Topographic effects on the spatial and temporal patterns of snow temperature gradients in a mountain snowpack

by Jeffrey Sinclair Deems

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences
Montana State University

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 utilized 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 using a portable snow temperature profile probe. These data were used to calculate temperature gradients for each profile. Topographic attributes were derived from a digital elevation model using a geographic information system. Linear regression models were used to quantify the relationships between the topographic variables and snow temperature gradient patterns in the spatially distributed dataset, and to demonstrate the relative importance of the terrain variables in determining spatial patterns of temperature gradients. Analysis showed a complex pattern of relationships between temperature gradients and the static topographic variables. A qualitative assessment of weather variables recorded onsite suggested the utility of using more dynamic variables such as weather data in future modeling efforts.

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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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 utilized 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 using a portable snow temperature profile probe. These data were used to calculate temperature gradients for each profile. Topographic attributes were derived from a digital elevation model using a geographic information system. Linear regression models were used to quantify the relationships between the topographic variables and snow temperature gradient patterns in the spatially distributed dataset, and to demonstrate the relative importance of the terrain variables in determining spatial patterns of temperature gradients. Analysis showed a complex pattern of relationships between temperature gradients and the static topographic variables. A qualitative assessment of weather variables recorded onsite suggested the utility of using more dynamic variables such as weather data in future modeling efforts.

INTRODUCTION

Snow temperature is a dominant variable in many physical processes in a seasonal snowpack. The snow temperature through the depth or profile of the snowpack reveals much about both the physical state of the snowpack and its likely future behavior. Temperature gradient-driven metamorphic processes within a cold snowpack can stabilize or weaken individual layers, and hence determine the likelihood of avalanche activity. The temperature stratigraphy of the snowpack directly influences a mountain watershed's hydrology, and affects the ability of the snowpack to buffer extreme melt events. The spatial geography of snow temperature gradients therefore influences snowmelt patterns through controls on snow layer texture (Blöschl et al, 1991), and influences avalanche hazard through the development of weak layers at many levels in the snowpack (Armstrong, 1976; McClung and Schaerer, 1993; Clarke and McClung, 1999). This project measured spatial variation in snow temperature gradients, and explored regression relationships between these gradients and the topographic attributes of the terrain in which they were measured.

Spatial and temporal variation in snow properties, including temperature gradients, present significant challenges for operational modeling of and research into snowcover processes such as avalanche forecasting and snowmelt prediction. Often the variation observed is recognized, but is not addressed explicitly; rather the observer or modeler relies on their experience to assess the representativity of a measurement or the applicability of a model. The problems caused by this variation have often been avoided by observing snow phenomena on scales where the variability is relatively small or quantifiable, such as an entire mountain range (Armstrong and Armstrong, 1987) or the individual snow crystal (Colbeck, 1982; Miller, 2002). However, most modeling efforts and operational forecasting function on scales intermediate to those above. Variation in snow properties between adjacent slopes, or within a single basin or watershed often provides the crux of the analysis (Blöschl et al., 1991; Birkeland et al. 1995; Cline et al., 1997; Landry 2002).

Topography exerts a significant control on spatial and temporal variation in snow temperature patterns (McClung and Schaerer, 1993; Gerrard, 1990). 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 through both orographic effects and the ambient air temperature, influenced by the environmental lapse rate (Armstrong and Williams, 1986). Topographic profile and planform curvature are other measures of topography that could prove important, as they describe the relative "sharpness" or exposure of the terrain. Vegetation and ground surface material may also have significant effects on snow temperature and snow temperature gradients.

Solar input and air temperature are directly related to snowpack temperature (Gray and Male, 1981). Both duration and intensity of sun exposure, as well as air temperature, increase from the winter solstice until the summer solstice. Additionally, as the melt season approaches and snow temperatures continue to increase, temperature gradients within the snowpack tend to decrease (McClung and Schaerer, 1993). Therefore, snow temperature gradients show a relationship to date of season.

An exploration of the relationship of snow temperature patterns to topography, utilizing spatial analysis and landscape-scale modeling, can potentially explain temperature variability in complex terrain. Quantification of the relationship between temperature gradients and topography could aid in explaining some of the variation observed in snow properties. Ferguson (1999) suggested that Geographic Information System (GIS) analysis of digital terrain data be used to establish a topographic attributes-based modeling approach for snowmelt prediction. Specifically, Ferguson (1999, p. 220) suggested "clear possibilities of using GIS tools and gridded Digital Elevation Model (DEM) data to set up zonal models distributed not just by elevation but also slope aspect and other topographic controls of snow accumulation and snowmelt."

