Seasonal snowpack characteristics influence soil temperature and water content at multiple scales in interior western U.S. mountain ecosystems

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Key Points

- Soil temperature and moisture data were examined for western U.S. mountains.
- Seasonal snowpack characteristics influence the soil environment.
- This has potential impacts for ecosystems and biogeochemical processes.

Abstract

Mountain snowpacks directly and indirectly influence soil temperature (T_{soil}) and soil water content (θ). Vegetation, soil organisms, and associated biogeochemical processes certainly respond to snowpack-related variability in the soil biophysical environment, but there is currently a poor understanding of how snow-soil interactions vary in time and across the mountain landscape. Using data from a network of automated snowpack monitoring stations in the interior western U.S., we quantified seasonal and landscape patterns in T_{soil} and θ, and their dependence on snowpack characteristics over an eleven year period. Elevation gradients in T_{soil} were absent beneath winter snowpacks, despite large gradients in air temperature (T_{air}). Winter T_{soil} was warmer and less variable than T_{air}, but interannual and across-site variations in T_{soil} were likely large enough to impact biogeochemical processes. Winter θ varied between years and across sites, but during a given winter at a site it changed little between the start of snowpack accumulation and the initiation of spring snow melt. Winter T_{soil} and θ were both higher when early-winter snow accumulation was greater. Summer θ was lower when summer T_{air} was high. Depending on the site and the year examined, summer θ was higher when there was greater summer precipitation, a larger snowpack, later snowpack melt, or a combination of these factors. We found that snowpack-related variability in the soil environment was of sufficient magnitude to influence biogeochemical processes in snow-dominated ecosystems.

Keywords

snow hydrology; SNOTEL network; soil microbial community; soil moisture; winter biogeochemistry

Introduction

Snowfall is the dominant hydrologic input to the mountain watersheds of the western U.S., making up 40–70% of annual precipitation [*Serreze et al.*, 1999]. Winter snowpacks persist for a large portion of each year and are primary controllers of the energy and water balance of soils in the region. Snowpack effects on soil temperature and water content directly and indirectly influence vegetation, soil microbial communities, and associated biogeochemical processes during the cold season and the warm season [*Lipson et al.*, 2002; *Monson et al.*, 2006b; *Litaor et al.*, 2008]. The western U.S. experiences high interannual and spatial variability in snowpack size, duration, and melt timing, but at present, there is no comprehensive understanding of how this variability influences the soil environment.

The rates of many biogeochemical processes vary with temperature and moisture. Studies of soil carbon cycling across elevation gradients, for example, have found that changes in soil respiration, rates of organic matter decomposition, and the storage of soil carbon are linked to soil temperature and moisture [*Amundson et al.*, 1989; *Trumbore et al.*, 1996; *Conant et al.*, 2000; *Kueppers and Harte*, 2005]. Despite colder temperature, these and other ecologically important processes occur beneath winter snowpacks. Below-snowpack soil respiration accounts for anywhere from ~12% to 50% of the annual carbon dioxide loss in ecosystems with persistent winter snowpacks [*Liptzin et al.*, 2009]. In addition, decomposition [*Hobbie and Chapin*, 1996; *Williams et al.*, 1998; *Kueppers and Harte*, 2005; *Baptist et al.*, 2009], nitrogen mineralization and immobilization by microbial communities [*Brooks and Williams*, 1999; *Grogan et al.*, 2004; *Schimel et al.*, 2004; *Kielland et al.*, 2006], and the production and consumption of greenhouse gasses such as methane and nitrous oxide [*Sommerfeld et al.*, 1993; *Mast et al.*, 1998; *Schurmann et al.*, 2002; *Groffman et al.*, 2006; *Filippa et al.*, 2009] all occur beneath seasonal snowpacks. Winter snowpack characteristics can influence soil temperature in ways that alter soil carbon cycling during the warm season [*Nowinski et al.*, 2010]. It is unknown how much these biogeochemical processes vary in time and space due to a poor understanding of how snowpacks influence the temperature and moisture environment of soils.

The energy and water balance of the soil surface changes dramatically beneath a snowpack. Because snow has high shortwave albedo and low thermal conductivity, snowpacks decouple soil energy exchange from the radiative and thermal environment at the snowpack surface [*Sturm et al.*, 1997; *Grundstein et al.*, 2005]. During winter, this slows cooling of soil through radiative, sensible, and latent heat exchange, and when energy availability increases in the spring, it slows warming of the soil by the same processes [*Sokratov and Barry*, 2002; *Bartlett et al.*, 2004; *Zhang*, 2005]. Snowpacks temporarily store water, thereby isolating soil from winter precipitation until sufficient energy is available to melt snow and deliver water to soils, streams, or the subsurface [*McNamara et al.*, 2005; *Hamlet et al.*, 2007; *Williams et al.*, 2009; *Bales et al.*, 2011]. Winter precipitation can be lost through sublimation or redistributed by wind, vegetation interception, topographic effects, and lateral water movement through the snowpack [*Daly et al.*, 1994; *Clark et al.*, 2011; *Ohara et al.*, 2011; *Eiriksson et al.*, 2013]. The impact of these processes on soil temperature and moisture varies depending on snowpack size, distribution, duration, and other snowpack and climate characteristics. Because the interannual and spatial variability in snowpack characteristics and climate are high in the western U.S., it is likely that soil temperature, soil moisture, and associated biogeochemical processes will be highly variable in response.

Numerous studies have identified declining trends in snowcover extent, duration, and snowpack size in the western U.S. [*Hamlet et al.*, 2005; *Mote et al.*, 2005; *Mote*, 2006; *Dyer and Mote*, 2007]. Model projections tend to agree that these trends will continue and intensify in the coming century [*Brown and Mote*, 2009; *Seager and Vecchi*, 2010]. Although observed changes have been most pronounced for maritime climates, snowpack changes have also been reported in the interior western U.S. [*Clow*, 2010; *Nayak et al.*, 2010; *Harpold et al.*, 2012]. Researchers have found trends toward earlier spring runoff timing [*Dettinger and Cayan*, 1995; *McCabe and Clark*, 2005; *Stewart et al.*, 2005; *Hamlet et al.*, 2007] and a larger proportion of precipitation falling as rain instead of snow [*Hamlet et al.*, 2005; *Regonda et al.*, 2005; *Knowles* *et al.*, 2006; *Gillies et al.*, 2012]. Climatic phenomena that influence snowpack size, distribution, and duration are linked to perturbations of ecosystems and human communities in this area, such as widespread increases in wildfire [*Westerling et al.*, 2006], drought [*Cayan et al.*, 2010], tree mortality [*Anderegg et al.*, 2011], and insect outbreaks [*Logan et al.*, 2010]. Understanding the relationships between climate, snowpack variability, and the soil environment is critical to predicting how ecosystems and biogeochemical processes will respond to future changes in climate.

Here we examine the extant variability in soil temperature and water content in the mountains of the interior western United States and how it is influenced by seasonal snowpack size, environmental conditions during snowpack accumulation, and melt timing. Our study area has a continental climate with cold winters, a seasonal precipitation pattern, and variable winter snowpacks. Sites with maritime climates, which are warmer and have more frequent late winter/early spring snowpack melt and rain-on-snow events [*Knowles et al.*, 2006; *Mote*, 2006; *Kapnick and Hall*, 2012], were deliberately excluded from our analysis because we expect them to have different snowpack, soil temperature, and soil moisture dynamics. This study takes advantage of a long-term dataset collected by the USDA Natural Resources Conservation Service (NRCS) Snowpack Telemetry (SNOTEL) network. We examine the following hypotheses:

1. There are no elevation gradients in soil temperature when seasonal snowpacks are present.
2. Soil temperature is dependent on snowpack characteristics such as snowpack size and the timing of accumulation.
3. Winter soil moisture a) changes minimally between the start of snowpack accumulation and the initiation of snowpack melt and b) is dependent on fall and early-winter conditions.
4. Warm season soil moisture is dependent on snowpack size and the timing of snowpack melt.

We show that snowpack-related variability in soil temperature and moisture is of sufficient magnitude to influence soil biological activity, and we discuss the relevance of this complex biophysical environment for ecosystems and biogeochemical processes.

Methods

Study area and sites description

The SNOTEL network is composed of automated stations located in middle to upper elevation basins throughout the western U.S. Data and maps of SNOTEL site locations are available on the NRCS SNOTEL website (http://www.wcc.nrcs.usda.gov/snow/). This network's purpose is to forecast water supply in regions where snowfall makes up a significant portion of annual precipitation. Our study area includes all sites in Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, and Wyoming (574 stations—which we refer to as all sites). We excluded all SNOTEL stations in coastal states (CA, OR, WA) because they include mountain ranges with a maritime climatic influence that is distinct from the climate of the interior western U.S. Typically, SNOTEL stations are located in natural or artificial clearings within forested areas and do not span the entire topographic range of the watersheds in which they are operated. Our results, therefore, do not fully represent watershed-scale hydrological processes.

