GEOGRAPHIC VARIATION IN SNOW TEMPERATURE GRADIENTS IN A MOUNTAIN SNOWPACK

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ABSTRACT

The objective of this study was to investigate the relative importance of topography in controlling the geographic patterns of snow temperature gradients within a seasonal snowpack. Regression models quantified relationships between topographic parameters and temperature gradient statistics for our spatially distributed dataset. Demonstration of the relative importance of topography in influencing spatial snowpack temperature gradients could aid future modeling of snow layer development and behavior, with benefits for avalanche and snowmelt modeling. This spatial, or geographic, analysis of the relationship of snow temperature gradient patterns to topography, utilizes landscape-scale modeling in an attempt to identify responses in complex, mountainous terrain.

During the snow season of 2001-2002, 30 temperature profiles were sampled on nine sample days. Profiles were collected through the use of a portable snow temperature profile probe (Deems, 2001). These data were used to calculate temperature gradients for each profile. Topographic attributes were derived using a Geographic Information System (GIS) and a Digital Elevation Model (DEM). Linear regression assessed the relationship between the topographic variables and snow temperature gradient patterns, and demonstrates the relative importance of the terrain variables in determining spatial patterns of temperature gradients. Analysis of the regression models shows a complex pattern of relationships between average temperature gradients and topographic variables. A qualitative assessment of weather variables suggests the utility of weather data in future modeling efforts.

INTRODUCTION

This project investigates the geographic patterns of snow temperature profiles using topographic parameters as predictor variables. Snow temperatures vary over many scales of space and time, from within a single profile to an entire mountain range, and from diurnal fluctuations to seasonal changes. This analysis attempts to address the spatial variability inherent in snowpack processes in a single snow season at the basin scale.

Snow temperature is a dominant variable in many physical processes in the seasonal snowpack. The temperature profile reveals much about both the current physical state of the snowpack and its likely future behavior (Gray and Male, 1981). Temperature gradient-driven metamorphic processes within a cold snowpack can stabilize or weaken individual layers, and hence determine the likelihood of avalanche activity (McClung and Schaerer, 1993). The snowpack temperature stratigraphy directly influences the shape of the basin hydrograph, and affects the ability of the snowpack to buffer extreme melt events. The geography of isothermal snow influences snowmelt runoff magnitude and timing (Blöschl et al, 1991), and can present a significant full-depth, wet avalanche hazard (Armstrong, 1976, Clarke and McClung, 1999).

Topography exerts a significant control on spatial and temporal variation in snow temperature patterns (McClung and Schaerer, 1993). The amount of solar radiation incident on a snow surface varies with slope aspect, and will vary within a given aspect as a function of slope angle. Elevation influences the amount of snowfall and the ambient air temperature. Topographic profile and planform curvature, vegetation, and ground surface material may also have significant effects on snow temperature.

Spatial variability in snowpack processes, specifically snow temperature gradients, is difficult to quantify. Several attempts have been made to quantify spatial variability in snow parameters such as stability (Conway and Abramson, 1984; Föhn, 1988; Conway and Wilbour, 1999; Landry, 2002), resistance (Birkeland et al., 1995), and combinations of factors such as topography, stability, depth, and resistance (Birkeland, 2001). Variations in weather and climate patterns have been examined in the context of avalanche and snowfall patterns (Armstrong and Armstrong, 1987; Mock and Birkeland, 2000). However, the spatial variation in snow temperature gradients has been only qualitatively addressed through general relationships of temperature with aspect and elevation (McClung and Schaerer, 1993).

A spatial analysis of the relationship of snow temperature patterns to topography, utilizing landscape-scale modeling, may help explain temperature responses to complex terrain. A better understanding of the *relative* importance of topographic factors in influencing snowpack temperature patterns through space and time could aid

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in development and refinement of snowmelt and avalanche forecasting models. Modeling techniques of this type could also help link the spatial resolution of a theoretical (physical) model with the predictive ability of an operational empirical model for snowmelt or avalanche prediction, combining process representation with reasonable data requirements.

METHODS

Field Techniques

Snow temperature profile data were collected during the snow season of 2001-2002, in Wolverine Basin, in the Bridger Mountain Range north of Bridger Bowl Ski Area near Bozeman, Montana (Figure 1). Data collection utilized a Snow Temperature Profile Probe (STTP), of original design and construction (Deems, 2001). Nine datasets were collected throughout the season, and labeled Dataset Number (DSN) 1-9 (Table 1).