Knowledge of the relative importance of topographic factors in influencing snowpack temperature gradient patterns through space and time could aid in development and refinement of snowmelt and avalanche forecasting models. If snow temperature gradients do indeed exhibit a significant correlation to topographic attributes, the result would support the conventional beliefs about terrain influence on snow temperatures. An assessment of the spatial variability of snow properties (i.e. temperature) as a function of terrain variables 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.

RESEARCH HYPOTHESES

The objective of this project was to observe variations in snow temperature gradients within a mountain basin, and to use topographic variables in an attempt to explain that variation. Specifically, this project tests the following hypotheses based on previous literature:

1. Snow profile temperature gradients will show a significant correlation to the topography. The largest temperature gradients will be observed on highest elevation, north-facing slopes, while the smallest temperature gradients will be found on south-facing slopes at all elevations.
2. The magnitude of snow profile temperature gradients will show a significant correlation to the date within an individual snow season. The largest snow temperature gradient values will occur early in the snow season and will decrease towards late season.

Hypothesis #1 is based on the atmospheric lapse rate, which predicts the occurrence of lower air temperatures at higher elevations, which would affect snow surface temperatures at these locations. It is also based on the differences in solar input among differing aspects.

Hypothesis #2 relies upon the general increase in air temperature throughout the season, as well as an increase in snow depth. These two factors combine to produce lower temperature gradients, as the temperature difference between the ground surface and air is distributed over a deeper snow cover.

LITERATURE REVIEW

This review is an examination of previous research concerning snow temperature gradients and associated applications. Previous investigators (e.g. Akitaya, 1974; Colbeck, 1982) have established that temperature gradients are a driving force controlling dry snow metamorphism, with important ramifications for avalanche hazard via the development of weak layers, and for meltwater drainage, by influencing snow texture (Kattelmann, 1984). Other research (e.g. Armstrong, 1985; Birkeland, 1998) has shown that diurnal fluctuations in near-surface snow temperatures produce large temperature gradients over small changes in depth. Spatial variability in snow temperature gradients has been linked to topographic variables (Dexter, 1986), and requires a consideration of the scale of observation relative to the scale(s) upon which the temperature gradients change (Blöschl, 1999). It is in the context of these issues that this project was designed to explore the topographic influence on the spatial variability in snow temperature gradients.

Temperature Gradients and Dry Snow Metamorphism

Temperature gradients in a snowpack generally result from a temperature differential between the air and the ground surface. Ground temperatures are typically at or near 0°C in midlatitude mountain environments where permanent snow or ice is not present (McClung and Schaerer, 1993). Winter air temperatures in this environment often drop below 0°C, creating a temperature gradient within the snowpack, between the ground and air. The magnitude of this gradient also depends upon the thickness of the snow cover and the character of the snow layers contained within. Local variations in topography, vegetation, or surface roughness (i.e. the presence of boulders or rocky outcrops) can affect the flow of heat energy through the snowpack and thereby affect snow temperatures and temperature gradients (Dexter, 1986; McClung and Schaerer. 1993; Aarons et al., 1998).

Snow temperature gradients can be measured in different ways, depending on the purpose in studying them. Often, for coarse-scale spatial or temporal assessment, a gradient over the full snow depth is determined from a measured air temperature and an assumption that the ground temperature is 0°C. This type of measurement is often used for characterization of snow climate effects (Armstrong and Armstrong, 1987; Mock and Kay, 1992; McClung and Schaerer, 1993). When studies call for the interpretation or prediction of snow crystal metamorphism, a smaller-scale gradient, usually on the order of a 5 to 10cm interval, is commonly used (McClung and Schaerer, 1993). Temperature gradients near the snow surface can be many times greater than are commonly found deeper in the snowpack (Birkeland, 1998). To measure near-surface temperature gradients, sensors may be arrayed over intervals smaller than a centimeter (Birkeland et al., 1998).

The magnitude of a temperature gradient within a snow layer directly affects the magnitude of the vapor pressure gradient within that layer, and consequently the rate and type of snow crystal metamorphism (Armstrong, 1985; Dexter, 1986). It has been found to be the controlling factor in dry snow metamorphism (McClung and Schaerer, 1993).

Large temperature gradients produce rapid crystal growth and the associated "kinetic" or "faceted" forms, while slower growth rates stem from smaller temperature gradients and tend to produce rounded, well-bonded snow grains (McClung and Schaerer, 1993). Armstrong, (1977) found that a temperature gradient of 10 °C/m produced a sufficient vapor pressure gradient to produce faceted crystals, given the conditions of his study in the San Juan Mountains in Colorado, and this is often cited as the boundary between faceting and rounding growth rate regimes. Other factors, such as snow temperature and density, also have a strong effect on snow metamorphism; however, the magnitude of the temperature gradient remains the most critical influence (Miller, 2002).