The standard set of SNOTEL measurements includes snow water equivalent (SWE, snow pillow), accumulated precipitation (storage gauge), snow depth (ultrasonic depth sensor), and air temperature (T_{air}, naturally ventilated extended range thermistor). Instrument specifications for these measurements are documented in the NRCS Snow Survey and Water Supply Forecasting National Engineering Handbook [*Service*, 2010]. In our 8-state study area, a subset of 252 stations (which we refer to as soil sites) were equipped with sensors (Stevens Hydraprobe I and II, Stevens Water Monitoring Systems, Inc., Portland, OR, USA) that monitor vertical profiles of soil temperature (T_{soil}) using integrated thermistors, and soil volumetric water content (θ) using a calibrated measurement of soil dielectric permittivity. The calibration equations used to determine T_{soil} and θ are the same for all sensors and soil types [*Seyfried et al.*, 2005] and are not updated after sensors are installed (Tony Tolsdorf, NRCS, personal communication). The instrument uncertainties for temperature and water content measurements are specified at ± 0.26 °C and 3.4%, respectively [*Seyfried et al.*, 2005; *Bellingham and Fleming*, n.d.]. Because the dielectric properties of ice and liquid water are different, measurements of θ decline sharply as soil water enters the solid phase [*Spaans and Baker*, 1996]. We did not correct for this effect. The number and placement of soil sensors varied among the soil sites, so we used only data from sensors at 5, 20, and 50 cm below the top of the mineral soil horizon for consistency. Soil sensor profiles were typically located within 20 m of the location of the standard SNOTEL instrumentation.

Our study sites spanned a range in elevation from 875 to 3542 m (Figure 1a), in mean annual temperature from -2.8 to 11.3 °C (Figure 1b), and in latitude from 32.9 to 49.0 °N (data not shown). For the period from 2001 to 2011 (inclusive), these sites had a broad range in snowpack size, snowpack start day, snow-free day, and other climatic variables (defined below, see Figure 1). Statistics for snowpack characteristics and selected climatic variables for our study sites during the 2001 to 2011 period are shown in Table 1.

Data processing

We examined hourly T_{soil} and θ data for all available years through 2011 from the soil sites. On average, there were 6.3 years of soil sensor data at these sites. We also examined daily measurements of SWE, precipitation, and air temperature at all sites for the years 2001 to 2011, or for longer periods in cases where the soil sensor record extended to before 2001 (mean = 10.1 years).

The USDA/NRCS provides limited maintenance and quality assurance of the data from SNOTEL soil sensors. For this reason, we created our own quality assurance procedures that excluded a large amount of problematic data. Measurements flagged as errors by the datalogger were removed and files with irregular measurement times (other than hourly) were excluded from analysis. Each individual sensor time series was then plotted and visually screened to identify and remove problematic data. When T_{soil}, θ, SWE, or T_{air} data were more than three standard deviations from the moving-window mean (24h window for hourly data, 10d for daily data) of a time series, they were classified as outliers and removed. Because soils have a broad range of textural and hydraulic properties, soil θ measurements were not directly comparable between individual sensors. To facilitate comparison across all sensors and sites, θ data for each sensor were normalized linearly according to its full observed range of values (lowest = 0, highest = 1). These procedures are documented, with examples and summary data, in Appendix A.

Following the quality assurance steps above, we calculated a number of statistics from each time series. The mean and standard deviation of T_{air}, SWE, T_{soil}, and θ were calculated for months and quarters (3-month means of OND, JFM, AMJ, and JAS) at all sites. We calculated accumulated precipitation for each warm season month (M, J, J, A, or S), and for the summer quarter (JAS). Time series of SWE were used to calculate several snowpack metrics. Peak SWE was calculated as the maximum SWE during a water year. Snowpack start day was the first day of persistent snow cover (> 5mm of SWE lasting 2 or more days) after Oct 1. Snow-free day was the first snow-free day following the day that peak SWE occurred. Total snow-covered days was the number of days with > 5mm of SWE. For the below-snow period between the snowpack start and snow-free days, we calculated the mean and standard deviation of T_{soil}, θ, and T_{air}. Finally, we calculated presnowpack T_{soil}, θ, and T_{air} for each water year, defined as the mean of each quantity during the 2-week period immediately prior to snowpack start day. When calculating any of the values above from these time series, time periods missing more than 5% of data (~28% of all calculations) were excluded.

Hypothesis testing

We examined both interannual and intersite variability in the quantities described above, and used both types of variability to test our hypotheses. Interannual variability refers to variation in a measured quantity over multiple years at one site. To test a hypothesis using interannual variability, we performed least-squares linear regression using all years of data from a site. We then repeated the same test for every site and summed the number of sites with significant relationships ($p < 0.05$). To test whether the slopes of these relationships were significant in the aggregate, we fit a multilevel linear model to data from all sites using site as a random variable.

Intersite variability refers to variation in a measured quantity across sites during one or multiple years. When a hypothesis involved clear two-variable relationships across sites, we used simple linear regression (e.g., temperature-elevation gradients or across-site relationships between soil θ at two time periods). Hypotheses involving intersite relationships between more than one explanatory variable were tested using a combination of principal component analysis (PCA) and multiple regression.

As is common with environmental data, many of our explanatory variables were correlated, which makes interpretation of multiple regression results unreliable. To overcome this limitation, we performed two PCAs, one for the below-snow period and one for the warm season. These used our calculated snowpack, soil, and climate statistics (see section 2.2 for a description) as explanatory variables to produce a number of new, uncorrelated principal component axes. All observations in our dataset then received a score for each axis. We used these scores as explanatory variables in multiple regression analysis of observations from all years together and subsets of individual year observations (2007, 2009, and 2011). These tests added statistical support for some hypotheses beyond that found using linear regression. A brief summary of the PCA results and our interpretation of the axes will be given in section 3.6. A detailed description of PCA and multiple regression methods and results is presented in Appendix B.

Hypothesis 1

We examined elevation gradients in T_{soil} and T_{air} using simple linear regression with data from all soil sites. To minimize the influence of latitude or continental location, we also performed the analysis with a geographically constrained subset of sites (Utah). The elevation gradients (slopes of the regressions) were examined for January and July.

Hypothesis 2

Interannual relationships between mean below-snow T_{soil} and several explanatory variables, including snowpack characteristics (Table 2), were examined using simple linear regression at each individual site, and a multilevel linear model to test slope significance for all sites together. We tested the significance of intersite relationships between these variables using multiple regression, with mean below-snow T_{soil} (in individual years, and all years together) as the dependent variable and below-snow principal component axes as explanatory variables.

Hypothesis 3a

We examined within-year variation in below-snow soil θ using two metrics. First, we quantified the month-to-month changes in mean soil θ from October to May at every soil site, in every available year. Second, we calculated the cumulative change between presnowpack soil θ and mean monthly θ in October through May.

Hypothesis 3b

To test this hypothesis we used simple linear regression between mean winter quarter (JFM) θ and the same explanatory variables used for Hypothesis 2 (Table 2) at each site. We used a multilevel linear model to test slope significance for all sites together. We also used multiple regression with below-snow principal component axes (Table 3) as explanatory variables.

Hypothesis 4

We tested this hypothesis using simple linear regression of summer quarter (JAS) θ versus a number of warm season variables and snowpack characteristics (see Table 4) at each site. We used a multilevel linear model to test slope significance for all sites together. We also used multiple regression with warm season principal component axes (Table 3) as explanatory variables. As an additional test for intersite differences in summer quarter θ, we compared groups of sites with high and low elevation (a proxy for air temperature), SWE, and summer rainfall. Sites in high summer rainfall groups received greater than 20% of total annual precipitation during the summer quarter (JAS). High and low thresholds for SWE and elevation were selected above and below the mean for all sites, at a value that allowed greater than seven sites in each group.

Results

Snowpack and the soil environment at one site

To illustrate the relationships between snowpack characteristics, T_{soil}, and θ, we highlight multiple years of observations at Currant Creek, Utah. In Figure 2a, ten consecutive 1-year time series of SWE are plotted on a common time axis. Despite similarities in the shape of the SWE hydrographs, there were large interannual differences. Total snow-covered days ranged between 133 and 185 days. Snowpack start day ranged between 22 October and 1 December, and snow-free day ranged between 1 April and 11 May (both varied by ~40 days). Peak SWE ranged between 96 and 400 mm. The data in Figure 2b illustrate the interannual variability and within-year stability of below-snow T_{soil}. Mean below-snow T_{soil} across years ranged between -0.5 and 2.3 °C. Below-snow T_{soil} varied little within any given year even though T_{air} consistently dropped far below 0 °C in December through February (data not shown). During the coldest year in the record (2010), T_{soil} dropped to almost -5 °C during December and remained well below 0 °C for most of the remainder of winter. The transition to springtime warming of the soil began at the snow-free date, and in some years this occurred after mean T_{air} had climbed above 0 °C. The beginning of spring soil warming varied between years by ~40 days (Figure 2b). Below-snow θ changed little until the spring melt began, even as large amounts of precipitation accumulated in the snowpack (Figure 2c). There are exceptions to this, however. In 2010 below-snowpack θ dropped to near zero during the cold soil event described above. This and similar events may indicate the freezing of soil water. Winter quarter θ at the site had high interannual variability, ranging between 3 and 23% (θ not normalized here). In a given year, peak θ coincided roughly with the snow-free date and then declined over the next 2 months. The timing of peak θ varied between years by ~40 days.