Thirty sample sites were selected to maximize topographic variability. These sites were revisited on each sample day. A range of topographic variables was measured for the sample sites (Table 2).

Using the STTP, an instantaneous profile of snow temperatures at 10cm increments from the ground up to the snow surface was collected. The probe was used in a slope-normal orientation in order to measure temperatures along the shortest path from ground to air. Other variables recorded manually at each site were snow depth, surface temperature, air temperature, and time of day. Nine datasets were obtained between December 4, 2001 and April 1, 2002.

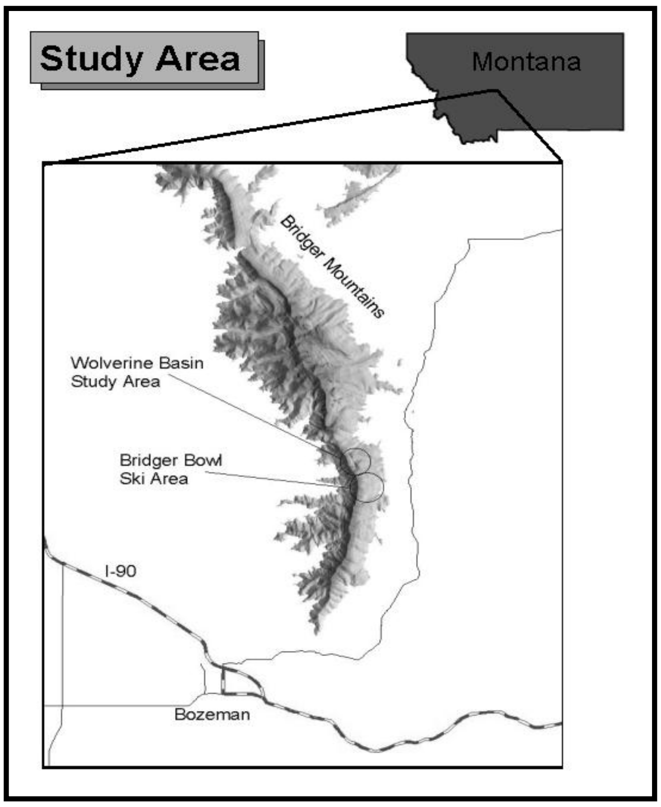

Figure 1: Wolverine Basin Study Area, Bridger Mountain Range, MT

Additionally, a remote weather station located in the center of Wolverine Basin collected data throughout the sample season. Recorded variables were snow depth, air temperature, relative humidity, wind speed, snow surface temperature, reflected shortwave radiation, and a 5cm increment temperature profile. The weather data was input at five-minute intervals, and was averaged to produce an hourly output interval.

Table 1: Snow Year 2001-2002 Sample Collection Dates and Dataset Number (DSN)

DSN 1	12/4
DSN 2	12/9
DSN 3	12/20
DSN 4	1/2
DSN 5	1/7
DSN 6	1/14
DSN 7	2/4
DSN 8	3/8
DSN 9	4/1

Analysis Techniques

Temperature gradients were calculated from the 10cm sensor up to the snow surface for each 10cm interval. The gradient for the 0 – 10cm interval was calculated as well, but later discarded when ground temperatures in several locations were observed to depart substantially from the assumed 0˚C, a result consistent with Tremper (1986). Temperature gradients were then averaged for the "deep" portion of the snowpack, defined here to be greater than 30cm below the snow surface (Armstrong, 1985; Birkeland et al., 1998). The deep temperature gradients were chosen for analysis, to eliminate problems associated with diurnal fluctuation

Table 2: Summary Statistics for Pooled Data

Variable code	Description	Minimum	Maximum	Mean	Std Dev
AvgTG_dp	Average deep temperature gradient (°Cm^{-1})	0.015	0.115	0.051	0.01
Elevation	Elevation (m)	2230	2400	2318	54.27
Slope	Slope angle (degrees)	4	39	20.18	8.78
DfromN	Degrees from north (degrees)	2	172	67.19	50.71
Profile	Profile curvature	0	22	9.16	5.61
Planform	Planform curvature	1	80	42.25	25.49
Aspect	Aspect (degrees)	2	354	169.33	123.42
Sine	Sine of aspect	-0.99	0.96	-0.11	0.71
Cosine	Cosine of aspect	-0.98	0.99	-0.05	0.70
SlpSine	Slope X sine aspect	-36.03	20.24	-3.75	15.23
SlpCos	Slope X cosine aspect	-23.8754	33.6304	-0.70	15.48
SlpDfrN	Slope X degrees from north	34	4472	1351	1165
OCanopy	Open forest canopy (%)	0	57.1	10.58	12.09
Solar	Cumulative global solar radiation input (Wm^{-2})	4084	241341	45050	49268

in near-surface snow temperatures. The average deep temperature gradients (*AvgTG)* were then used as a response variable in a regression model.