A conventional assumption holds that the highest temperature gradients are found on high elevation, north-facing (Northern Hemisphere), shaded slopes, where there is less solar input than sun-exposed slopes, and colder air temperatures due to the standard atmospheric lapse rate (Dexter, 1986; McClung and Schaerer, 1993). LaChapelle and Armstrong (1977), however, found that various combinations of air temperature and snow depth resulted in similar temperature gradients on north-facing and south-facing aspects, at similar elevations. Dexter (1986) observed highest temperature gradients at lower elevations on south-facing slopes, which he attributed to the shallower snow depths at those locations. Other factors, such as areas of increased heat flow or conduction from the ground surface, can influence the distribution of temperature gradients on a scale smaller than an entire slope (McClung and Schaerer, 1993; Tremper, 1995; Aarons et al., 1998). Snow temperatures and temperature gradients are also influenced by forest canopy cover, which limits incoming shortwave radiation traps outgoing longwave radiation, dependent on the density of the canopy (McClung and Schaerer, 1993).

Diurnal Temperature Fluctuations

The daily cycle of air temperatures produces fluctuations in snow temperatures, the magnitude of which diminishes with increasing depth in the snowpack (McClung and Schaerer, 1993). Snow depths greater than about 30 cm show little to no diurnal snow temperature change, due to the insulating capacity of the overlying snow (Armstrong, 1985). The near surface, diurnal temperature fluctuations are capable of producing large or extreme temperature gradients over small distances, driving rapid faceted crystal growth (Birkeland, 1998). These faceted crystals, if buried by subsequent snowfall, can form persistent weak layers leading to increased avalanche hazard (Birkeland et al., 1998). Warm air temperatures can form melt-freeze layers at or near the surface, affecting crystal growth (Birkeland, 1998) and later influencing meltwater runoff (Marsh and Woo, 1984a; Kattelmann and Dozier, 1999).

Fukuzawa and Akitaya (1993) examined growth of near-surface faceted crystals, and found that strong temperature gradients in the 100-300 °C/m range drive the rapid crystal growth. Meteorological conditions leading to these extreme gradients were also examined, with results indicating the largest temperature gradients were associated with clear-sky conditions permitting the escape of longwave radiation from the snow surface.

The formation of a layer of near-surface facets and nearby avalanche activity was documented by Birkeland et al. (1998). They measured temperature gradients greater than 200 °C/m in the top 5 cm of the snowpack. Gradients 15-20 cm below the surface were considerably weaker. The faceted layer created by these gradients was observed to exist over a wide geographic area (on the order of 50 km). Avalanche activity on the faceted crystals was reported at various elevations and on all aspects, implying that the conditions that created this weak layer were not differentiated by topographic influences.

Hardy et al. (2000) reported observations of near-surface faceted crystals in a high elevation, tropical climate. They attributed the crystal development to unique energy balance conditions in that environment, consisting of high solar input at high elevation, low albedo snow cover, and rapid longwave cooling associated with the thin atmosphere at high altitude.

Snowmelt Processes and Wet Snow Metamorphism

Snowmelt processes, like temperature gradients and dry snow processes, have been shown to be related to the nature of the topography involved (Coughlan and Running, 1997; Carey and Woo, 1998). While melt processes are not directly temperature gradient dependent (except on the microscale), the previous temperature profile history of the snowpack combines with terrain controls to affect snow texture, and, therefore, influence spatial melt patterns (Kattelmann, 1984).

Isothermal snow is defined as snow at a temperature of 0°C in equilibrium with free, liquid water (Marsh and Woo, 1984; McClung and Schaerer, 1993). An isothermal snowpack (or any part of a given snowpack deemed isothermal) is 0°C throughout, has free water at all depths, and contributes to the snowmelt hydrograph of its given basin

(Michaels, 1983). A snowpack becomes isothermal differentially; therefore, isothermal, or ripe, snow can exist without having an entirely ripe snow*pack*.

An isothermal snowpack is the result of melt metamorphism, also called *maturing* (Colbeck, 1977), *aging*, or *ripening*. This process is initiated by the introduction of liquid water into the snowpack (either from snowmelt or rainfall), which can be distributed to the full-depth of the snowpack by the propagation of water through pore spaces and along strata within the snow structure (Kattelmann and Dozier, 1999). The movement of water within the snowpack is largely controlled by the relative texture of different snow layers (Kattelmann, 1984). Large-grained snow, like that which has been influenced by a large temperature gradient, exerts less capillary pressure on meltwater than does smaller-grained snow. At layer boundaries where small-grained snow overlies large-grained snow, meltwater may be impounded in the small-grained snow and move laterally until a suitable penetration location (i.e. smaller grains or a previously established meltwater channel) allows the water to progress downward through the snow strata. Therefore, the spatial patterns of snow temperature gradients during the winter, by exerting a control on the snow texture, can have an effect on ripening and melt runoff patterns in the subsequent melt season.