Change in temperature with elevation

In the warm season (July), both T_{soil} and T_{air} declined with elevation across all sites, but in January the T_{soil} elevation gradient was absent (Hypothesis 1; Figure 3a, b). Results were similar when sites were geographically restricted (Utah, Figure 3c, d). The Utah sites had a July T_{soil} (20 cm depth) elevation gradient of -4.2 °C/km (Figure 3c, $p < 0.001$), which was slightly smaller than the July T_{air} gradient (Figure 3d, -5.0 °C/km, $p < 0.001$). In January the T_{soil} elevation gradient for the Utah sites was minimal, but statistically distinguishable from no relationship (-0.7 °C/km, $p < 0.001$), while a gradient in T_{air} remained (-2.9 °C/km, $p < 0.001$). The difference between T_{soil} and T_{air} ($T_{soil} - T_{air}$) during January increased with elevation (2.0 °C/km, $p < 0.01$) in both groups of sites (data not shown).

Stability of winter soil moisture

Once a snowpack accumulated, there were only small month-to-month changes in normalized soil θ (averaged across all sites) until the snowpack began to melt (Hypothesis 3a; Figure 4). Between October and November, monthly mean θ increased by ~0.1 (normalized units, dimensionless). There was a slight decline in θ of surface soils (5 and 20 cm depths), possibly due to soil freezing, between November and December, followed by little month-to-month change from December to February. There was an increase in θ again in March (Figure 4a). Cumulative changes in mean winter month θ were small (Figure 4b), increasing, on average across all sites, by less than 0.25 (normalized units) between the presnowpack period and March.

Interannual variability in below-snow soil temperature

Interannual variability in below-snow T_{soil} was related to snowpack characteristics (Hypothesis 2). During water year 2005 at the Mosby Mountain site (Utah, Figure 5), for example, a large snowpack accumulated early and T_{soil} never dropped below 0 °C. In contrast, during water year 2010, the snowpack accumulated slowly and was thin during the early-winter. This allowed the soil to cool, and T_{soil} remained well below 0 °C for most of the winter. Similar occurrences of low below-snow T_{soil} (< 0 °C) during years with small early-winter snowpacks were widespread in our study area (Figure 6).

Mean below-snow T_{soil} was warmer in years when mean November, December, and January SWE were higher (Figure 7a, one site for December; Table 2, all significant results, January data not shown), and when mean T_{air} during the below-snow period was higher (Table 2). These relationships, however, were only significant at 23–42 sites, depending on soil depth (Table 2). At some sites, T_{soil} was positively correlated with snowpack start day and below-snow period T_{air} (12–15 sites, Table 2), meaning later snowpack accumulation or warmer winter weather was associated with warmer T_{soil} at those sites. The multilevel linear model (Table 2) and multiple regression (section 3.6) provided additional statistical support for some of these relationships.

Interannual variability in soil moisture

Interannual variability in winter quarter soil θ was dependent on fall and early-winter snowpack conditions (Hypothesis 3b). At 19–53 sites (depending on soil depth), mean winter quarter θ was higher in years when mean November, December, or January SWE were higher (Figure 7b, one site for December; Table 2, all significant results, January data not shown). Some sites had higher winter quarter θ in years with a later snowpack start day (12–16 sites, Table 2). Winter quarter θ was also positively related to winter T_{air} at around 6–14 sites and to peak SWE at around 6–16 sites (depending on depth of θ measurements, Table 2).

Interannual variability in summer quarter θ was dependent on summer precipitation, snowpack characteristics, and summer air temperature (Hypothesis 4). At 7–26 sites (depending on soil depth), mean summer quarter θ was higher in years with greater summer quarter precipitation (One site shown in Figure 7c; Table 4, all significant results). This relationship was significant most often at the 5 cm measurement depth (26 sites). Summer quarter θ was also higher in years with greater peak

SWE at 11–21 sites (depending on soil depth), but this relationship was significant more often at the 50 cm measurement depth (21 sites, Table 4). At some sites (9–16 sites, soil depth dependent), summer quarter θ was higher in years with a later snow-free date, and lower in years with warmer summer T_{air} (Table 4). Again, multilevel linear models and multiple regression added statistical support to some of these relationships (Tables 2 and 4, section 3.6).

Intersite variability in soil temperature and water content

There was high intersite variability in below-snow T_{soil}, winter quarter soil θ, and summer quarter soil θ in our study area. Mean January T_{soil}, for example, had a range of 11 °C across the soil sites, about half the range in mean January T_{air} (Figure 8). To test whether intersite differences in these variables were related to snowpack and other climatic variables across our study sites, we used multiple regression analysis with PCA scores as the explanatory variables. Detailed PCA and multiple regression results are presented in Appendix B, but we summarize these results here and in Table 3.

The first four principal component axes from our below-snow PCA were significant as explanatory variables for mean below-snow T_{soil} and winter quarter θ (20 cm depths) in multiple regression analyses (Hypotheses 2 and 3b; Table 3). Based on their explanatory variable loadings (Table B.2), we interpreted these axes as the spring snowmelt axis (PC1), the winter temperature axis (PC2), the snowpack start temperature axis (PC3), and the fall snow/soil axis (PC4). Mean below-snow T_{soil} was significantly higher at sites with warmer winter T_{air} (PC2) and warmer presnowpack T_{soil} and T_{air} (PC3). Sites with warmer presnowpack temperatures tended to be those with an early snowpack start day (Table B.2). Below-snow T_{soil} was also significantly warmer at sites with higher early-winter SWE accumulation (PC1 and 4). Mean winter quarter θ was significantly higher at sites with warmer winter T_{air} (PC2), but unlike T_{soil}, it was lower at sites with warm presnowpack T_{soil} and T_{air}. Winter quarter θ was significantly higher at sites with greater October and November SWE and sites with higher presnowpack θ (PC4). Some of these axes were not significant when individual years of data were tested with these multiple regression models.

The first three principal component axes from our warm season PCA (testing Hypothesis 4) were significant explanatory variables for mean summer quarter θ (20 cm; Table 3). We interpreted these axes (Table B.6) as the summer T_{air} axis (PC1), the spring snowmelt/summer precip axis (PC2), and the winter T_{soil} axis (PC3). Mean summer quarter θ was significantly lower at sites with warmer summer T_{air} (PC1). Summer quarter θ was significantly higher at sites with greater warm season precipitation, higher peak SWE, and later snow-free date (PC2 and 3). Again, the significance of some of these axes changed when individual years of data were used in the model. Some explanatory variable loadings for the warm season PCA changed between individual years (Table B.6).

Examination of summer quarter soil θ distributions (Hypothesis 4) revealed differences between groups of sites with high and low elevation, SWE, and summer rainfall (Figure 9). We found that the high summer rainfall sites had, on average, higher summer quarter θ than low summer rainfall sites. Groups with high peak SWE and high elevation had higher summer quarter θ when compared to groups with lower peak SWE or elevation.

Discussion

Soil temperature variation below seasonal snowpacks

Temperature in the bulk atmosphere and near surface air declines with elevation (Figure 3). Hence, one might expect T_{soil} to also decline with elevation. Soil temperature showed little dependence on elevation when a snowpack was present, despite large gradients in T_{air} in our study area (Figure 3). The moist adiabatic lapse rate is generally between 3 and 7 °C/km [*Whiteman*, 2000] and we observed July T_{air} and T_{soil} elevation gradients similar to this across our sites. Elevation gradients in T_{soil} were much smaller than T_{air} gradients when a snowpack was present (Figure 3). These data support our first hypothesis that seasonal snowpacks remove elevation gradients in T_{soil} and are evidence that insulation by snow dramatically reduces energy exchange at the soil surface.

Insulation by snowpacks kept soils warmer than air during the winter. Across all sites, we found mean below-snow T_{soil} values of 0.3, 0.7, and 1.3 °C at 5, 20, and 50 cm depths, respectively, all of which were warmer than mean T_{air} during the same period (-1.8 °C, Figure 3 and 8). Other studies have shown similar T_{soil} patterns, with below-snowpack T_{soil} exceeding T_{air} when a snowpack is present [*Brooks et al.*, 1995; *Van Miegroet et al.*, 2000; *Hardy et al.*, 2001; *Seyfried et al.*, 2001; *Körner and Paulsen*, 2004; *Monson et al.*, 2006a; *Lundquist and Lott*, 2008; *Sutinen et al.*, 2009; *Masbruch et al.*, 2012; *Schmid et al.*, 2012; *Raleigh et al.*, 2013], but to our knowledge, these landscape-scale changes in T_{soil} gradients have not been demonstrated.

