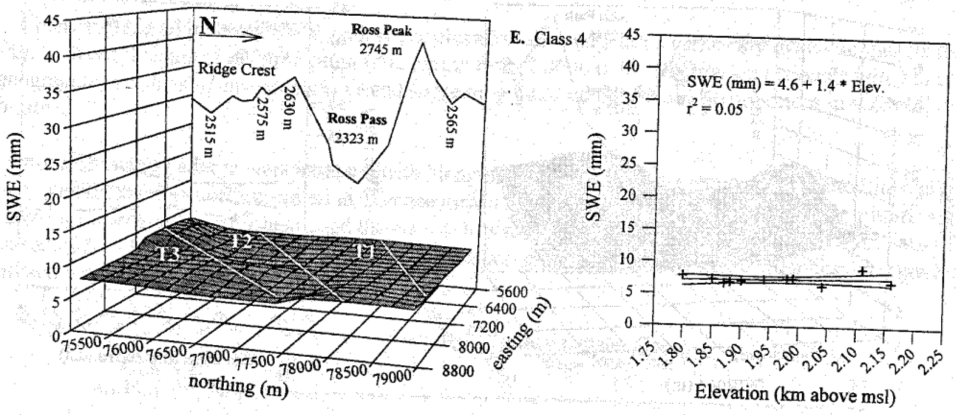


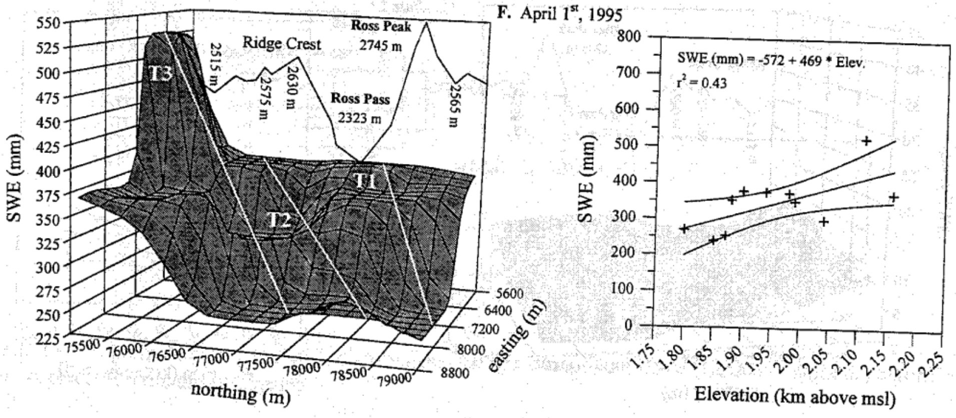
Figure 3A. Interpolated surfaces of the Ross Pass Study Area topography and ridge crest outline.
Figure 3B. Interpolated storm SWE surface and SWE-elevation regression example of class 1 storms.
Figure 3C. Interpolated storm SWE surface and SWE-elevation regression example of class 2 storms.
Locations of transect lines are marked in white and labeled T1, T2, T3.



D. Class 3



E. Class 4



F. April 1st, 1995

Figure 3D. Interpolated storm SWE surface and SWE-elevation regression example of class 3 storms.
Figure 3E. Interpolated storm SWE surface and SWE-elevation regression example of class 4 storms.
Figure 3F. April 1st interpolated SWE surface and SWE-elevation regression.
Locations of transect lines are marked in white and labeled T1, T2, T3.

and transect 3 (T3), relative to their elevations. Storm class 3 (Figure 3D) indicates the strongest correlation between elevation and snowfall yet there is again evidence of depletion on transect 2. Storm class 4 (Figure 3E) indicates a negligible effect of topography on snowfall distribution.

Wind field characteristics (Table 2) vary noticeably among storm classes. Surface wind velocities are generally identical between storms and 500 Mb wind velocities are roughly moderate for classes 1 and 2 and strong for classes 3 and 4. Wind azimuths average NW in class 1, SW in class 2, and W in classes 3 and 4.

Table 2. Wind field characteristics for storms and storm classes.