Snowpack ripening has been shown to depend on aspect, by Carey and Woo (1998). In a study in the Canadian subarctic, they found a time difference in snow ripening of 10 days between north- and south-facing slopes, and attributed this largely to differences in solar radiation receipt on these slopes.

Snow depth and snowmelt are known to vary with elevation, an effect addressed in all snowmelt models (Ferguson, 1999). In a study of snow depletion date (the date at which the snowcover is entirely melted at a given site), Coughlan and Running (1997) found a codependency on site orientation (aspect) and elevation. Furthermore, their results showed that vegetation cover was more important than aspect as a snowmelt variable, due to the vegetation effects on shortwave energy input. Snow depletion and snowpack ripening were found to share common variables, such as vegetation cover (leaf-area index) elevation, and aspect (Coughlan and Running, 1997; Carey and Woo, 1998).

The presence of vegetation above the snowcover can distort or mute topographic snowmelt effects. Coughlan and Running (1997) determined that a leaf-area index variable was the most important variable for modeling snow accumulation and melt at higher elevations. Furthermore, the type of vegetative cover is important if its effect on snow temperature and melt patterns is to be determined. Gary and Coltharp (1967) found that a spruce-fir forest type held snow 4-5 weeks longer than other tree and grassland cover types. They also noted large differences in snow depletion date based on aspect.

Hardy et al. (1990), studying logging effects, and Skidmore et al. (1994), studying fire effects, reported that snow accumulation decreased as canopy density increased, for their studies in southwest Montana. Additionally, they related canopy density to snow ablation, with high canopy densities correlating to low ablation rates, and the highest ablation rates occurring in low canopy density areas.

Avalanche Forecasting and Snowmelt Modeling

Computer-based avalanche forecasting models vary in their approach to the problem of accurate forecasting, due to the scale of forecast required and the type of data available for input. Several tools attempt to model the evolution of the snowpack structure, using high-resolution meteorologic data, such as CROCUS (Durand, et al., 1999) and SNOWPACK (Lehning et al., 1999). Temperature and temperature gradient data are critical to these models, which attempt to predict the formation of different snow crystal types in the snowpack. Since these models operate on the point scale, some estimation of temperature gradients based on terrain relationships is needed if this data is to be available for applying the models at a regional scale.

Judson et al. (1980) included a temperature gradient parameter in their "process-oriented" avalanche danger model. It was implemented in order to simulate the development of faceted crystals. The thickness of the faceted layer was then factored into the overall avalanche danger assessment.

In response to concerns about the extreme heterogeneity that troubles energy-balance snowmelt models, alternatives to purely physically based models have been proposed (Andersson, 1992; Ferguson, 1999). A combination of measured snow variables and inclusion of topographic parameters, such as aspect, as modifications to existing conceptual models could prove effective in simulating melt patterns. According to Andersson (1992), future model development should strike a balance between conceptual and physically based models, utilizing simple inputs and implicit variable representation while working at relatively high spatial and temporal resolutions.

Ferguson (1999) recommended incorporating multiple topographic variables such as elevation and aspect to enhance conceptually based models.

The ability to predict snowmelt response (including ripening patterns) depends on the understanding of the relative importance of melt-controlling variables, particularly those related to topography (Michaels, 1983). The scale used must have a sampling grid or mosaic of a size small enough to detect changes due to topographic influence. Variability of snowpack attributes such as density, grain types, porosity, and finger flow paths within grid elements must be implicit in the size of mosaic chosen (Blöschl, 1991). Field measurements should include multiple elevations, slopes and aspects, and be designed to statistically represent grid size (Blöschl et al, 1991). A model of this type could find application in many aspects of study and development in mountainous regions, "including ski development, avalanche forecasting, montane ecology and climate change" (Ferguson, 1999, p.220).

Spatial Variability

Spatial variability in the seasonal snow cover's many properties and scales has been noted. Dexter (1986) tested the observations of previous researchers involving elevational and aspect controls on depth, snow-water equivalent (SWE), temperature, temperature gradient, and density. During one field season in the Colorado Front Range, Dexter noted that high elevation, north-facing slopes remained coldest for the duration of the season. The steepest temperature gradients occurred in the early portion of the snow season, during cold air and shallow snow conditions. For the majority of the season, the low elevations held the steepest temperature gradients, likely due to shallower snow depths at these locations.