Despite insulation by snowpacks, there was considerable variability in T_{soil} during winter. We found interannual and intersite ranges in below-snow T_{soil} as large as 7 (mean = 1 °C) and 11 °C (mean = 6 °C), respectively, in our study area (Figure 8). To our knowledge, interannual variability in winter T_{soil} has only been quantified in a few isolated studies in western U.S. mountains. At Niwot Ridge, Colorado, for example, there was a 1.5 °C range in below-snowpack T_{soil} over a 6-year period [*Monson et al.*, 2006b]. Spatial variability in below-snowpack T_{soil} has been shown to be linked to snowpack depth and T_{air} in arctic environments [*Taras et al.*, 2002]. Studies in snow-dominated mountains are few, but have demonstrated that below-snowpack T_{soil} is often related to snowpack, as well as slope position and aspect [*Körner and Paulsen*, 2004; *Tyler et al.*, 2008; *Scherrer and Körner*, 2010].

Much of the observed variability in below-snow T_{soil} was related to fall and early-winter conditions, including snowpack size, presnowpack T_{air} and T_{soil}, and snowpack start day. Snowpack thermal resistance increases with depth, and at greater snow depths soil temperature stops responding to seasonal surface temperature fluctuations [*Sturm et al.*, 1997; *Sokratov and Barry*, 2002; *Bartlett et al.*, 2004; *Grundstein et al.*, 2005; *Zhang*, 2005]. We found that soils were frequently warmer when there was greater early-winter SWE accumulation (Table 2, Table 3, PC1 and PC4). Cold soils (mean monthly T_{soil} < 0 °C) during early winter months were more common at sites with small snowpacks, while sites with large snowpacks were generally above 0 °C (Figure 6, only Dec. and Jan. shown). We estimated the SWE at which fitted T_{soil} was within 90% of its upper temperature bound to be 308 to 480 mm. At 30% snow density, this is equivalent to a 1 to 1.6 meter snowpack. This is higher than the estimate of 0.4 m in *Brooks and Williams* [1999]. The model of *Bartlett et al.* [2004] predicts that a snow depth of 1 meter insulates the ground from most seasonal T_{air} fluctuations and halts the early-winter decline in soil temperature. These results support our second hypothesis that winter soil temperature is dependent on snowpack characteristics. Below-snow T_{soil} was also warmer in years with later snowpack start days (Table 2) at some sites, which is inconsistent with our expectations. A number of sites had higher θ in years with late snowpack start days, so it is possible that warmer T_{soil} in late accumulation years can be accounted for by the high heat capacity of water in the soil or by latent heat release during soil freezing [*Brooks et al.*, 2011].

Soil moisture variation below seasonal snowpacks

Soil moisture below the snowpack was generally stable for several months within a given winter, providing support for our hypothesis (3a) that soil moisture changes minimally between the start of snowpack accumulation and the initiation of snowpack melt. After November, there was little month-to-month or cumulative change in mean monthly θ, and below-snow θ remained similar to presnowpack θ until February (Figure 4). Both are evidence that evapotranspiration was low, and little precipitation or snowmelt water infiltrated into soils for 3 winter months or more. In March and April, month-to-month and cumulative increases in θ were observed, suggesting that snowmelt began to reach the soil at this time (Figure 4).

Winter quarter soil moisture was dependent on fall and early-winter snowpack and soil conditions. On average, mean winter quarter θ was around 0.4 (normalized) suggesting that, in general, soil moisture was not fully recharged in fall and early-winter months. Winter quarter θ was higher when there was greater early-winter SWE accumulation or greater presnowpack θ (Table 2, Table 3, PC4). In some years, winter quarter θ was lower at sites where presnowpack T_{soil} and T_{air} were high (Table 3, PC3), indicating that higher evapotranspiration during this period may have dried soils. These observations, coupled with the stability of soil θ during the cold season (Figure 4), provide support for our hypothesis (3b) that midwinter θ was determined by conditions in fall and early-winter. We also found, however, a positive relationship between winter quarter θ and winter T_{air} (Table 2, Table 3 – PC2), suggesting that winter melt events at warmer sites or in warm years may lead to some recharge of soil moisture.

The fall and early-winter period can be viewed as a transitional state between the relative stability of the warm and cold seasons. During this transition, the soil environment is highly sensitive to variability in temperature and precipitation [*Grayson et al.*, 1997; *McNamara et al.*, 2005]. This is understandable because the phase (rain or snow) of precipitation, and the likelihood that snowfall will melt and recharge soil θ, are both highly sensitive to temperature fluctuations during this time. We did not use fall and early-winter precipitation or snowmelt as explanatory variables in multiple regression analysis, and it is possible that these would have provided some additional information. Whatever the dominant drivers of θ are during this fall and early-winter transition period, it appears that winter θ is sometimes determined at this time.

Warm season soil moisture and snowpack variability

We found some evidence that summer quarter air temperature, rainfall, and prior spring snowpack characteristics influenced summer soil moisture. Summer quarter θ was lower during warmer years (Table 4), but only at 8–13 sites (depending on soil depth). Sites with warmer T_{air} (Table 3 – PC1) also had lower summer quarter θ. Low summer quarter θ may have been the result of high evapotranspiration rates in warm years that removed water from soil. Evapotranspiration is enhanced by warmer air temperature and associated higher evaporative demand. Soil water is primarily recharged by water pulses from snowmelt or summer rain events. Accordingly, we found higher summer quarter θ when there was greater summer precipitation, larger prior spring snowpacks, and later snow-free dates (Table 4, Table 3, PC2 and 3). These relationships were not significant at all sites or in all individual years tested, indicating that the importance of precipitation and snowpack varied in time and space. This provides limited support for our hypothesis (4) that warm season soil moisture is influenced by snowpack characteristics. Warm season air temperature, however, was a more consistent explanatory variable. In our comparison of sites grouped by summer rainfall, elevation, and snowpack size, the group with the highest mean summer quarter θ was the one with sites at high elevations (cooler), with large snowpacks, and large amounts of summer rainfall (Figure 9). High summer rainfall sites were generally wetter than sites with less summer rainfall, and median summer θ was lower at low elevation and low SWE groups. We also found evidence that warm season rainfall events primarily wet the upper layers of the soil profile, while snowmelt recharged θ at greater depth (Table 4).

These results, though complex, agree with other studies of soil water recharge at catchment [*Seyfried*, 1998; McNamara et al., 2005; *Williams et al.*, 2009] and regional scales in the western U.S. [*Loik et al.*, 2004; *Hamlet et al.*, 2007]. Both *Seyfried* [1998] and *Williams et al.* [2009] found that spatial variability in snowpack size and melt timing explained spatial variability in θ early in the warm season. As θ declined after the snowpack melted, however, those spatial patterns were replaced by soil moisture patterns determined by summer rain. Mountain soils are often shallow and have a small water storage capacity that limits soil moisture recharge by snowmelt water [*Smith et al.*, 2011]. A possible explanation for the weak relationships we observed between summer quarter θ and snowpack is that snowmelt-derived soil water was depleted prior to the summer quarter at many sites. This is consistent with recent observations in the region [*Molotch et al.*, 2009]. Local controls, such as soil texture, vegetation, and topography can also greatly influence soil water storage and the rate of θ drawdown during the warm season [*Litaor et al.*, 2008; *Williams et al.*, 2009; *Bales et al.*, 2011]. These and other site-specific variables are undoubtedly important and highly variable in our study area.

Implications for ecosystems and biogeochemical processes

Soil microbial activity occurring near the freezing point of water is highly sensitive to temperature. This has been observed in laboratory [*Fang and Moncrieff*, 2001; *Mikan et al.*, 2002; *Öquist et al.*, 2009] and field studies of soil biogeochemical processes [*Brooks et al.*, 1996; *Elberling and Brandt*, 2003; *Monson et al.*, 2006b]. Other than the effect of temperature on biochemical reaction kinetics, several explanations for this phenomenon have been made, including changes in the availability of liquid water [*Mikan et al.*, 2002; *Öquist et al.*, 2009] and organic carbon substrates [*Brooks et al.*, 2005; *Schimel and Mikan*, 2005; *Davidson and Janssens*, 2006], and the exponential growth of soil microbial communities at low temperatures [*Schmidt et al.*, 2009]. Because of this temperature sensitivity, seemingly minor changes in winter soil temperature can have major effects on biogeochemical processes, even at the ecosystem level. In the study by *Monson et al.* [2006b], for example, an interannual range in below-snow T_{soil} from -1.5 to 0 °C was responsible for a 21% variation in cumulative annual net ecosystem CO_2 exchange at Niwot Ridge, Colorado. We found that below-snow T_{soil} averaged around 0 °C across our western U.S. study sites, but interannual and intersite ranges in below-snow T_{soil} were large enough to significantly impact rates of biological activity in soils (Figure 8).