	Surface Velocity		500 Mb Velocity		500 Mb Azimuth	
Storm	m/s	(std. dev.)	m/s	(std. dev.)	Class	(std. dev.)
Class 1						
Storm 2	3	(2.5)	6	(3.5)	W	(152.2°)
Storm 16	7	(3.3)	12	(2.4)	NW	(68.7°)
Storm 3	5	(1.2)	12	(2.5)	N	(116.9°)
Class means	5	(2.8)	10	(4.0)	NW	(104.9°)
Class 2						
Storm 11	4	(0.8)	7	(2.4)	SW	(25.5°)
Storm 15	4	(5.7)	21	(5.7)	SW	(42.4°)
Storm 1	6	(2.1)	17	(3.5)	SW	(25.5°)
Class means	5	(2.6)	13	(7.4)	SW	(26.7°)
Class 3						
Storm 10	6	(1.7)	11	(11.4)	SW	(44.1°)
Storm 13	4	(1.9)	24	(5.5)	W	(18.1°)
Storm 6	9	(0.0)	28	(4.9)	NW	(7.8°)
Class means	5	(2.5)	20	(10.2)	W	(40.0°)
Class 4						
Storm 5	4	(0.8)	30	(3.3)	W	(6.5°)
Storm 8	5	(1.4)	11	(5.7)	W	(2.8°)
Storm 7	8	(3.5)	21	(5.7)	W	(2.8°)
Storm 12	5	(0.8)	29	(10.8)	NW	(10.5°)
Storm 14	4	(1.3)	17	(3.9)	W	(14.2°)
Storm 9	5	(1.2)	15	(0.7)	W	(1.4°)
Storm 4	6	(2.1)	19	(9.2)	W	(36.1°)
Class means	5	(1.7)	22	(8.7)	W	(28.6°)

Seasonal Snowpack

Seasonal snowpack in the RPSA (Figure 3F) shows a unique distribution that is not strongly influenced by elevation. Transect 1 (T1) has a small elevational range and slightly more seasonal accumulation as does transect 2 (T2) which has a much larger elevational range. Transect 3 (T3) seasonal accumulation dramatically increases with elevation and is at a lower elevation than the upper end of T2 (Figure 3A). Overall, the seasonal snowpack in the RPSA has only a moderate relationship with elevation with a r^2 of 0.43 ($P = 0.029$).

Predictive ability of the Bridger Range (NRCS) snow-elevation gradient for 1994-95 was tested using the individual transects within the RPSA (Figure 4A). All RPSA transects fell within the 95% confidence interval of the Bridger Range gradient of 938 mm SWE per vertical kilometer (mm km^{-1}) for their respective elevational distributions; however, each transect has a different gradient. Transect 1 (1,432 mm km^{-1}) has a much steeper gradient over a small elevational range; transect 2 has the most shallow gradient (268 mm km^{-1}) and greatest elevation range while transect 3 (1,139 mm km^{-1}), which is located below the ridge crest, mirrors the NRCS gradient closely. The ability of NRCS data to "predict" snow distributions elsewhere in the range is mostly a product of low precision forced by the small sample size ($n = 4$). Additionally, the NRCS sites in the Bridger Range are not randomly distributed across elevation, but are set in high-low elevation pairs and do not satisfy standard regression assumptions (Griffith and Amrhein 1991).

