Topographic influence on the spatial patterns of snow temperature gradients in a mountain snowpack

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Abstract: The objective of this study was to investigate the importance of topography in controlling the geographic patterns of deep snow temperature gradients within a seasonal snowpack. 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 each of 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 from a digital elevation model (DEM) using a Geographic Information System (GIS). Linear regression models quantified the relationships between the topographic variables and snow temperature gradient patterns in our spatially distributed dataset, and demonstrate the relative importance of the terrain variables in determining spatial patterns of temperature gradients.. Analysis shows a complex pattern of relationships between temperature gradients and the static topographic variables. A qualitative assessment of weather variables recorded onsite suggests the utility of using more dynamic variables such as weather data in future research.

Keywords: spatial variation, temperature gradients, topography, regression, GIS.

1. Introduction

This project investigates the spatial 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 an important factor 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 affect avalanche hazard (McClung and Schaerer, 1993). The profile of snowpack temperatures directly influences the shape of the basin hydrograph, and affects the ability of the snowpack to buffer extreme melt events. The geography of snow temperatures 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; Jamieson, 1995; Landry, 2002), and resistance (Birkeland et al., 1995). Birkeland, (2001) explained snow stability patterns using combinations of factors such as topography, snow depth, temperature gradient, and resistance. Variations in weather and

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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 in development and refinement of snowmelt and avalanche forecasting models. The techniques used in this study might 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.

2. Methods

2.1 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). Thirty sample sites were selected to maximize topographic variability, and were revisited on each sample day. A range of topographic variables was measured for each of the sample sites (Table 1).

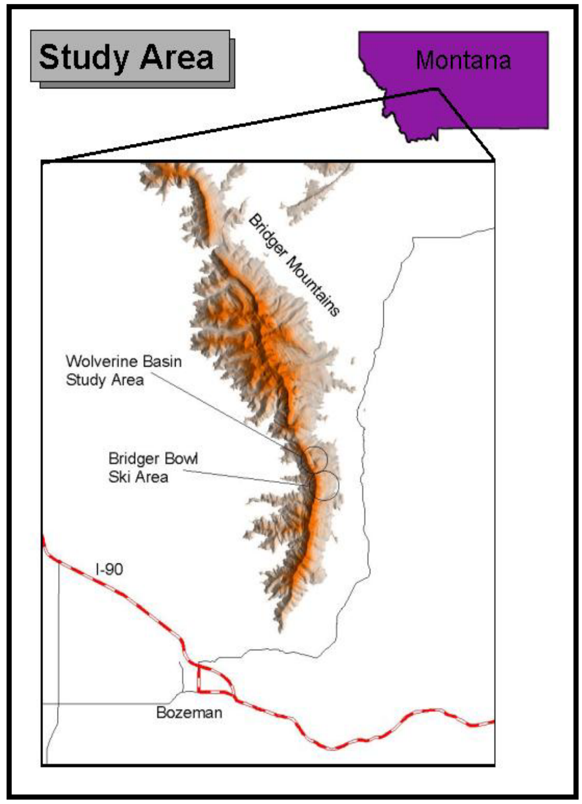

Figure 1: Study area location.

Table 1: Variable codes, descriptions, and summary statistics.

Variable code	Description	Minimum	Maximum	Mean	Std Dev
AvgTG	Average deep temperature gradient (°Cm^{-1})	0.15	1.15	0.5	0.2
MaxTG	Maximum deep temperature gradient (°Cm^{-1})	0.3	2.4	0.96	0.4
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 (Rate of change in Slope)	0	22	9.16	5.61
Planform	Planform curvature (Rate of change in Aspect)	1	80	42.25	25.49
Aspect	Aspect (degrees)	2	354	169.3	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	-23.88	33.63	-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 input (Wm^{-2})	4084	241341	45050	49268

Profile is the profile curvature, or rate of change in *Slope*, showing the terrain "sharpness" in the vertical dimension. *Planform* is the planform curvature, or rate of change in *Aspect*, showing the exposure of a site in planform. *Aspect* is further broken down into its sine and cosine components, as well as degrees from north. These aspect derivatives potentially aid in interpretation of the regression models. The existence of Aspect in a regression would suggest its importance, but due to the circular nature of aspect data would be difficult to interpret in a linear relationship. Variables like degrees from north or cosine of aspect are more easily interpreted.

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 12/4/01 and 4/1/02.

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 were collected at five-minute intervals, and were averaged to produce an hourly output interval.

2.2 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, an observation backed up by previous research (Tremper, 1986). Gradients in the "deep" portion of the snowpack, defined here to be greater than 30cm below the snow surface were selected for analysis. The deep gradients were chosen in order to eliminate problems associated with diurnal fluctuation in near-surface snow temperatures (Armstrong, 1985; Birkeland et al., 1998). The average of the deep temperature gradients (*AvgTG)* and maximum deep temperature gradient (*MaxTG*) were then used as response variables in the regression models.