Soil frost events become less likely in temperate mountain ecosystems as the sizes of seasonal snowpacks increase. Frost formation damages root and microbial biomass and because some soil organisms are more cold-sensitive than others, soil community composition can change [*DeLuca et al.*, 1992; *Sutinen et al.*, 1999; Tierney et al., 2001; *Feng et al.*, 2007; *Comerford et al.*, 2013]. Frost damage is thought to release labile carbon and nutrient rich cell contents into the soil [*Matzner and Borken*, 2008], and a variety of effects on soil biogeochemical processes have been observed following freeze-thaw events. These include increases in soil respiration [*Schimel and Clein*, 1996; *Brooks et al.*, 1997; *Feng et al.*, 2007], higher soil inorganic nitrogen concentration and N2O emission [*DeLuca et al.*, 1992; *Brooks et al.*, 1996; *Groffman et al.*, 2001, 2006], and greater export of carbon, nitrogen, and other nutrients from soils in solution [*Boutin and Robitaille*, 1995; *Brooks et al.*, 1998; *Fitzhugh et al.*, 2001; *Haei et al.*, 2010]. Some studies, however, have found that soil frost events have little net effect on, or reduce the rates of these same biogeochemical processes [*Lipson et al.*, 2000; *Grogan et al.*, 2004; *Hentschel et al.*, 2009; *Muhr et al.*, 2009; *Groffman et al.*, 2011]. We found indirect evidence of soil frost at one site (Figure 2b and c), and extensive evidence that fall and early-winter conditions influenced whether soil temperature dropped below 0 °C during the winter (Figure 6).

Soil moisture also has a well-recognized influence on soil biological activity and associated biogeochemical processes [*Orchard and Cook*, 1983; *Borken and Matzner*, 2009]. Below-snow soil microbial processes, such as those that emit carbon dioxide, methane, and nitrogen oxides during winter, respond to variations in soil moisture [*Mast et al.*, 1998; *Filippa et al.*, 2009; *Liptzin et al.*, 2009; *Aanderud et al.*, 2013]. There is some evidence that the availability of soil water beneath melting spring snowpacks stimulates the upregulation of photosynthesis and transpiration in conifer forests in our study area [*Monson et al.*, 2005; *Zarter et al.*, 2006]. Within a given winter, we generally found stability in below-snow soil θ (Figure 4), but considerable interannual and intersite variability was driven by fall and early-winter snow and temperature conditions.

Winter biological and biogeochemical activity can be substantial given the below-snow T_{soil} and moisture conditions found in our study area. Below-snow soil respiration, for example, has been shown to account for anywhere from ~12 to 50% of the annual respiration flux in seasonally snow-covered ecosystems [reviewed in *Liptzin et al.*, 2009]. Aside from some studies of soil processes along elevation transects in our region [*Amundson et al.*, 1989; *Trumbore et al.*, 1996; *Kueppers and Harte*, 2005], there is little data on how biogeochemical processes vary spatially and temporally in seasonally snow-covered mountain ecosystems. There has been some effort to synthesize aspects of the interactions between snow, soil, and winter biogeochemical cycling into a conceptual model [*Brooks and Williams*, 1999; *Liptzin et al.*, 2009; *Brooks et al.*, 2011]. In this framework, snowpacks limit soil biological activity when they are shallow or transient enough to allow frozen soil for long periods or permanent enough to restrict warm-season primary production and thereby reduce the supply of carbon for soil heterotrophs. The majority of our study sites fall between these extremes. Short duration frost events occur, often in response to fall and early-winter snow and weather conditions. These may enhance nutrient availability via organic matter fragmentation [*Hobbie and Chapin*, 1996] and turnover of microbial biomass [*Schimel and Clein*, 1996; *Brooks and Williams*, 1999]. Typically, however, soils are thawed during winter, permitting the activity and growth of a large below-snowpack soil microbial community [*Lipson et al.*, 1999; *Schmidt et al.*, 2009]. The decomposition of autumn plant litter inputs provides a carbon source for the growth of this community and fuels the winter biogeochemical activity discussed above [*Taylor and Jones*, 1990; *Hobbie and Chapin*, 1996; *Schmidt and Lipson*, 2004].

The influence of winter snowpacks on the soil biophysical environment also extends to the warm season. Following the winter growth of large below-snow microbial communities, the spring melt is accompanied by a change in microbial community and a rapid decline in microbial biomass [*Brooks et al.*, 1996; *Lipson et al.*, 1999]. The subsequent flush of nutrients can be lost in spring runoff [*Hood et al.*, 2003] or exploited by plants during the warm season [*Brooks et al.*, 1998; *Jaeger III et al.*, 1999; *Lipson et al.*, 1999]. The spring snowmelt also marks the beginning of the growing season for most plant communities, and changes in the timing of melt can alter the timing of plant phenological events, such as greening and flowering, in alpine plant communities [*Steltzer et al.*, 2009]. Warm season activity by plant and soil communities in snow-dominated ecosystems depends heavily on snowmelt water [*Brown-Mitic et al.*, 2007; *Litaor et al.*, 2008; *Riveros-Iregui and McGlynn*, 2009], and differences in snowpack size and melt timing can have significant effects on forest productivity [*Molotch et al.*, 2009; *Tague et al.*, 2009; *Hu et al.*, 2010]. Our results support the idea that snowmelt enhances warm season soil moisture availability, but this effect is variable and dependent on snowpack size, melt timing, and summer air temperature for a particular site or year.

Limitations and future research

There are a number of limitations to this study, many of which provide opportunity for future investigation. We focused our study on elucidating the climatic drivers of T_{soil} and θ, and consequently ignored many site-specific variables that influence the soil biophysical environment. Soils vary widely in composition and texture, for example, which have significant effects on water retention and thermal or hydraulic conductivity [*Campbell et al.*, 1994; *Abu-Hamdeh and Reeder*, 2000; *Haverkamp et al.*, 2005]. Our study sites also vary in topographic position and vegetation cover, which may strongly influence precipitation accumulation, evapotranspiration rate, soil and groundwater flow, and soil surface energy balance. None of these site-specific variables, or other potential sources of uncertainty, are accounted for in our study The statistical models we fit in this study explained only a small amount of the variance in T_{soil} and θ across our study sites (R^2 of 0.07–0.42, Table 3), and it is likely that inclusion of additional site-specific variables and uncertainties would have improved this analysis.

Another limitation stems from our use of artificial, rather than hydrologically defined, seasonal periods. Averaging data into quarterly or monthly values, which are arbitrary with respect to the annual hydrologic cycle, risks losing important information about hydrologic events and processes. In studies examining intersite or interannual variability, such as ours, it may be advantageous to compare hydrologically based events and seasons rather than artificially imposed ones. Such an approach has been successfully used to study interannual variability in forest ecohydrological processes [*Thomas et al.*, 2009].

Finally, though provided by a trusted government agency, the data we used are somewhat provisional and limited in quality. Our own quality assurance procedure for T_{soil} and θ data (see Appendix A) removed the majority of problematic data, but additional sources of uncertainty remain in the dataset. We corrected for obvious instances of sensor change at each site, but there may be cases where sensors changed during the time series used to examine interannual variability. Additionally, soil sensor profiles are not precisely colocated with other SNOTEL measurements (SWE, T_{air}, precipitation) and this may have introduced a mismatch between these measurements and T_{soil} or θ data. These limitations illustrate that publically available datasets are not always what they appear and researchers should approach them with appropriate caution. Nevertheless, we consider the USDA/NRCS SNOTEL dataset a valuable one with significant potential to inform ecosystem studies in the western U.S.

Conclusions

We found that seasonal snowpack characteristics had significant effects on the soil biophysical environment. First, snowpacks decoupled T_{soil} from T_{air}, reducing elevation gradients in T_{soil} across the landscape during the cold season. Second, below-snow T_{soil} was greatly influenced by the timing and magnitude of snow accumulation, and low early-winter snowpacks led to cooler soil and higher likelihood of freeze-thaw events. Third, θ changed little between the start of snowpack accumulation and the initiation of snowpack melt. Fourth, winter quarter θ was influenced by fall and early-winter precipitation and temperature. Finally, snowmelt-derived soil moisture was a limited resource, but availability of this resource was more likely with large snowpacks and later melt timing.

These findings suggest that seasonal snowpack change in the western U.S. will be accompanied by shifts in spatial and temporal patterns of soil temperature and soil moisture. Of particular importance are changes in fall and early winter snowpack development, as seasonal snowpacks isolate the soil environment until spring snowpack ablation begins. Temperature, precipitation, and snowpack variations during this transition from fall to winter give rise to below-snowpack T_{soil} and θ differences large enough to impact soil biological activity and associated biogeochemical processes. This appears to be important at many locations across the western U.S. Snowpack size (peak SWE) and melt timing, while critical to the hydrological processes of the western U.S., only significantly impacted warm season soil water availability at a few of our study sites.