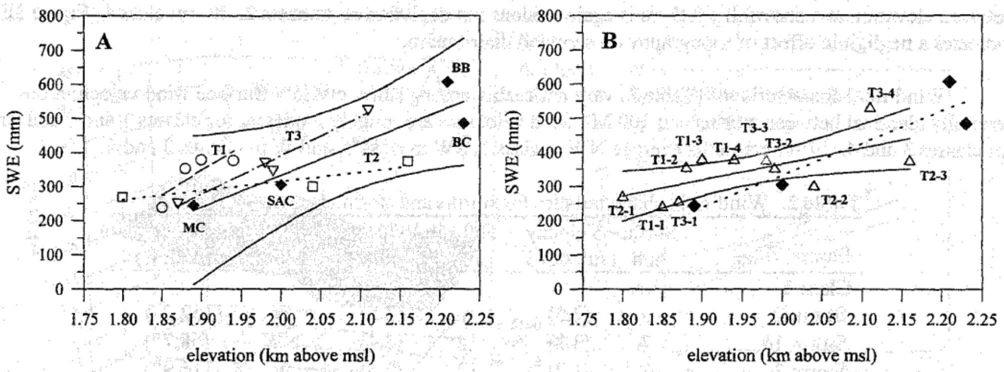


Figure 4A. April 1st RPSA snow-elevation gradients for individual transects compared against the NRCS gradient. T1 - open circles, T2 - open squares, T3 - open triangles; NRCS data, gradient and 95% confidence interval - black diamonds and solid lines.
Figure 4B. April 1st NRCS snow-elevation gradient (dashed line) compared against the RPSA gradient and 95% confidence intervals (open triangles and solid lines). Individual RPSA sites are labeled.

The snow-elevation model in the RPSA for 1994-95 does not predict the snow-elevation gradient as measured by the NRCS (Figure 4B). Note also that the RPSA sites are not randomly distributed across elevation, but are skewed toward lower elevations.

DISCUSSION

Snowfall Distributions

Zones of snowfall depletion and augmentation varied between storm classes, which implies a degree of meteorological influence on snowfall distributions. Meteorological parameters were grouped by storm class to assess trends in temperature and relative humidity. Temperatures at the 700 Mb level were appropriate for crystal formation and relative humidities consistently favored snowfall production at this level (Pipp 1997). However, neither variable showed any trend within or across storm classes.

Atmospheric stability and vertical wind profiles are known to influence local scale wind flow (Barry 1992, pg. 125 - 132). Although these parameters were not measured locally, they are suspected as contributing meteorological controls on local scale snowfall. Class 1, 2, and 3 storms display strong depositional differences along transect lines (Figure 3B, 3C, and 3D). This suggests ridge crest airflow separation and a ridge eddy enhanced by an unstable atmosphere and strong orographic snowfall with minimal downwind displacement. Atmospheric stability is suggested during class 4 storms where snow accumulations were effectively similar regardless of site elevation or distance from the ridge crest (Figure 3E). This implies that ridge level airflow separation is reduced and the ridge eddy is absent. Snowfall distributions are most notably different between class 3 and 4 storms, which had similar wind fields (Table 2). This supports the existence of one or more additional (unmeasured) variables that significantly influence snowfall distributions.

Snowpack Distributions

Local scale snowpack distribution in the Ross Pass area is driven by a combined interaction of topographic and meteorological factors. Comparison of Figures 3A and 3F shows that the highest elevation transect (T2) has a seasonal accumulation slightly less than the lowest elevation transect (T1), while transect 3 has dramatically more seasonal accumulation at a slightly lower elevation than T2. Elevation's relationship with snow accumulation in the area influenced by Ross Pass, although significant (P = 0.029), is being strongly overridden by other contributing (unmeasured) factors.

Meso-scale snowpack distribution for the Bridger Range however is strongly related to elevation with a r^2 of 0.62 ($P < 0.001$) and standard error of 67.7 mm (2.7 in) (Figure 5A). Residuals of the snow-elevation model did not correlate significantly to any set of XY variables and scatter plots did not reveal any simple trends. A residuals map (Figure 5B) suggests complex spatial controls on seasonal snow distribution in the central Bridger Range in the Ross Pass area. The residual map has a "-", "+", or "0" at each site based on whether the site was below, above, or inside the 95% confidence interval (Figure 5A).

The spatial distribution of dry (-) and wet (+) sites in Figure 5B can be interpreted as two distinct patterns generated by the ridge and the pass. First, the influence of the Bridger ridge topography, with high relief over a short distance perpendicular to prevailing winds, augments snow accumulation closer to the ridge (sites T3-4 and BB) than would be predicted by elevation alone. This observed accumulation is consistent with snow drift patterns behind snow fences and topographic features (Tabler and Jairell 1980) and snow distribution patterns over sharp ridge lines (McClung and Schaerer 1993).