Terrain variables were calculated using a USGS 30m Digital Elevation Model (DEM) and ArcView GIS software with the Spatial Analyst extension (ESRI, Redlands, CA). Canopy density was measured with a spherical densiometer (Forest Densiometers, Bartlesville, OK). Potential global solar input was calculated from the DEM using the Solar Analyst extension for ArcView (HEMI, Los Alamos, NM).

Two statistical analyses were performed: Pearson correlation and multiple regression modeling. Pearson correlation coefficients were calculated for the pooled data and for each dataset. Regression was performed using the SAS statistical software package (SAS Institute, Inc., Cary, NC). The data was analyzed in two parts: pooled data for the entire season, and separated by sample date. A stepwise regression method was utilized, Due to the small sample sizes and the significant scatter in the data, a p-value criterion of 0.2 was required for a variable to be retained at each step, in an attempt to identify potential relationships at the expense of a robust model.

Sources of Error

Several sources of error exist in the study methods. First, measurement errors exist in all weather and temperature sensors used. These errors should be systematic, and therefore not create invalid data points. The individual sensors on the STTP are accurate to ±0.1˚C. The STTP was calibrated to an ice bath at 0˚C, and resulting offsets were accounted for in the sample data.

Second is the scale disjunct between the point temperature profile measurements and the 30m grid cells of the DEM used to derive terrain parameters. It is assumed that the profile measurements adequately represent the temperature conditions in the surrounding 900m^2, however this is unquantified. Additionally, DEM errors could misrepresent terrain parameters at a given grid location. Subsequent modeling is also performed on the 30m grid cells; therefore the scale discrepancy exists only in the initial extrapolation of temperature profiles.

RESULTS AND DISCUSSION

Pairwise Variable Correlations

Analysis of the variable correlations shows few significant relationships and little pattern in the type of predictors that are significant as the season progresses (Table 3). Some interesting relationships are present, however. In the pooled data, temperature gradients are negatively correlated to solar and date variables, suggesting that temperature gradients generally decrease throughout the season and with greater solar input. This agrees with experience. Notably, the elevation and aspect variables show no significant correlation to the pooled average deep temperature gradients.

The individual sample days show a more complex response. *Solar* and *OCanopy* cover variables seem to gain importance as the season progresses, though they are absent from *DSN 6* and *DSN 9*. Their absence from these two datasets might be due to the preceding period of warm air temperatures in each case. *Elevation* shows no significant correlation in any of the datasets, likely due to the relatively narrow range of elevations sampled (Table 2). *Slope* and *Profile* are correlated to *AvgTG* in the first dataset, *Profile* again in *DSN* 3 and *Slope* again in *DSN 6*, but are otherwise uncorrelated. The aspect and interaction variables likewise show infrequent correlations. Slope variables seem to act as amplifiers, enhancing the effects of other variables while being uncorrelated individually. Aspect is a difficult variable to assess, as the circular nature of the data makes inclusion in a linear relationship difficult.

Regression Modeling

The results of stepwise least-squares multiple regression are generally similar to the correlation results above, but it is clear that the *combined* effects of the terrain variables are more significant than are the individual, pairwise relationships (Table 4). This is the case for many multivariate relationships with snowpack and snow stability parameters (i.e. Birkeland, 2001). Some variables that do not show strong correlation to *AvgTG* individually are significant in a predictive regression model when included with other variables (e.g. *Slope*). This implies that separating terrain components to relate them to snow parameters is perhaps not valid in all circumstances.

For the pooled data, a significant regression was generated for *AvgTG* using *Slope* and *Date* (r^2 = .32). The strong relationship to date of season is intuitive and confirmed by experience.