There is growing appreciation for the importance of seasonal snowpacks for ecosystem and biogeochemical processes. This research highlights the important role that spring and fall transitions between snow-covered and snow-free states have in setting the stage for these processes in the montane ecosystems of the western U.S. Studies of current hydroclimate, and projected trends in this region indicate that snowpack and temperature changes during these seasons are underway and likely to intensify [*Brown and Mote*, 2009; *Seager and Vecchi*, 2010; *Barichivich et al.*, 2012; *Kapnick and Hall*, 2012]. We therefore anticipate changes to the soil temperature and soil moisture environment of the region and a significant response from ecosystems and biogeochemical processes.

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Tables

Table 1: Mean and standard deviation of elevation, snowpack metrics, and selected climate variables for the years 2001 to 2011 (inclusive). Data for all sites (n = 574) and the soil sites (n = 252) are shown.

	All sites		Soil sites	
Variable	Mean	SD	Mean	SD
Elevation (m)	2511.4	513.5	2549.8	483.0
Mean annual T_{air} (°C)	3.4	2.1	3.9	2.2
Annual precip. (mm)	821.1	322.1	791.6	301.1
Summer quarter precip. (mm)	124.0	73.3	114.1	68.3
Peak SWE (mm)	463.6	285.9	456.9	268.4
Total snow-covered days (d)	204.1	39.6	197.8	37.6
Snowpack start day	24 Oct.	17.8	26 Oct.	17.5
Snow-free day	23 May	25.2	20 May	23.1

Table 2: Summarized results for linear regression of mean below-snow T_{soil} and mean winter quarter θ on a number of explanatory variables. Results from 5 cm, 20 cm, and 50 cm soil depths are shown (n = 252 sites). All regression coefficients (not shown) indicated positive relationships to the explanatory variable. For each variable, numbers represent the total number of sites in which simple linear regression was significant ($p < 0.05$). Asterisks denote the level of significance of the explanatory variable in a multilevel linear model using site as the random variable (*** for $p < 0.001$; ** for $p < 0.01$; * for $p < 0.05$).

	Below-snow T_{soil}			Winter quarter θ		
Explanatory variables	5 cm	20 cm	50 cm	5 cm	20 cm	50 cm
Peak SWE	14***	11***	12***	16***	14***	6***
Snowpack start day	13	14	15	13	12	16*
Presnowpack T_{air}	8***	8***	10***	7	10***	4***
Below-snow period T_{air}	12***	12***	13***	14***	13***	6***
Snow-free day	5***	4*	4	8***	9***	8**
Mean Nov. SWE	23***	25***	25***	31***	25***	19***
Mean Dec. SWE	40***	42***	29***	53***	46***	27***

Table 3: Multiple regression results for three dependent variables. Mean below-snow T_{soil} and winter quarter θ were regressed against principal component scores from the below-snow PCA, and mean summer quarter θ was regressed against scores from the warm season PCA (see Appendix B for PC axis details). Each multiple regression model was tested using data from all years together and data from each of three individual years. Regression coefficients for each PC axis and asterisks denoting their significance as explanatory variables in the model (*** for $p < 0.001$; ** for $p < 0.01$; * for $p < 0.05$) are shown.

Dependent variables	Explanatory variables	All years	2007	2009	2011
Below-snow T_{soil}	Spring snowmelt (PC 1)	-0.02 **	0.01	-0.01	0.03 **
	Winter temperature (PC 2)	0.14 ***	-0.08 ***	-0.14 ***	-0.12 ***
	Snowpack start temperature (PC 3)	-0.04 *	-0.07 *	0.12 **	0.08 **
	Fall snow/soil (PC 4)	0.13 ***	-0.25 ***	-0.16 **	0.02
	Model Adjusted R^2	*0.23*	*0.27*	*0.26*	*0.33*
Winter quarter θ	Spring snowmelt (PC 1)	0.00 *	-0.01	0.01 *	0.02 ***
	Winter temperature (PC 2)	0.05 ***	0.02 **	-0.05 ***	-0.04 ***
	Snowpack start temperature (PC 3)	0.01 **	0.05 ***	-0.01	-0.01
	Fall snow/soil (PC 4)	0.04 ***	-0.10 ***	-0.09 ***	-0.08 ***
	Model Adjusted R^2	*0.24*	*0.36*	*0.42*	*0.38*
Summer quarter θ	Summer T_{air} (PC 1)	-0.02 ***	0.03 ***	-0.01 **	-0.03 ***
	Spring snowmelt/summer precip (PC 2)	0.01 ***	0.02 ***	0.00	-0.01
	Winter T_{soil} (PC 3)	0.03 ***	0.01	-0.02 *	-0.03 **
	Model Adjusted R^2	*0.19*	*0.31*	*0.08*	*0.18*

Table 4: Summarized results for linear regression of mean summer quarter θ on a number of explanatory variables. Results from 5 cm, 20 cm, and 50 cm soil depths are shown (n = 252 sites). Negative regression coefficients are indicated in parentheses, all others were positive. For each variable, numbers represent the total number of sites in which simple linear regression was significant ($p < 0.05$). Asterisks denote the level of significance of the explanatory variable in a multi-level linear model using site as the random variable (*** for $p < 0.001$; ** for $p < 0.01$; * for $p < 0.05$).

Explanatory variables	5 cm	20 cm	50 cm
Peak SWE	11***	18***	21***
Snow-free day	11***	12***	16***
Summer qtr. T_{air}	10(-)***	8(-)***	9(-)***
Summer qtr. Precip.	26***	16***	7***
Winter qtr. 5cm T_{soil}	9	5	3

Figures

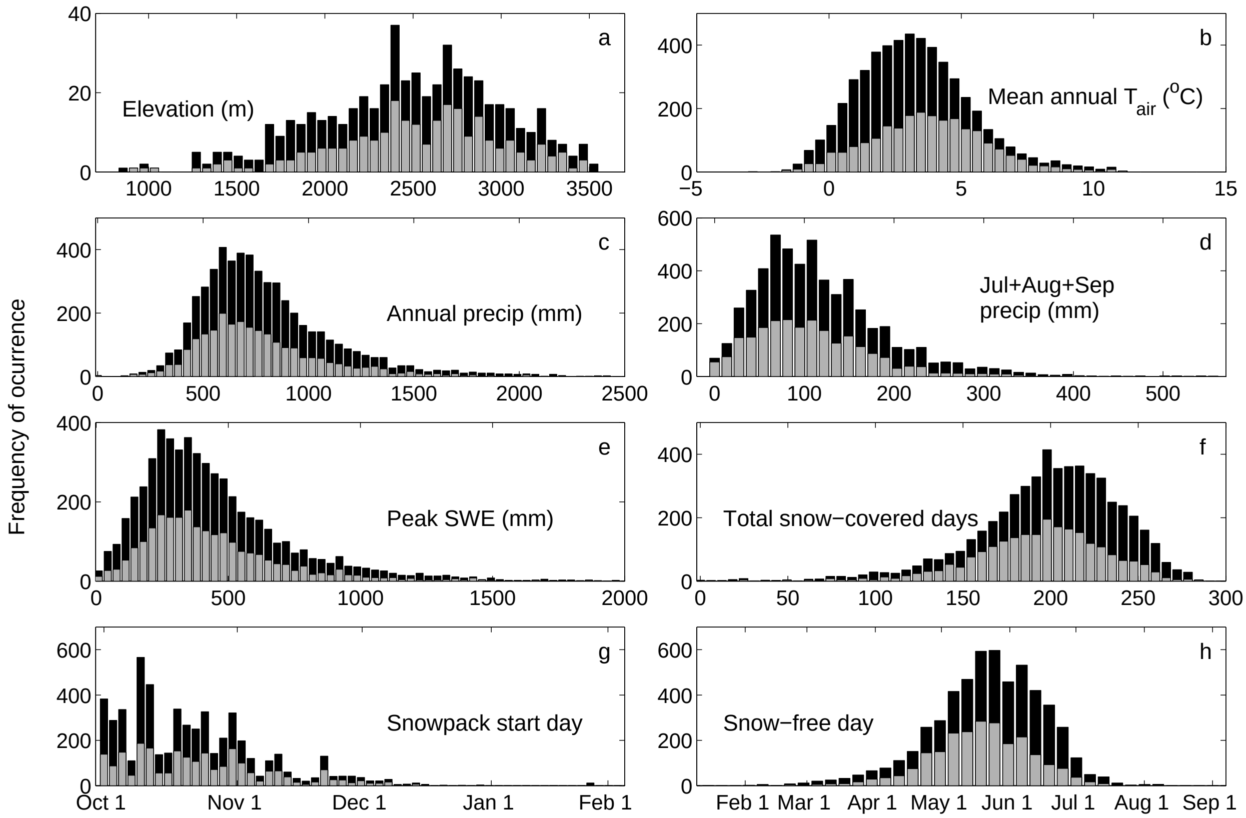

Figure 1: Frequency distributions for selected climate and snowpack characteristics during water years 2001 to 2011, inclusive. Distributions are shown for the full set of SNOTEL stations in the interior western U.S. (black bars, 574 sites in AZ, CO, ID, MT, NM, NV, UT, WY) and for the subset of those sites that have soil sensor profiles installed (gray bars, 252 sites).