Second, the influence of the Ross Pass topography is to augment snow accumulation at a greater distance downwind of the ridge crest and at lower elevations (sites T1-2, T1-3, and T1-4) than would be predicted by elevation alone. Additionally, depletion zones are observed north and south of Ross Pass (sites T2-3, T2-2, and SAC), in areas that are both closer to the ridge and/or at higher elevations than predicted by elevation alone. A snow fence model described by Peterson and Schmidt (1984) might be applied. Given an averaged gap size (*W*) of 400 m for Ross Pass, a depletion zone would be expected to extend 1,000 m downwind (2.5*W*), with an augmentation zone below that. Site T1-4 is located roughly 1,600 m downwind of Ross Pass.

A wind eddy model (Figure 5C) can be interpreted from the seasonal snowpack distribution in the central Bridger Range. Factors controlling of this pattern are increased wind velocities through topographic constrictions (Oke 1987; Barry 1992), entrainment of snow crystals in strong wind fields (Kind 1981; McClung and Schaerer 1993), and conditional flow separation of air stream lines over barriers (McKay and Gray 1981; Barry 1992) that create eddies in the meso-scale wind field. The increased wind velocities through Ross Pass entrain snow crystals further downwind. This entrainment creates areas of relative snowfall depletion below and to the sides of the pass and an area of relative snowfall augmentation further downwind than is observed downwind of the ridge crest. NRCS sites BB and SAC lie within the region inferred as affected by wind eddies. Data from those sites, thus, are likely to give a skewed picture of snowfall and snowpack accumulation within the Bridger Range.

CONCLUSIONS

Storm Snow Distributions

Elevation and distance downwind of the barrier are local scale, topographic predictors of snowfall distribution. Although ridge distance was a better predictor of the 1994-95 storm distributions, strong covariance with elevation hinders isolation of a unique signal. Thus, elevation and ridge distance are considered equally competent, linear predictors of snowfall in this study.

Additional factors influencing storm snowfall distributions are wind azimuth, wind velocity, and atmospheric stability. Wind azimuth had a minor influence on snowfall distributions as indicated by comparing storm classes 3 and 4 (Figures 4D, 4F, and Table 2). Wind velocities influence snow entrainment and transport, as well as windflow separation at the range crest as velocities increase. Atmospheric stability is suspected as being an integral factor influencing storm distributions, but was not measured in this study. The degree of instability effects windflow separation at the range crest, with unstable conditions favoring flow separation and eddy formation and stable conditions reducing eddy formation. The existence of a range crest eddy affects the downwind distribution of storm snowfall.

Seasonal Snow Distributions

The seasonal snowpack is the summed snowfall events, less mid-winter ablation (5% in 1994-95). April 1st snowpack in the RPSA was significantly correlated to 81% of storm snowfalls. Development of the seasonal snowpack is strongly influenced by the winter storm track and the depositional patterns characteristic of each storm