Birkeland et al. (1995) examined spatial variation in snow resistance on single slopes. They found that while snow depth and average temperature gradient were important in determining snow resistance, these variables were in turn controlled by complex relationships with wind, vegetation, and microtopography.

Variability in SWE was shown to change with elevation (Ingersoll et al., 1996), with high elevation sites showing dramatically more spatial variation than lower, forested sites. Based on their results, they suggest dividing the basin into zones of similar terrain, thereby enabling different sampling schemes based on the anticipated level of variation in the snowcover for each zone.

Elder et al. (1998) used a regression tree analysis to estimate the spatial variability of SWE in an alpine basin. They found deepest snowpacks on high elevation, north-facing slopes. Additionally, sites receiving highest net radiation input had lower snow depths. They also found a slope threshold at around 37° that separated higher and lower accumulation zones.

Conway and Wilbour (1999) addressed temporal variation in snow stability with their stability index model by including the rate of snow accumulation. It was recognized, however, that complex interactions between wind and topography made accurate accumulation predictions difficult.

Birkeland (2001) considered spatial variation in snow stability over the mesoscale, comparing terrain, snowpack, strength, and stability data. Results were mixed, showing different relationships between sampling days, which was attributed to differing weather patterns. Observed spatial patterns at the regional scale were confounded by microscale variations in snowcover properties, attributed to terrain fluctuations. However, some generalizations were possible, indicating a differing degree of predictability based on the appropriate scale of observation.

The research cited above represents most of the efforts addressing spatial variation in various snow properties. In all cases, relationship with or dependence on topography was addressed or noted. While Dexter (1986) is the only study specifically addressing temperature gradients, it can be inferred that since topographic effects are important influences on the spatial variation in snow properties, spatial patterns of snow temperature gradients must also be influenced by topography to some degree.

Scale Issues

Issues of scale are inherent in studying snow processes. Small areas studied in detail may exhibit extreme heterogeneity, while larger areas studied in less detail may allow for identification of patterns and homogeneity (Blöschl, 1999). A more accurate understanding of the processes of interest, however, would integrate several scales of observation, including the linkages between the scales (Hägeli and McClung, 2000). To study the geography of snowpack temperature gradients within a given basin, the scale of observation must be of sufficient detail or resolution to measure differences in inputs (i.e. elevation, aspect, slope, or snow depth) yet of low enough resolution to exclude microscale effects such as grain size and type differences, small variations in water flow paths, density horizons, and differences in porosity. In other words, topographic effects must be addressed explicitly, while heterogeneity in the microscale must be implicit in the size of the observational unit chosen (Blöschl et al, 1991).

The relationship between microscale snow structure, macroscale climatic factors, and mesoscale avalanche formation has been examined (Armstrong, 1977; Jamieson and Johnston, 2001). They observed the importance of including microscale snow information in response to observations of nonlinear interactions between weather patterns and avalanche formation, with the size of avalanche showing little correlation to the size of precipitation event.

Temperature gradient data is categorized as Class II (snowpack) data, of intermediate level entropy between Class III (meteorologic data) and Class I (snow stability data) (McClung and Schaerer, 1993). Therefore, temperature gradient data, which are point data, could only be applied at one scale of observation and analysis (the scale at which they are measured) unless a scaling factor is applied (Blöschl, 1999; Hägeli and McClung, 2000). Topographic data, however, spans several scale orders, and thus holds potential as a scaling factor, if a relationship between temperature gradients and topography can be known.

METHODS

In order to assess spatial variability in snow temperature gradients, some measure of that variability had to be obtained. This required a study site with a wide variety of potential sample locations, as well as easy, consistent access. Additionally, a method of sampling was needed that enabled rapid data collection and portability of measuring devices from site to site. Once the spatial dataset was obtained, correlation and regression procedures were applied. Finally, weather data collected within the study area were qualitatively analyzed to explain some of the regression relationships developed.

Study Area

The study area used for this project is a mountain basin referred to as Wolverine Basin, in the Bridger Mountains of southwest Montana (Figure 1). The basin is located roughly one kilometer north of Bridger Bowl Ski Area, 15 miles north of Bozeman. This study area was chosen for several reasons, but of first consideration was ease and safety of access. The Bridger Bowl Ski Patrol provided ski lift access and authorized crossing the northern ski area boundary. This accessibility facilitated installation of the weather instrumentation, promoted safety for the data collectors, and allowed a higher frequency of collection dates than would be possible with a more remote site. Second, the study area provided a variety of slopes, aspects, and elevations as required for this project. Third, other researchers were using this area and adjacent sites, providing both a margin of safety as well as opportunities for collaboration in data collection efforts.