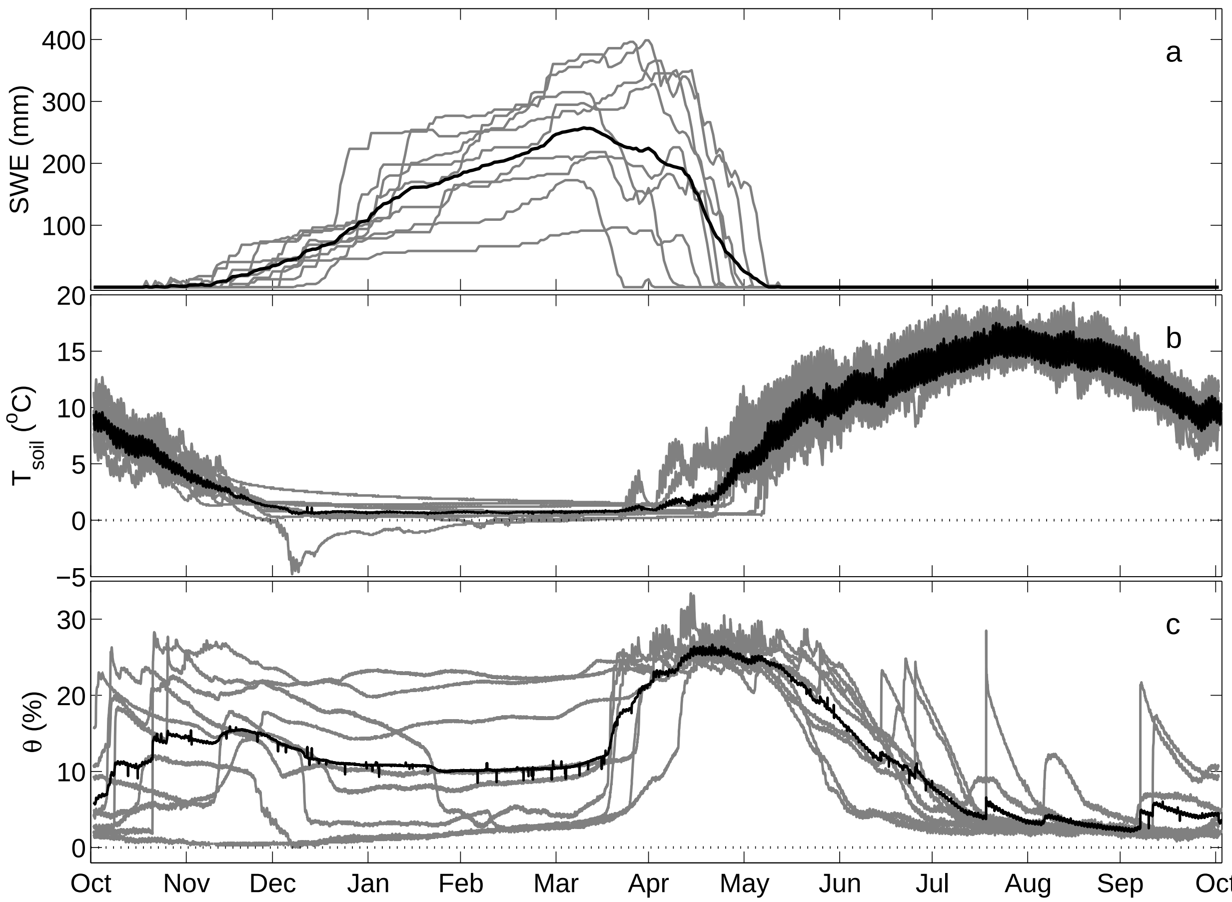

Figure 2: Time series of SWE (a), 20 cm T_{soil} (b), and 20 cm θ (c) from 2002–2011 at the Currant Creek site (UT). One time series for each individual year since installation of the soil sensors is plotted in gray, and the mean of all these years is plotted in black.

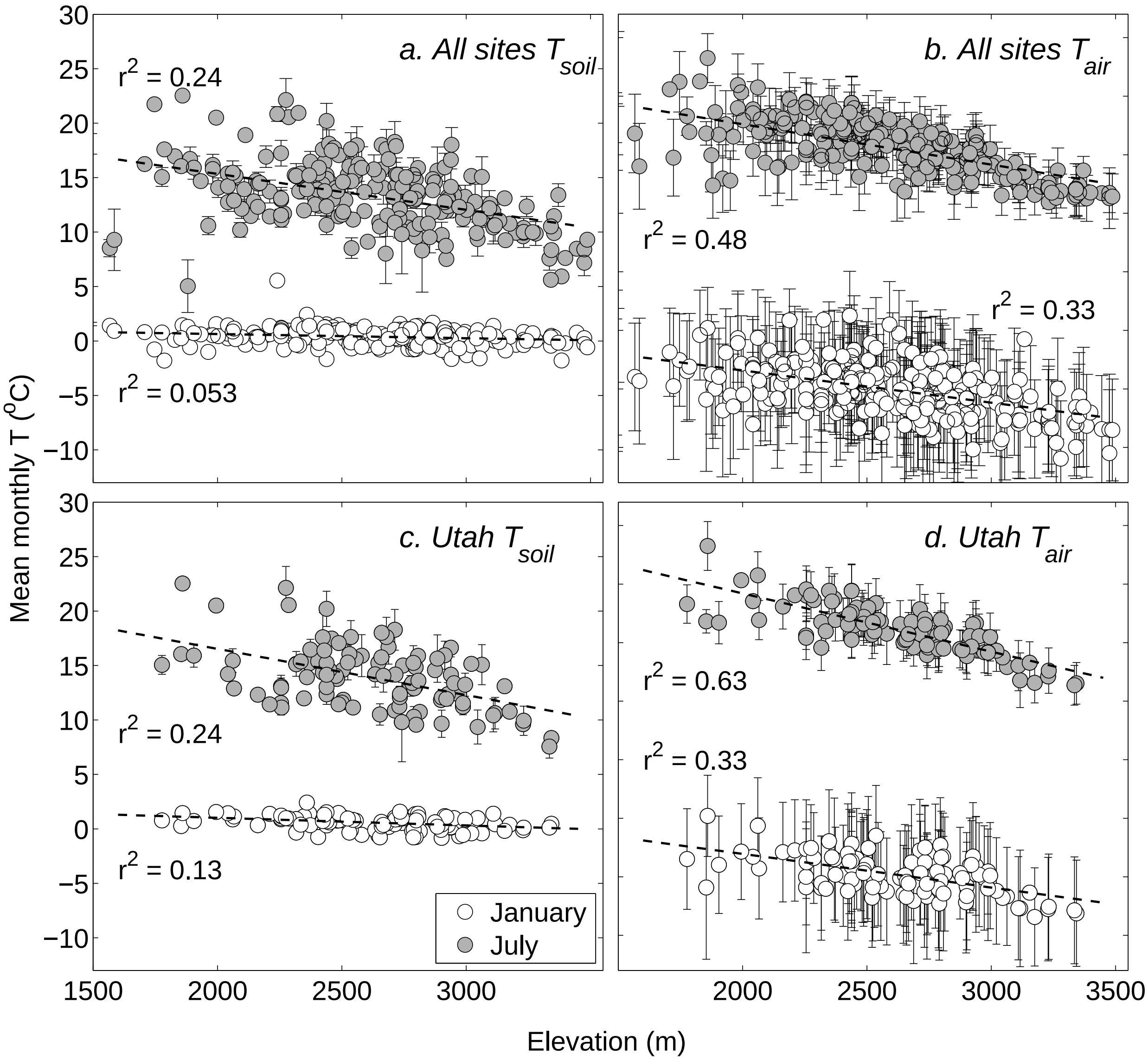

Figure 3: Elevation gradients in mean monthly T_{soil} (left panels) and T_{air} (right panels). January and July data at all soil sites (n = 252) are shown in panels (a) and (b), and at Utah soil sites (n = 102) in panels (c) and (d). All points are multiyear means of January or July measurements from all available water years, and error bars are 1 standard deviation (some are smaller than the symbols). Dashed lines are least-squares linear regressions. T_{soil} measurements are from 20 cm depth. Regression equations for panels (a) and (b): July mean T_{soil} = -3.3x + 21.94; January mean T_{soil} = -0.4x + 1.40; July mean T_{air} = -3.4x + 24.49; January mean T_{air} = -2.8x + 2.08. All slopes are significantly different than zero ($p < 0.001$). Utah regression coefficients are given in the text.