Separate regression models for each dataset varied in their ability to explain variability in the response, with r^2 values between 0 (no models created) and 0.62. The pattern of included variables shows no trend according to time of season. Furthermore, variable coefficients included in several models often are of opposite sign in different

Table 3: Pearson correlation coefficients

	Elevation	Slope		Aspect					Interactions			Solar/Vegetation			Date
Response	**Elevation**	**Slope**	**Profile**	**Planform**	**Aspect**	**DfromN**	**Sine**	**Cosine**	**SlpSine**	**SlpCos**	**SlpDfrN**	**OCanopy**	**Solar**	**CanSolar**	**Date**
Pooled Data															
AvgTG All	-0.08	-0.10	-0.07	-0.03	0.06	-0.03	0.00	0.02	0.02	0.01	-0.08	-0.06	**-0.48**	**-0.47**	**-0.56**
p-value	*0.19*	*0.11*	*0.27*	*0.59*	*0.33*	*0.69*	*0.97*	*0.80*	*0.76*	*0.84*	*0.21*	*0.35*	*<.0001*	*<.0001*	*<.0001*
By Sample Day															
AvgTG 1	-0.26	**-0.59**	**-0.47**	0.05	-0.05	0.26	0.27	-0.10	0.30	-0.08	-0.07	-0.10	0.33	0.29	0.00
p-value	*0.30*	*0.01*	*0.05*	*0.84*	*0.86*	*0.30*	*0.27*	*0.68*	*0.23*	*0.74*	*0.78*	*0.70*	*0.18*	*0.24*	*1.00*
AvgTG 2	-0.22	-0.04	0.02	-0.03	0.19	-0.23	-0.01	0.05	-0.11	0.04	-0.10	-0.08	0.06	0.00	0.00
p-value	*0.32*	*0.84*	*0.93*	*0.90*	*0.41*	*0.30*	*0.95*	*0.82*	*0.64*	*0.85*	*0.67*	*0.72*	*0.79*	*1.00*	*1.00*
AvgTG 3	-0.17	-0.21	**-0.34**	-0.27	0.30	**0.52**	-0.25	-0.02	-0.16	-0.07	0.33	-0.20	0.16	0.11	0.00
p-value	*0.44*	*0.33*	*0.10*	*0.21*	*0.16*	*0.01*	*0.23*	*0.92*	*0.46*	*0.74*	*0.11*	*0.36*	*0.44*	*0.62*	*1.00*
AvgTG 4	-0.18	-0.13	0.04	0.02	0.31	0.28	-0.09	0.30	-0.04	0.23	0.25	0.02	**0.45**	**0.40**	0.00
p-value	*0.37*	*0.53*	*0.84*	*0.91*	*0.12*	*0.16*	*0.65*	*0.13*	*0.85*	*0.25*	*0.20*	*0.91*	*0.02*	*0.04*	*1.00*
AvgTG 5	0.22	-0.29	-0.17	-0.08	-0.03	0.25	-0.17	-0.18	-0.06	-0.12	-0.03	**0.37**	**0.32**	**0.37**	0.00
p-value	*0.24*	*0.13*	*0.38*	*0.69*	*0.88*	*0.19*	*0.38*	*0.35*	*0.76*	*0.53*	*0.86*	*0.05*	*0.09*	*0.05*	*1.00*
AvgTG 6	0.15	**-0.44**	-0.15	0.01	**0.38**	-0.14	-0.02	0.09	0.13	-0.04	**-0.35**	-0.09	0.03	-0.01	0.00
p-value	*0.44*	*0.02*	*0.44*	*0.97*	*0.04*	*0.46*	*0.94*	*0.66*	*0.50*	*0.85*	*0.06*	*0.63*	*0.88*	*0.97*	*1.00*
AvgTG 7	-0.11	-0.05	-0.16	-0.05	0.28	-0.21	-0.02	**0.47**	0.00	**0.39**	-0.18	**-0.46**	**-0.43**	**-0.50**	0.00
p-value	*0.56*	*0.79*	*0.41*	*0.78*	*0.14*	*0.28*	*0.90*	*0.01*	*0.99*	*0.04*	*0.35*	*0.01*	*0.02*	*0.01*	*1.00*
AvgTG 8	-0.08	0.12	-0.01	0.03	0.08	-0.07	0.08	-0.05	0.13	0.04	-0.01	**-0.38**	-0.29	**-0.37**	0.00
p-value	*0.68*	*0.53*	*0.96*	*0.89*	*0.68*	*0.73*	*0.68*	*0.81*	*0.50*	*0.84*	*0.95*	*0.04*	*0.12*	*0.05*	*1.00*
AvgTG 9	-0.16	0.01	0.16	0.03	-0.20	-0.16	0.07	-0.29	0.09	-0.13	-0.21	0.06	-0.07	-0.02	0.00
p-value	*0.40*	*0.96*	*0.41*	*0.87*	*0.29*	*0.42*	*0.70*	*0.12*	*0.65*	*0.50*	*0.27*	*0.77*	*0.74*	*0.91*	*1.00*