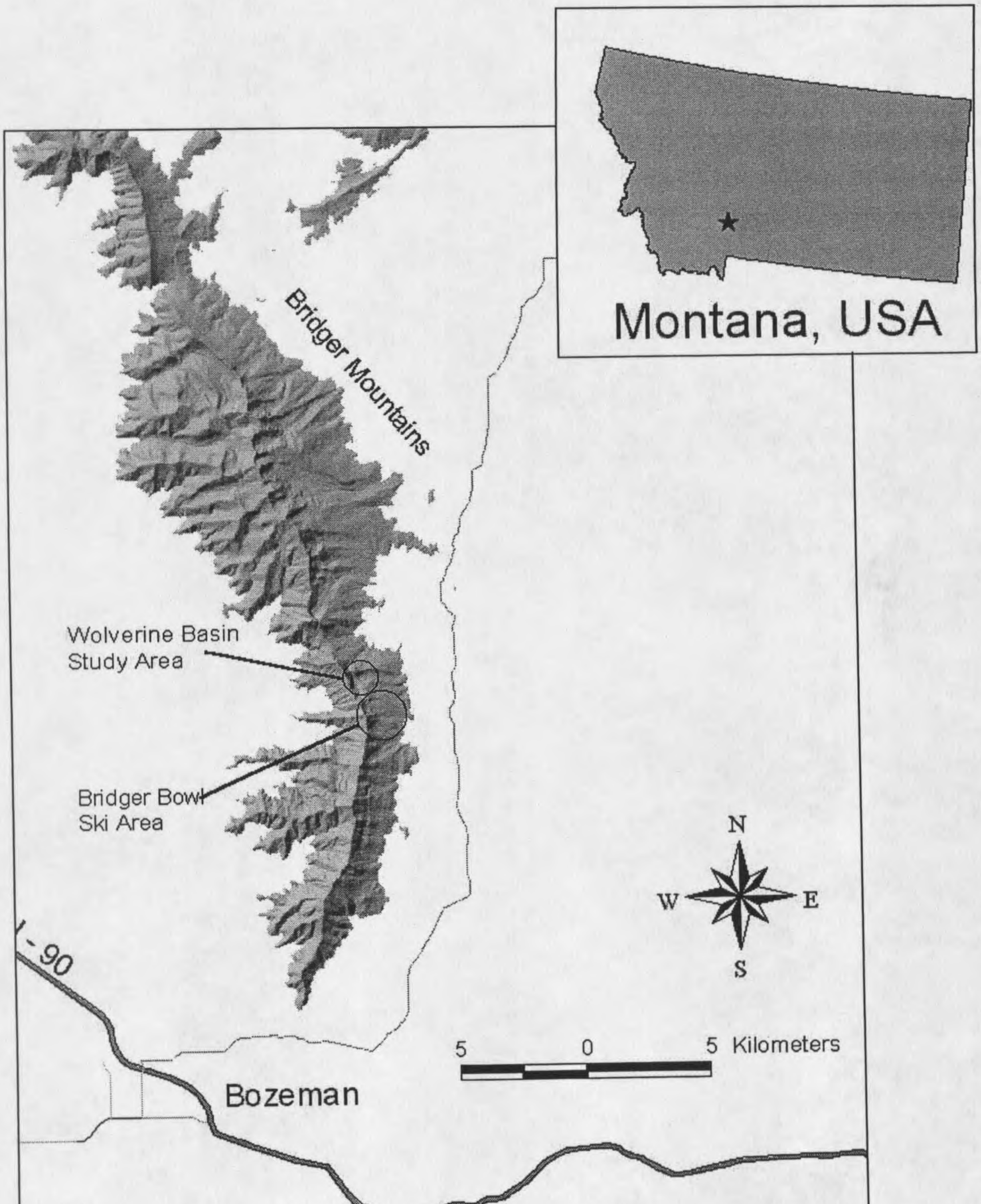

Figure 1: Wolverine Basin, in the Bridger Mountain Range, Southwest Montana, USA.

The Bridger Mountains are in an intermountain snow climate (Mock and Birkeland, 2000), often exhibiting characteristics of both continental and maritime snow climates. Lowest air temperatures generally occur December through February, and maximum precipitation and snowfall typically occur in February and March (Table 1).