Terrain variables were calculated using a 30m DEM and ArcView GIS software. Canopy density was measured manually. Potential cumulative solar input was calculated from the DEM using Solar Analyst extension for ArcView (Helios Environmental Modeling Institute, Los Alamos, New Mexico).

Stepwise, least-squares, multiple linear regression modeling was performed using the SAS statistical software package (SAS Institute, Inc., Cary, North Carolina). The data were analyzed in two parts: pooled data for the entire season, and separated by sample date. Due to the small sample sizes, a p-value criteria 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 predictive model.

3. Results and discussion

The results of the regression modeling do not show any straightforward trends, but it is clear that the combined effects of the terrain variables are more significant than are individual, pairwise relationships (Deems, 2002). This is the case for many multivariate relationships with snowpack and snow stability parameters (Birkeland, 2001), and would seem to indicate that the common practice of separating terrain components to relate them to snow parameters is perhaps not valid in all circumstances.

3.1 Average Temperature Gradients

The pooled *AvgTG* data showed a significant relationship ($R^2 = 0.32$) with *Slope* and *Date* (Table 2). The relationship to date of season is confirmed by the weather station data, in which the average temperature gradient displays a negative linear trend through the season (Figure 2). The inclusion of *Slope* either suggests that slope angle acts as an amplifier of other terrain effects, or is an artifact of sampling bias in the sites selected.

Separate regression models for each sample day vary 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 discernable trend according to time of season. Furthermore, coefficients of variables included in several models often are of opposite sign on different sample days, such as for *Elevation* in the *MaxTG* regressions on 1/2 and 2/4. The sign change would seem to indicate that other, more dynamic factors (e.g. air temperature), which also vary with altitude, are partly controlling the temperature gradient patterns. *Elevation* is notably absent from the majority of models, perhaps due to the limited range of elevations represented in the sample. Solar and vegetation variables are important throughout the season, but in different capacities as represented by the signs of the coefficients.

3.2 Maximum Temperature Gradients

As with the results for the average temperature gradients, the regression models developed for the maximum temperature gradients demonstrate a lack of coherent pattern (Table 3). Most notable is that the pooled *MaxTG* data show no relationship with the date of season. A look at the weather station data shows that the maximum temperature gradient varies about a mean of 7.3 °C/m, with no decline in the mean during the measurement period. If data had been collected past the isothermal date, a falloff in *MaxTG* would likely be evident. According to the regression analysis, the important variables in determining the maximum gradient for the pooled data are *OCanopy* and *Aspect*, along with the interaction of *Slope* and *DfromN*. The canopy and aspect variables provide significant energy balance controls on snow temperatures, while the interaction term indicates that the smallest maximum gradients were found on low-angle, south-facing slopes.

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Table 2: Partial regression coefficients for average deep temperature gradients (AvgTG).

		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	0.32		-0.10													-0.56
By Sample Day																
12/04/01	0.35		-0.59													
12/09/01	N/R															
12/20/01	0.39						0.86								-0.49	
01/02/02	0.53	-0.45				0.34			0.31					0.56		
01/07/02	0.14														0.37	
01/14/02	0.26		-0.36			0.27										
02/04/02	0.62			-0.51							0.65				-0.56	
03/08/02	0.15												-0.38			
04/01/02	0.31								-1.28		1.09	-0.37				

Table 3: Partial regression coefficients for maximum deep temperature gradients (MaxTG).

		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																
MaxTG	0.03					-0.17						-0.11	-0.11			
By Sample Day																
12/04/01	0.37		-0.38			-0.55										
12/09/01	0.10										-0.32					
12/20/01	0.68						0.68		-0.32				-0.61	-0.43		
01/02/02	0.39	-0.60							0.31						0.31	
01/07/02	0.11								-0.33							
01/14/02	N/R															
02/04/02	0.25	0.29												-0.46		
03/08/02	0.11												-0.32			
04/01/02	0.11								-0.34							

The individual sample days demonstrate a remarkable fluctuation in the explanatory power of the models, as well as in which variables are important on any given day. R^2 values range from 0 to 0.68, thus even the best regression leaves ⅓ of the variability in the data unexplained. *Cosine* is included in several models, insinuating that maximum gradients are more sensitive to the North/South orientation of the sample site than the East/West orientation. This makes sense because of the dramatic difference in solar input between north and south-facing slopes, as opposed to the moderate differences in solar input between east and west-facing slopes. Solar and vegetation variables are also frequently important, with negative coefficients indicating that smallest maximum gradients were associated with the largest solar potential. *Elevation* appears twice, though with opposite signs for the coefficients.