Table 4: Partial standardized regression coefficients and R^2 values

		Elevation	Slope		Aspect					Interactions			Solar/Vegetation			Date
Response	**R^2**	**Elevation**	**Slope**	**Profile**	**Planform**	**Aspect**	**DfromN**	**Sine**	**Cosine**	**SlpSine**	**SlpCos**	**SlpDfrN**	**OCanopy**	**Solar**	**CanSolar**	**Date**
Pooled Data																
AvgTG All	**0.32**		**-0.10**													**-0.56**
p-value			0.06													<.0001
By Sample Day																
AvgTG 1	**0.35**		**-0.59**													
p-value			0.01													
AvgTG 2	**N/R**															
p-value																
AvgTG 3	**0.39**						**0.86**								**-0.49**	
p-value							0.00								0.05	
AvgTG 4	**0.53**	**-0.45**				**0.34**			**0.31**					**0.56**		
p-value		0.01				0.04			0.06					0.00		
AvgTG 5	**0.14**														**0.37**	
p-value															0.05	
AvgTG 6	**0.26**		**-0.36**			**0.27**										
p-value			0.05			0.14										
AvgTG 7	**0.62**			**-0.51**							**0.65**				**-0.56**	
p-value				0.00							0.00				0.00	
AvgTG 8	**0.15**												**-0.38**			
p-value													0.04			
AvgTG 9	**0.31**								**-1.28**		**1.09**	**-0.37**				
p-value									0.01		0.02	0.05				

datasets. This implies that terrain variables, while certainly important as evidenced by the models, can only explain a small portion of the overall variability in the spatial patterns of snow temperature gradients.

Weather Data

A qualitative assessment of weather data from the remote weather station in Wolverine Basin reveals relationships that could aid in explaining spatial variation in temperature gradients (Figure 2). Datasets 1-4 were collected in the early part of the season, when snow depths were less than 1 meter. In these conditions, the average deep temperature gradients show strong sensitivity to air temperature. Later in the season, when snow depths are greater, this sensitivity is decreased substantially. In addition, in the latter part of the season, fluctuations in the deep temperature gradients seem to show increased sensitivity when the values of air and snow surface temperatures are close.

The daily upper quartile of reflected shortwave radiation with a four-day moving average is shown in Figure 3. While not a direct measure of incoming solar radiation, the short-term fluctuations can be taken to represent intervals of cloudy and non-cloudy periods. A general increase in shortwave energy is seen as the season progresses, as expected. More solar input would serve to increase snow temperatures, and reduce average temperature gradients, as is evidenced by the general decrease in the average temperature gradients throughout the season. A local maximum in reflected shortwave occurs at *DSN 4*, which may explain the inclusion of *Solar* in the model for that dataset. In contrast, *DSN 8* and *DSN 9* coincide with local minima in the reflected shortwave curve. This explains why *Solar* is not included in the models for those datasets, and suggests that other variables such as air or snow surface temperature are responsible for the spatial patterns observed.

The weather data collected are not distributed spatially, and as such represent a single point. Despite the high temporal resolution, these data can only give a qualitative explanation for the component of spatial temperature gradient variation not explained by terrain. An estimation of the spatial variation in time series of weather parameters could be useful in improving our understanding of the relationship between terrain, weather, and snowpack temperature profiles.