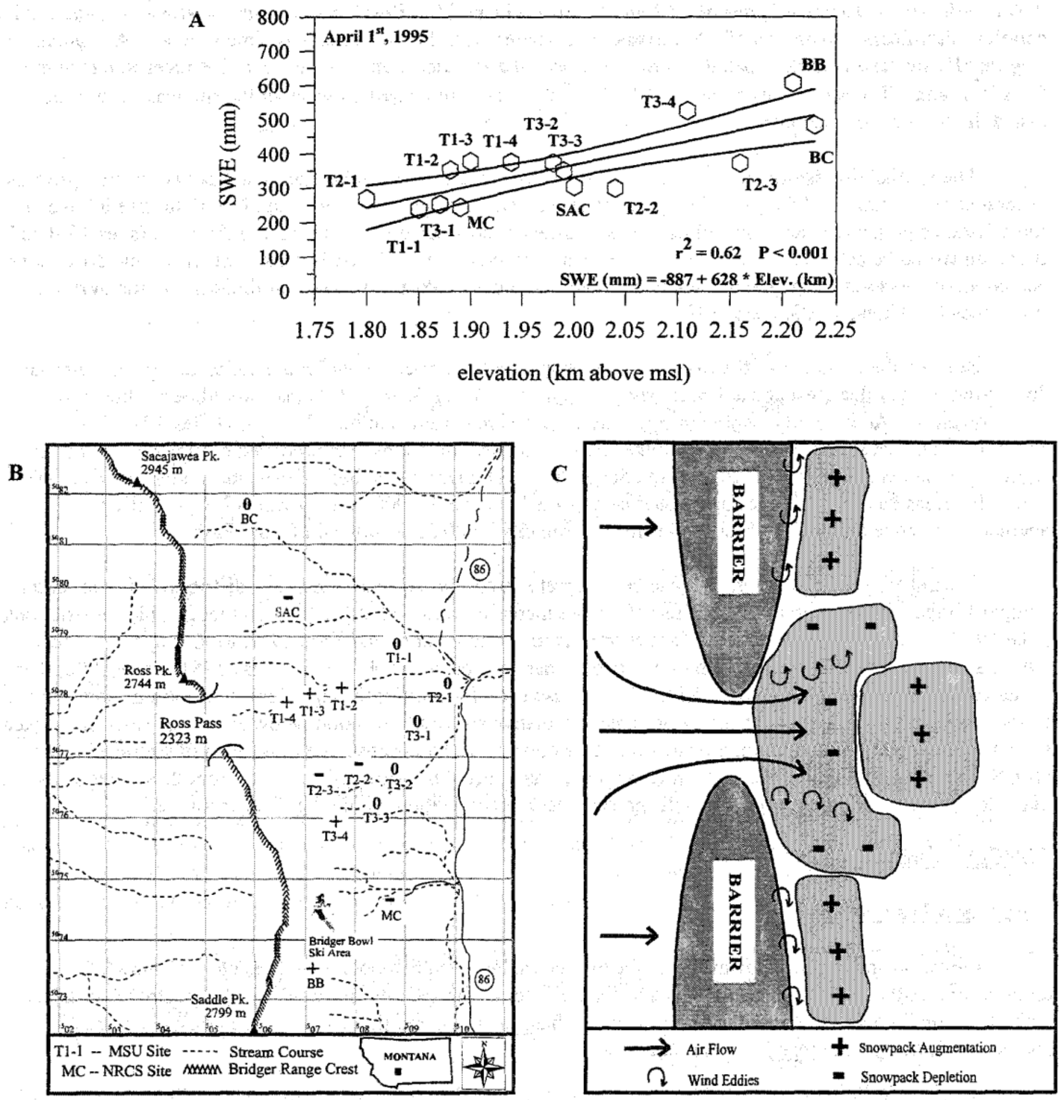


Figure 5A. April 1st SWE-elevation regression using all measurement sites in the Bridger Range (n = 15).
Figure 5B. Residuals map of SWE-elevation regression (A).
Figure 5C. Interpretation of a wind eddy model influencing snow distribution in the Ross Pass area of the central Bridger Range, SW Montana.

class. Seasonal snow distribution, and the snow-elevation gradient, is an average of the winter's storm patterns. Interaction of the pass topography and range crest with meteorological conditions during storms creates areas of high local scale variability in snow accumulations. Dominance of a particular storm class will influence the seasonal snowpack to a greater extent than will any individual, disproportionately large storm event. Moreover, dominance of high gradient storms (e.g., class 1, 2, or 3) or extreme low gradient storms (e.g., class 4) could develop a seasonal snowpack that varies substantially from 30-year averages.

Eddy Models

Snow distribution residuals in the Ross Pass area resemble accumulation patterns created by snow fences and shrub barriers. This suggests that snow fence models might be extended to explain local scale snow distributions at the mountain barrier level. If so, nesting snow fence models within meso-scale precipitation models could enhance local scale predictive accuracy and precision without increasing the measurement network.

Areas of topographically affected accumulation caused the local snow-elevation gradient in the Ross Pass area to be significantly different from the NRCS gradient. What remains to be tested is whether this measured local scale variability may explain some of the differences in basin runoff when compared with forecasted runoff based on synoptic or regionally modeled seasonal snowpack accumulation.

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