Table 1: Bridger Bowl Ski Area weather data summary, 1968-1995 (WAN, 1995)

	Maximum Daily Air Temperature (°C)	Minimum Daily Air Temperature (°C)	Average Daily Air Temperature (°C)	Average Monthly Snowfall (m)	Average Monthly Precipitation (mm)
November	0.0	-7.4	-3.8	1.22	107.4
December	-4.9	-19.1	-12.0	2.68	168.3
January	-3.2	-10.9	-7.1	2.88	178.9
February	-1.1	-10.0	-5.7	2.99	204.6
March	1.5	-7.9	-3.2	3.50	252.9
Total				13.26	912.1

Instrumentation

Probe Design

I designed the Snow Temperature Profile Probe (STPP) to enable rapid sampling of a large number of temperature profiles with minimal site disturbance. A direct digital interface was desired to speed up sampling and to ease data transfer and processing. The final design was lightweight and field portable, and was interfaced with a handheld, personal computer.

The probe was 2.3 m long, constructed of clear polycarbonate plastic, with an aluminum cutting tip for snowpack penetration. Direct-to-digital temperature-sensing chips (Dallas Semiconductor DS18s20) extend through the plastic at 10cm intervals, beginning at 10cm from the ground surface, and continuing up the probe to 2 meters from the cutting tip. The interior of the probe was filled with white foam beads, in order to insulate each sensor from internal temperature conduction by minimizing air circulation and solar input. The chips were wired to a processing unit (Spiderplant Corp., Waltham, MA), which communicates directly with the handheld PC.

Computer Interface

The temperature sensor processing unit required a serial port interface (RS-232) to communicate with any platform compatible with that protocol. For the purposes of this project, I chose a Compaq iPAQ 3650 for field use due to its size and programming versatility. I designed a program in Visual Basic for Applications in MS Excel (Microsoft Corp., Seattle, WA) to communicate with the probe device. The program prompted the user for manually measured variables, including site number, snow depth, snow surface temperature, air temperature, and any additional comments. It then commanded the probe unit to sense temperatures, read data from the probe, and wrote the data to a text file. The data text file was then available to import into a spreadsheet for data processing.

Probe Testing and Calibration

The accuracy of the probe was critical to the interpretation and analysis of the field data. To this end, it was necessary to calibrate the probe sensors in two respects: accuracy of the measured temperatures and time required for equilibration. The measurement accuracy had a direct effect on the reliability of the field data, while the equilibration time was necessary for development of the sampling routine.

The STPP was calibrated in an ice bath at 0°C. This was accomplished by the construction of a shallow trough made of PVC drainpipe. The trough was filled with ice water, measured with dial-stem and digital thermometers to be at or very near 0°C. While the trough was being filled, the probe was allowed to equalize to the ambient air temperature outdoors, approximately -3°C. The probe temperatures were continuously logged during equilibration and testing.

Once the trough was filled and the probe equalized to air temperature, the probe was inserted in the trough, with the individual sensors immersed in the ice bath. The insertion time was noted. The probe was allowed to remain in the bath for a full 20 minutes.

I analyzed the log file for equilibration temperatures and time to equilibration. The final, stable temperatures were noted, so that they may be used to adjust the readings from the field datasets. It was determined that the sensors equilibrated to within 0.1°C of the final stabilization temperature within 3 minutes of immersion (Figure 2).