The explanatory power of the regression models varies wildly through the season, as do the variables included in the models. This leads to the conclusion that terrain variables, can only statistically explain a small portion of the overall variability in the spatial patterns of average snow temperature gradients, and points to the existence of other, more dynamic, controls on spatial variation in snow temperature gradients

3.3 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. Figures 2 and 3 show 4-day moving averages of weather parameters measured at the weather station. The 4-day averages were chosen to represent a cumulative effect of weather factors on the snowpack, as short interval fluctuations can be effectively buffered by the insulating capacities of the snowpack (Armstrong and Williams, 1986).

Datasets 1-4 were collected in the early part of the season, when snow depths were under 1 meter. In these conditions, the average and maximum deep temperature gradients show strong sensitivity to air or snow surface temperature. Later in the season, when snow depths are greater, the sensitivity of the average gradient is decreased substantially, while the maximum gradient seems to retain this sensitivity.

The daily upper quartile of reflected shortwave radiation is the 75^{th} percentile of all measurements for that day, capturing maximum daily solar input. While not a direct measure of incoming solar radiation, short-term fluctuations can be taken to represent intervals of cloudy and non-cloudy weather. A general increase in shortwave energy is seen as the season progresses, as day length and sun angle increase. 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 on 1/2/02, which may explain the inclusion of *Solar* in the model for that dataset. In contrast, 3/8/02 and 4/1/02 coincide with local minima in the reflected shortwave curve. This can explain why *Solar* is not included in the *AvgTG* models for those datasets, and suggests that other factors such as aspect or air temperature are responsible for the spatial patterns observed.

The plot of *MaxTG* shows a large decrease during January, a period of warm air and snow surface temperatures and increasing snow depth, potentially explaining the poor regression models on 1/7/02 and 1/14/02. By 2/4/02 the snowpack had experienced large air and snow surface temperature swings, seemingly increasing the variability of *MaxTG* enough to produce a valid model.
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 the terrain parameters. 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.

4. Conclusions

This project investigated spatial 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 calculated from each profile. Temperature gradient data were related to physical (topographic, solar and vegetation) variables through multiple linear regression procedures.

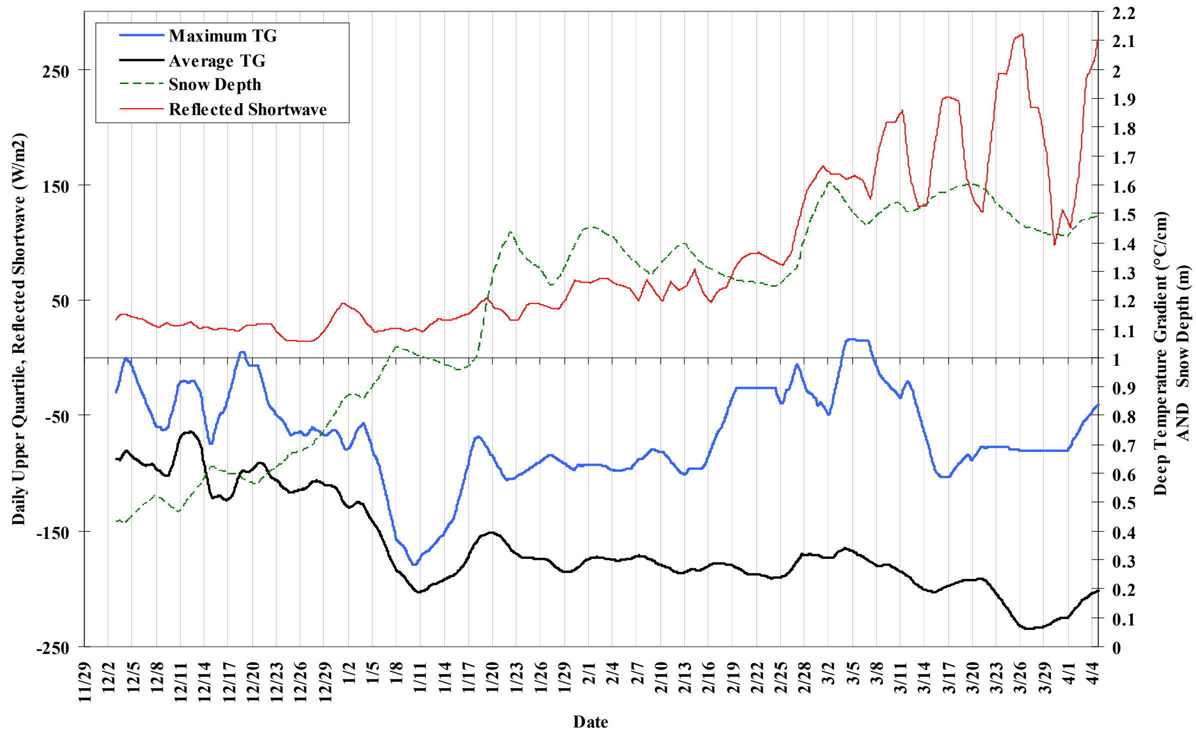

Figure 2: 4-day moving averages of maximum temperature gradient, average temperature gradient, snow depth, and reflected shortwave, measured at the Wolverine Basin Meteorologic Station.