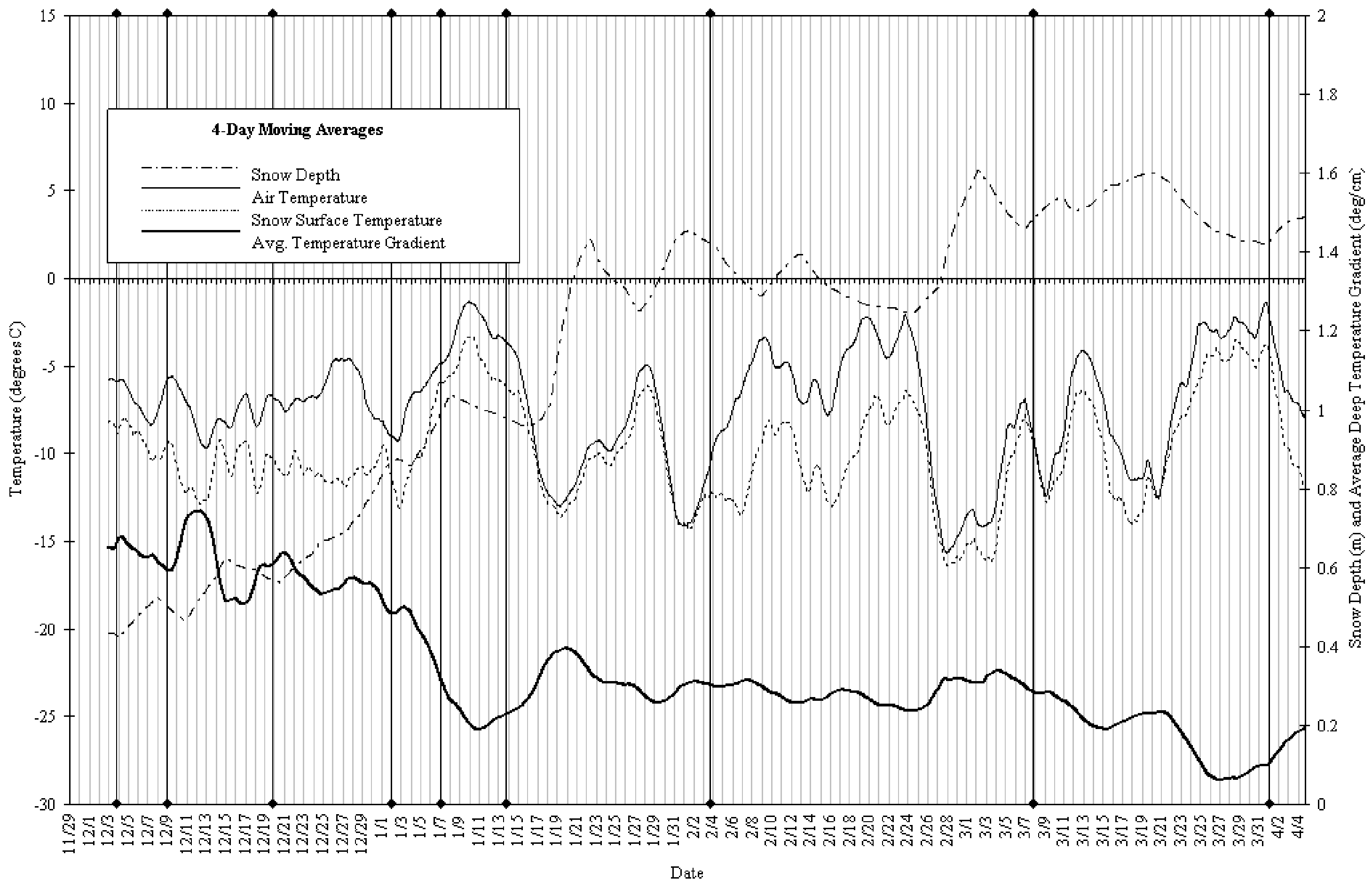

Figure 2: Four-day moving averages of weather parameters. Vertical lines represent temperature gradient data collection dates.

