TOPOGRAPHIC CONTROLS ON SPATIAL AND TEMPORAL VARIATION IN SNOW TEMPERATURES IN A MOUNTAIN SNOWPACK

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ABSTRACT

The objective of this project is to analyze and model the geographic patterns of snow temperature profile characteristics as functions of topographic variables. The results of a pilot study are presented here. Snow temperature is a dominant variable in many physical processes in the seasonal snowpack. This spatial, or geographic, analysis of the relationship of snow temperature patterns to topography, utilizing landscape-scale modeling, attempts to identify temperature responses to effects of complex terrain. Data from the pilot study is used to create regression models predicting temperature profile characteristics throughout a basin, based on a combination of slope and slope aspect parameters at similar elevation. Prediction maps demonstrate the potential of this modeling technique. Future plans include collection and use of a larger dataset, inclusion of more topographic variables, and incorporation of a change-over-time component. Knowledge of the patterns of snow temperature profile characteristics over space and time could aid in avalanche prediction and snowmelt modeling.

INTRODUCTION

This project attempts to analyze and model the geographic patterns of snow temperature profile characteristics using topographic parameters as predictor variables. The results discussed in this paper are of a pilot study intended to explore the feasibility of the model technique. A Geographic Information System (GIS) regression model has been created to predict snow temperature profile characteristics from spatial topographic data. This model attempts to address the spatial variability inherent in snowpack processes at the basin scale.

Snow temperature is a dominant variable in many physical processes in the seasonal snowpack. The profile of temperature through the depth of the snowpack reveals much about both the 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 Schaefer, 1993). The temperature stratigraphy of the snowpack 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 (Clarke and McClung, 1999, Armstrong, 1976).

Topography exerts a significant control on spatial and temporal variation in snow temperature patterns (McClung and Schaefer, 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.

A spatial analysis of the relationship of snow temperature patterns to topography, utilizing landscape-scale modeling, can potentially predict temperature responses to complex terrain. Ferguson (1999) suggested that GIS analysis of digital terrain data be used to establish a topographic attributes-based modeling approach for snowmelt prediction, in the interests of minimizing both the number of data inputs and parameterization complexity. Knowledge 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. 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 profiles were collected during the snow season of 2000-2001, in Wolverine Basin, north of Bridger Bowl Ski Area near Bozeman, Montana (Figure 1). Profile sites were selected to maximize slope aspect variability and to minimize elevation variability. All profiles were measured on slope angles between 6 and 15°.

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Snow temperatures were collected at 10cm increments from the ground up to the snow surface, at the same five sites on each day. Other variables recorded were height to snow surface, surface temperature, air temperature, and time of day. Two datasets were obtained, the first on March 23, and the second on March 30.

**Modeling Techniques**

Descriptive variables (maximum temperature gradient between two adjacent measurements (MaxTG), height to MaxTG (HTG), and HTG as a percentage of total snow height (HTG/HS)) were calculated for each dataset and for the pooled data. The data was georeferenced and linked to topographic data. S-Plus statistical software (Insightful Corp., Seattle, WA) was used to develop the regression equations.

The regression equations derived with S-Plus were then applied to the topographic data using the Map Calculator function in ArcView GIS software (ESRI, Redlands, CA), and grid maps were produced of predicted MaxTG, HTG, and HTG/HS values. The prediction maps were then evaluated qualitatively, looking for prediction patterns that generally agreed with expected locations of temperature profile characteristics.

**RESULTS AND DISCUSSION**

Many combinations of explanatory variables were tested for statistical performance, and it was decided that a combination of three variables performed best: 1: Slope x Sine Aspect, 2: Slope x Cosine Aspect, and 3: the product of the first two respectively (Slope² x Sine Aspect x Cosine Aspect). These variables produced the best fit to the data (R² = 0.96, 0.99, and 0.59), despite being statistically insignificant (p-values > α = 0.05). The combination of high R² and high p-values was interpreted to be a factor of the very small sample size, and therefore the regressions were deemed adequate for this exploratory study.