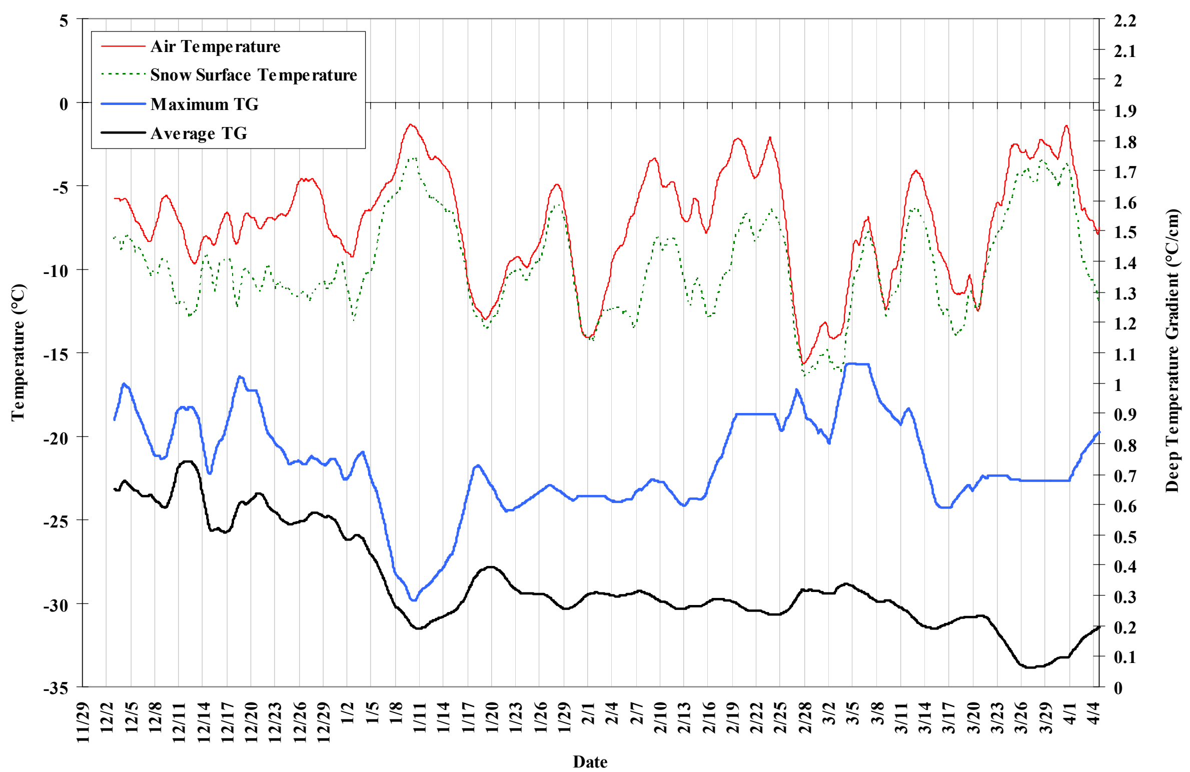

Figure 3: 4-day moving averages of maximum temperature gradient, average temperature gradient, air temperature, and snow surface temperature, measured at the Wolverine Basin Meteorologic Station.

While the regression results certainly show some terrain dependence in the temperature gradient data, they demonstrate a generally poor predictive ability using the terrain-related variables applied in this work. The regression models developed for individual sample days explain from 0% to just under 70% of the spatial variation in average and maximum deep temperature gradients. Modeling the pooled data demonstrated the significance of time of season for average temperature gradients, yet could only account for 32% of the variance. The pooled relationship for the maximum temperature gradients suggested the importance of canopy cover and aspect, but provided virtually no explanation of the variance in the data.

The results of this study suggest that, while terrain is certainly an important consideration, static topographic effects alone cannot account for the spatial variation seen in snow temperature gradients. Dynamic factors, such as changing weather, are critically important. Efforts must be extended to include more dynamic factors. A qualitative analysis of weather data collected indicates that spatially observed time series of weather parameters could be important components in future models.

5. Acknowledgements

This project was supported by the Montana State University Department of Earth Sciences, the Barry C. Bishop Scholarship for Mountain Research, the American Avalanche Association, and the American Alpine Club. In-kind services were provided by Bridger Bowl Ski Area and Helios Environmental Modeling Institute. Many thanks to individuals for assistance and field help: Chris Landry, John Borkowski, Cal Ruleman, Denny Capps, Jeanette Romig, Matt Blank, Chris Lundy, and Brian Seneker,

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