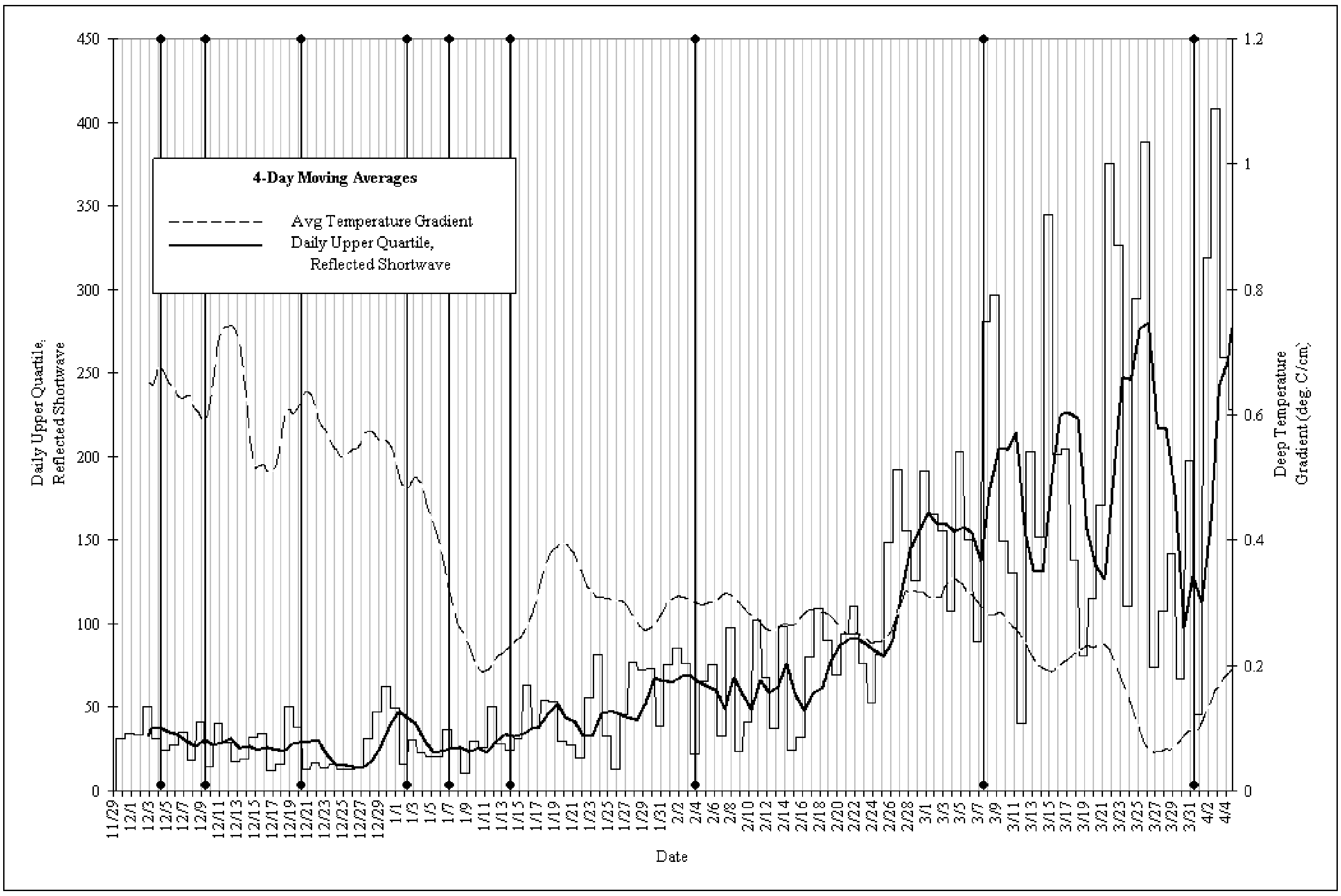

Figure 3: Four-day moving averages of reflected shortwave and average deep temperature gradient. Vertical lines represent temperature gradient collection dates.

CONCLUSIONS

This project investigated geographic patterns of snow temperature gradients at the basin scale as influenced by topographic variables over the course of a single snow season. Nine spatially distributed datasets of temperature profiles were collected, and temperature gradient statistics were calculated from each profile. Temperature gradient data were related to physical (topographic, solar and vegetation) variables through correlation and regression procedures.

Pairwise correlation shows no particular trend in the type of terrain variable significant at different points in the season. Regression results demonstrate a generally poor predictive ability using the terrain-related variables applied in this work. The regression models developed explain from 0% to just over 60% of the spatial variation in temperature gradients. Modeling the pooled data demonstrated the significance of time of season, yet could only account for 32% of the variance in temperature gradients.

The initial results of this study suggest that, while terrain is certainly an important consideration, topographic effects alone cannot account for the spatial variation observed in snow temperature gradients. A qualitative analysis of weather data collected indicates that inclusion of spatially observed weather parameters could be an important component to future models.