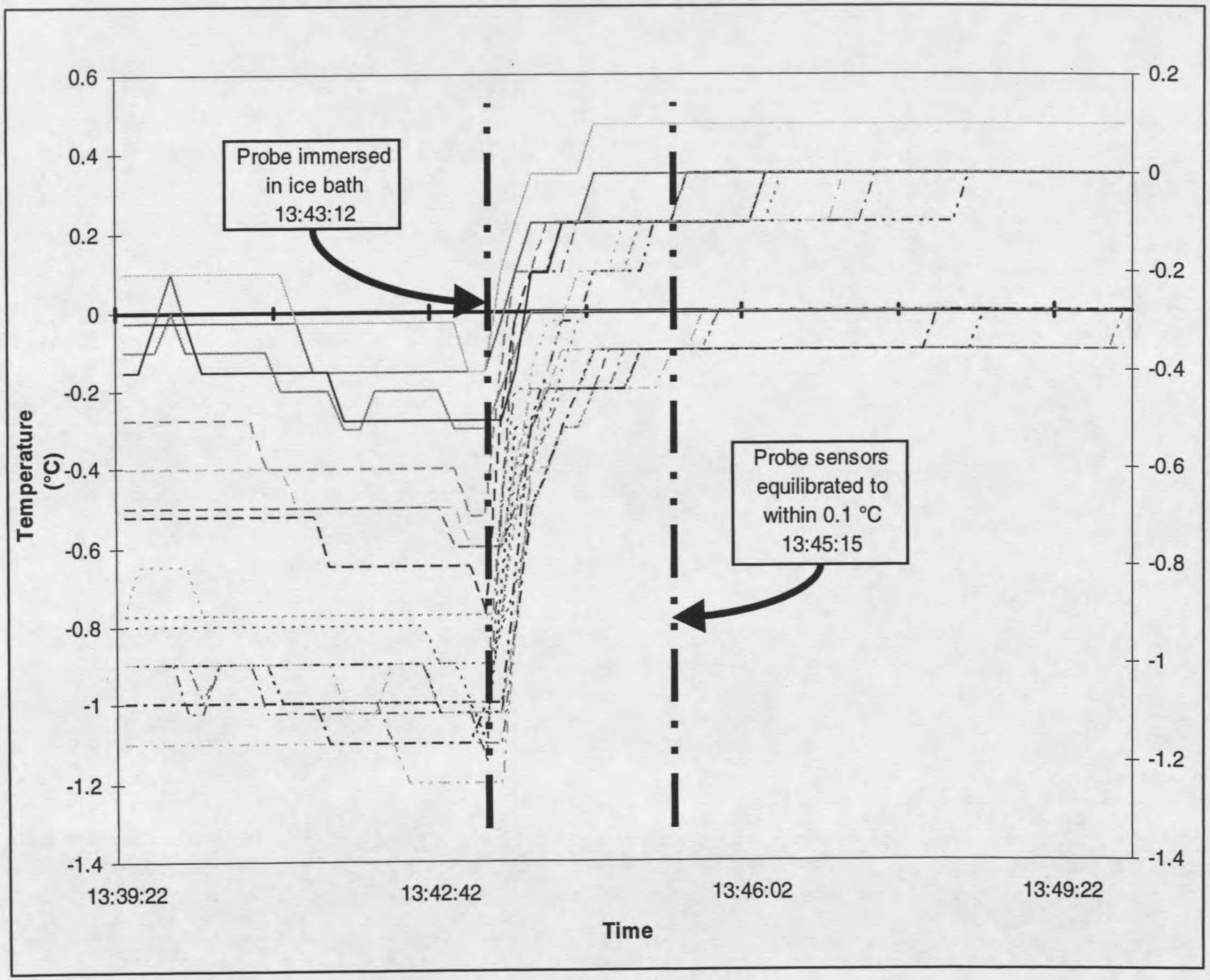

Figure 2: Temperature Probe calibration data. Each plot line represents a single temperature sensor.

Use of the Probe

The point sampling routine using the STPP was as follows: First, the probe was inserted into the snowpack perpendicular to the snow surface. It was inserted in this manner in order to permit sampling of a full profile over the widest possible range of snow depths, as well as to sample temperatures along the shortest path to air. Second, while the probe sensors were equilibrating, the user entered manual measurements of snow depth, snow surface temperature, and air temperature. Once sufficient time had elapsed for sensor equilibration, the computer was instructed to log the probe data. The entire routine required about 3-5 minutes to complete for each individual measurement site.

Weather Instrumentation

The weather station used in this project was located in the center of Wolverine Basin, in a low-angle (ca. 2° SE) clearing at an elevation of 2240 meters. This site has been used for weather data collection in the past (Lundy et al, 2000).

The weather station measured wind speed, snow surface temperature, snow depth, reflected shortwave radiation, and a full-depth snow temperature profile. The data was logged using a Campbell Scientific CR10X Datalogger (Campbell Scientific Corp., Logan, UT). The station collected data at 5-minute intervals, and output averages once per hour. This sampling rate effectively covered the sample dates of this study, enabling an analysis of weather phenomena as related to snow temperature gradients.

Field Data Collection

Sampling Design

Of concern in the design of a sampling routine was the number and location of sampling points, frequency of repetition, order and efficiency of collection, and safety of field personnel. These issues were addressed in the design phase of the project.

A large sample size representing a variety of topographic variables was desired for statistical purposes, as indicated by the results of a pilot study. Additionally, the sample point distribution needed to approximate the distribution of available sites in the field area. This was assessed by comparing the distribution of terrain characteristics in the set of sample points to the distribution of terrain characteristics in the basin.

Safety was of primary concern in the sampling design, as there were numerous avalanche slopes within the study area. Sites which had slope values over 30 degrees or those which possessed a high exposure to avalanche danger (e.g. in a confined runout path) were omitted from sample consideration.

The sampling route (Figure 3) was designed for once weekly repetition. Data from all sample points was collected each field day. This approach attempted to maintain a continuity of data collection throughout the season as well as sample the full range of topographic variables on a single day. Thirty points were selected in the effort to balance all of the above factors, and their positions were recorded by a differentially corrected Global Positioning System (GPS) unit. Topographic attributes for the sample points (Table 2) were calculated from a USGS 30m DEM, using ArcView GIS software with the Spatial Analyst extension (ESRI, Redlands, CA). *Profile* was the profile curvature, or