The maps produced by the regression equations predict snow temperature profile characteristics throughout the basin based on data from five points of limited geographic extent. Furthermore, the model includes only slope and aspect as topographic predictor variables, intentionally excluding elevation in this exploratory study both for the sake of simplicity and due to the limited elevational range in the data. Therefore, it is unreasonable to assume that the model is accurate in its predictions. However, several important patterns are present in the model output that appear to validate the modeling technique.

In the map of predicted MaxTG for March 23, for example (Figure 2), the greatest temperature gradients are found on steep slopes facing north to northeast. Additionally, the smallest gradients are found on steep, south-facing slopes. This result would seem to agree with temperature gradient patterns expected due to the differing amounts of solar radiation received by different areas in the snowpack, the distribution of which is heavily aspect-dependent (McClench and Schaerer, 1993).

The map of predicted MaxTG for March 30 (Figure 3), however, displays the opposite pattern, in that it predicts the greatest MaxTG on the south facing slopes, and the lowest gradients on the north-facing slopes. This result is contrary to the expected patterns, especially considering that the south-facing slopes were isothermal the week before. However, the prediction map is consistent with the data for March 30, which show the steepest temperature gradient on the southeast-facing slope. The reversal of pattern from the previous week can be attributed to a
snowfall event in the interval, which deposited over 35 cm of snow, with over 48 mm of snow-water equivalent recorded at a nearby SNOTEL site (NRCS SNOTEL Data Network website).

The predicted MaxTG map for the pooled datasets shows a pattern similar to the March 23 result (Figure 4). The data from March 23 show a larger range in temperature gradient magnitude than on March 30, which apparently overwhelms the range of gradients present in the March 30 data. This produces a similar prediction pattern, although slightly reduced in overall deviation from the mean predicted gradient compared to the March 23 map.

Prediction maps of HTG and HTG/HS exhibit similar patterns to the MaxTG maps. These maps will be an important component in future analysis and model development, as the height within the snowpack that the largest temperature gradient occurs can be used to differentiate longer-term temperature gradient changes from diurnal fluctuations.

CONCLUSIONS

This project is a pilot study to explore the feasibility of modeling snow temperature profile characteristics based on GIS-derived topographic data. A limited dataset was used to develop regression equations based on the predictor variables slope and slope aspect. Despite statistical shortfalls, initial results indicate that the modeling technique is promising, and could produce valuable results when applied to a larger dataset.

Future Development

The most pressing need for this project is a larger dataset from which to spatially predict temperature profile characteristics. This larger dataset will be obtained during the 2001-2002 snow season with the use of a Snow Temperature Profile Probe. This instrument, of original design and construction, rapidly collects a 10cm temperature profile up to two meters in depth. The Profile Probe will allow collection of temperature profiles over a large range of terrain types in a single field day. Data from this instrument will provide a dataset on which a statistically valid regression model can be based.

Additionally, the future regression models will include elevation as an explanatory variable. This is a critical variable for spatial prediction of snowpack properties, as many parameters, including air temperature and precipitation, are known to be elevation correlated. Other potential explanatory variables to be explored are ground cover, profile and planform curvature, and tree canopy density.

The sampling pattern in the 2001-2002 field season will be repeated regularly (weekly or bi-weekly interval), collecting data from the same locations each field day, over the entire snow season. This component will allow a change-over-time analysis of the temperature profile properties to be added as a model component.

The effects of other environmental variables that are more difficult to parameterize, such as radiation balance and turbulent heat flux, could be estimated using the topographic variables studied here. Additionally, if other integrated correlations can be established at the landscape scale, accuracy of existing models can be improved while adding only a small amount of complexity. The spatial analysis techniques used in this study address the modeling complexities of spatial variability in snow processes, and could be used for any combination of predictive and response variables in snow science. The patterns produced by a tiny dataset are encouraging, and suggest that when applied to a larger dataset, they will produce exciting results.
REFERENCES