REFERENCES

Armstrong, R.L. and B.R. Armstrong, 1987. Snow and avalanche climates of the western United States: a comparison of maritime, intermountain and continental conditions, in *Avalanche Formation, Movement and Effects*, Proceedings of the Davos Symposium, September 1986. IAHS publication no. 162.

Armstrong, R. L., 1976. Wet snow avalanches, in *Avalanche Release and Snow Characteristics*, Occasional Paper no. 19, Institute of Arctic and Alpine Research, University of Colorado, 67-81.

Armstrong, 1985. Metamorphism in a subfreezing, seasonal snow cover: The role of thermal and vapor pressure conditions. Ph.D. dissertation, Department of Geography, University of Colorado. 175 pp.

Birkeland, K. W., K. J. Hansen, and R. L. Brown, 1995. The spatial variability of snow resistance on potential avalanche slopes, *Journal of Glaciology* 41(137) 183-189.

Birkeland, K. W., R. F. Johnson, and D. S. Schmidt, 1998. Near-surface faceted crystals formed by diurnal recrystallization: a case study of weak layer formation in the mountain snowpack and its contribution to snow avalanches, *Arctic and Alpine Research* 30(2) 200-204.

Birkeland, K. W., 2001. Spatial patterns of snow stability throughout a small mountain range, *Journal of Glaciology* 47(157) 176-186.

Blöschl, G., R. Kirnbauer, and D. Gutknecht, 1991. Distributed snowmelt simulations in an alpine catchment 1. Model evaluation on the basis of snow cover patterns, *Water Resources Research*, 27(12), 3171-3179.

Bradley, C. C., 1970. The location and timing of deep slab avalanches, *Journal of Glaciology* 9(56), 253-261.

Clarke, J. and D. McClung, 1999. Full-depth avalanche occurrences caused by snow gliding, Coqiuhalla, British Columbia, Canada, *Journal of Glaciology*, 45(151), 539-546.

Conway, H. and Abrahamson, 1984. Snow stability index, *Journal of Glaciology*, 30(106), 321-327.

Conway, H. and C. Wilbour, 1999. Evolution of snow slope stability during storms, *Cold Regions Science and Technology*, 30, 67-77.

Deems, J., 2001. Topographic Controls on Spatial and Temporal Variation in Snow Temperatures in a Mountain Snowpack, Poster, Western Snow Conference, 2001, Sun Valley, ID.

Ferguson, R. I., 1999. Snowmelt runoff models, *Progress in Physical Geography*, 23(2), 205-227.

Föhn, P.M, 1988. Snowcover stability tests and the areal variability of snow strength, in *Proceedings of the 1988 International Snow Science Workshop*, Whistler, Canada, 262-273.

Gassner, M., H.-J. Etter, K. Birkeland, and T. Leonard, 2000. NXD2000: An improved avalanche forecasting program based on the nearest neighbor method, *Proceedings of the International Snow Science Workshop 2000*, Big Sky, Montana.

Gray, D. M. and D. H. Male, 1981. *Handbook of Snow: Principles, Processes, Management and Use.* Willowdale, Ontario, Canada, Pergamon Press, 776p.

Kirnbauer, R., G. Blöschl, and D. Gutknecht, 1994. Entering the era of distributed snow models, *Nordic Hydrology* 25, p. 1-24.

Landry, C.C., 2002. Spatial variations in snow stability on uniform slopes: implications for extrapolation to surrounding terrain. MSc Thesis, Department of Earth Sciences, Montana State University, 248pp.

Lundy, C., R. L. Brown, and E. E. Adams, 2000. A statistical validation of the SNOWPACK model in a Montana climate, *Proceedings of the International Snow Science Workshop 2000*, Big Sky, Montana.

McClung, D. and P. Schaerer, 1993. *The Avalanche Handbook.* The Mountaineers, Seattle, WA.

McClung, D. and J. Tweedy, 1994. Numerical avalanche prediction: Kootenay Pass, British Columbia, Canada, *Journal of Glaciology*, 40(135), 350-358.

Mock, C.J. and K.W. Birkeland, 2000. Snow avalanche climatology of the western United States mountain ranges, *Bulletin of the American Meteorological Society* 81, 2367-2392.

Tremper, B., 1986. How ground temperature affects temperature gradient metamorphism: an empirical study, *Proceedings of the 1986 International Snow Science Workshop*, Lake Tahoe, CA, 146-152.