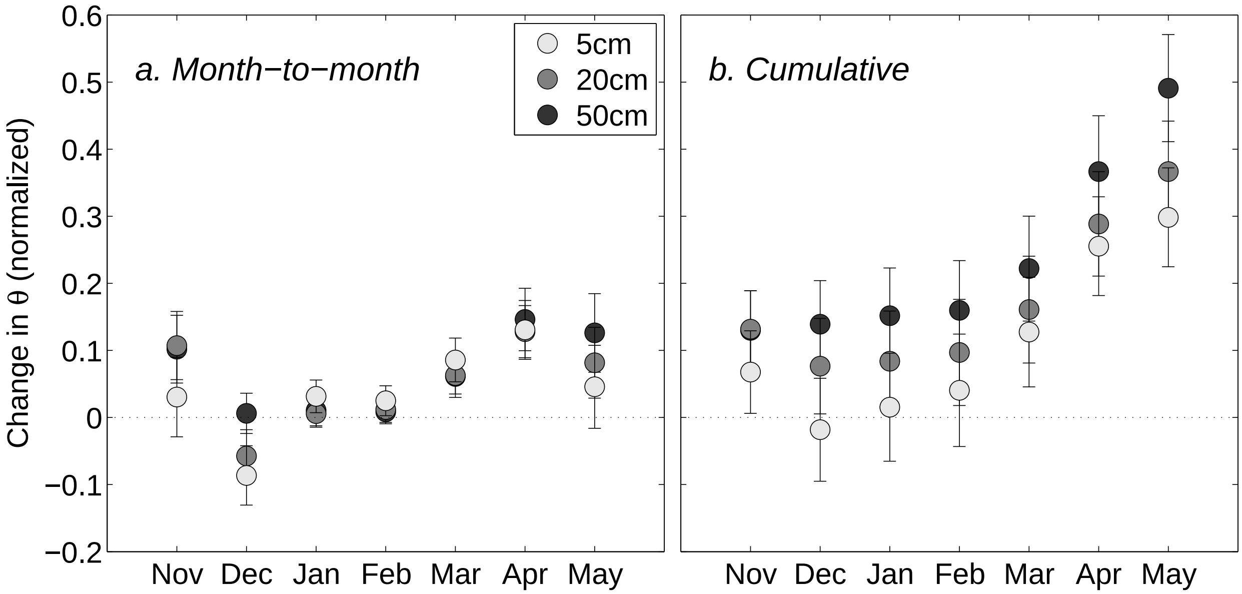

Figure 4: Monthly change in normalized soil θ (dimensionless) at three soil depths. Panel (a) shows one-month changes in mean θ (mean month θ – mean prior month θ). Panel (b) shows the cumulative change in soil θ since the presnowpack period as described in the text (mean month θ – presnowpack θ). Points represent the mean change for the soil sites (n = 252) at the indicated depth. Error bars are 1 standard error. A dotted line indicating no change in θ is plotted for reference.

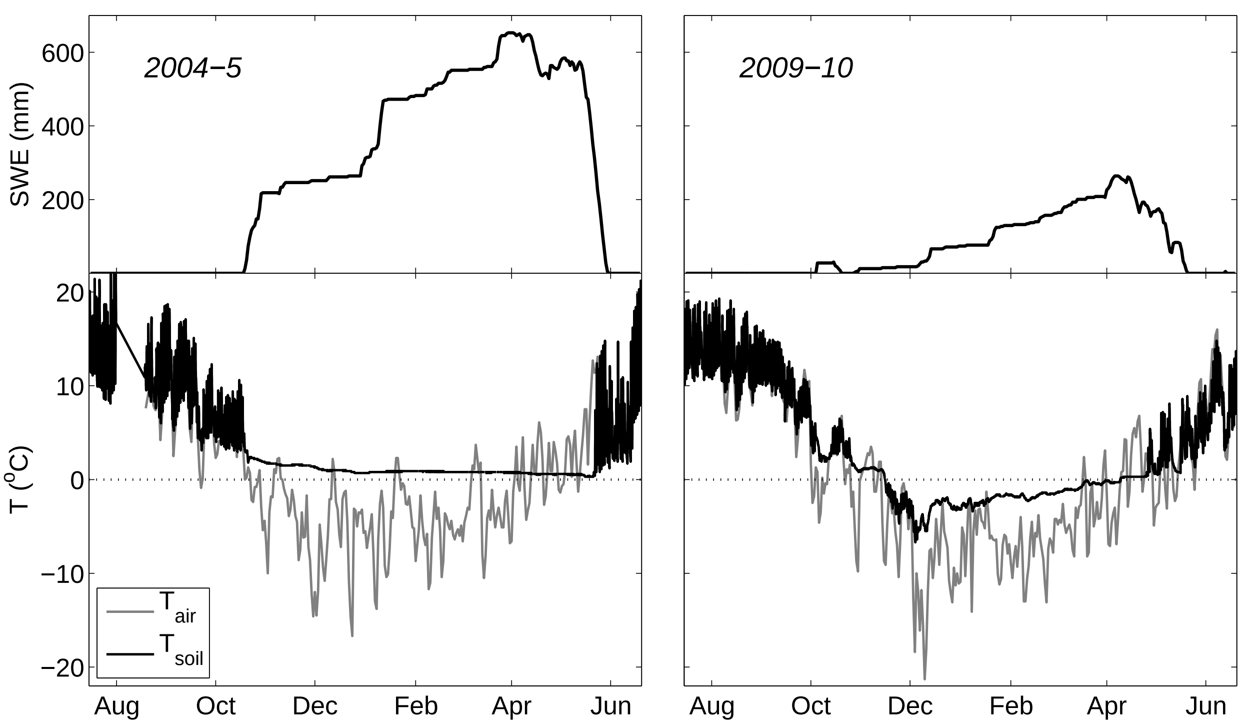

Figure 5: Daily T_{soil} (5 cm depth), T_{air}, and SWE at Mosby Mountain site (UT) during 2 contrasting years. In water year 2005, a large snowpack (SWE) accumulated early, leading to stable, above-zero T_{soil} during the entire below-snow period. In water year 2010, a small early-season snowpack led to subzero T_{soil} for much of the below-snow period.

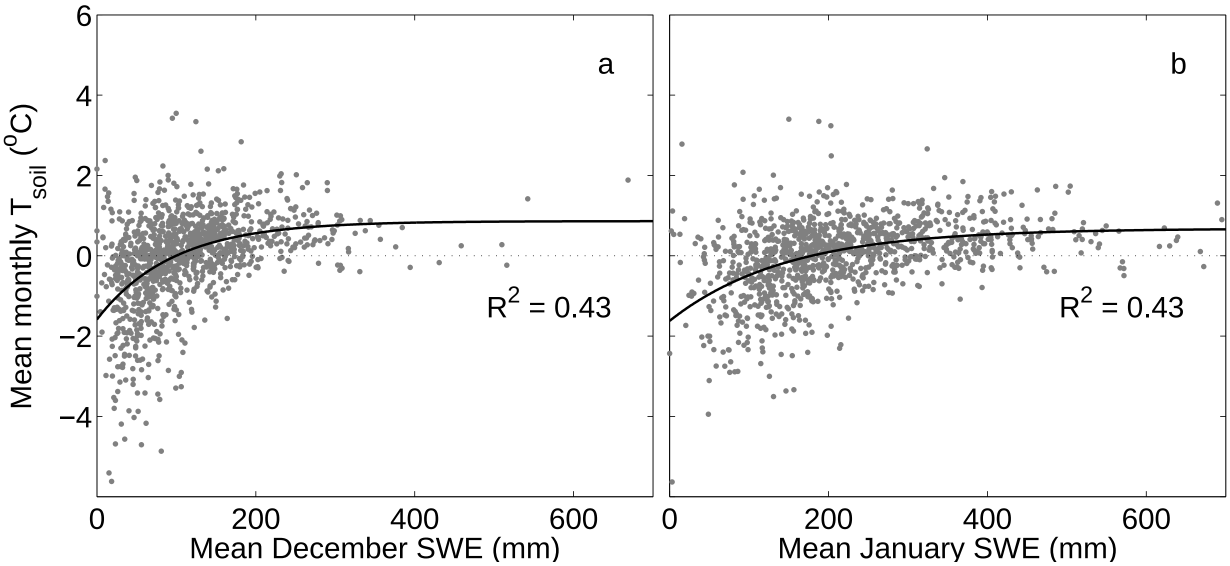

Figure 6: Mean monthly T_{soil} as a function of mean monthly SWE in early winter for all sites (n = 252). Each point represents the mean T_{soil} at 5 cm depth for 1 month at an individual site. The solid lines are the least-squares fit to a bounded exponential function ($y = a(1 - be^{-cx})$). The fitted values of the upper temperature bounds in December and January are 0.89 and 0.67 °C, respectively. The fitted values of SWE at 90% of these upper bounds are 308.6 and 480.3 mm, respectively. Data for December and January of all available water years are shown here, but similar patterns were present during February (R^2 = 0.35) and at other depths (not shown, 20 cm R^2 values = 0.34–37, 50 cm R^2 values = 0.27–0.31). Low early season T_{soil} occurred more frequently with a small snowpack.

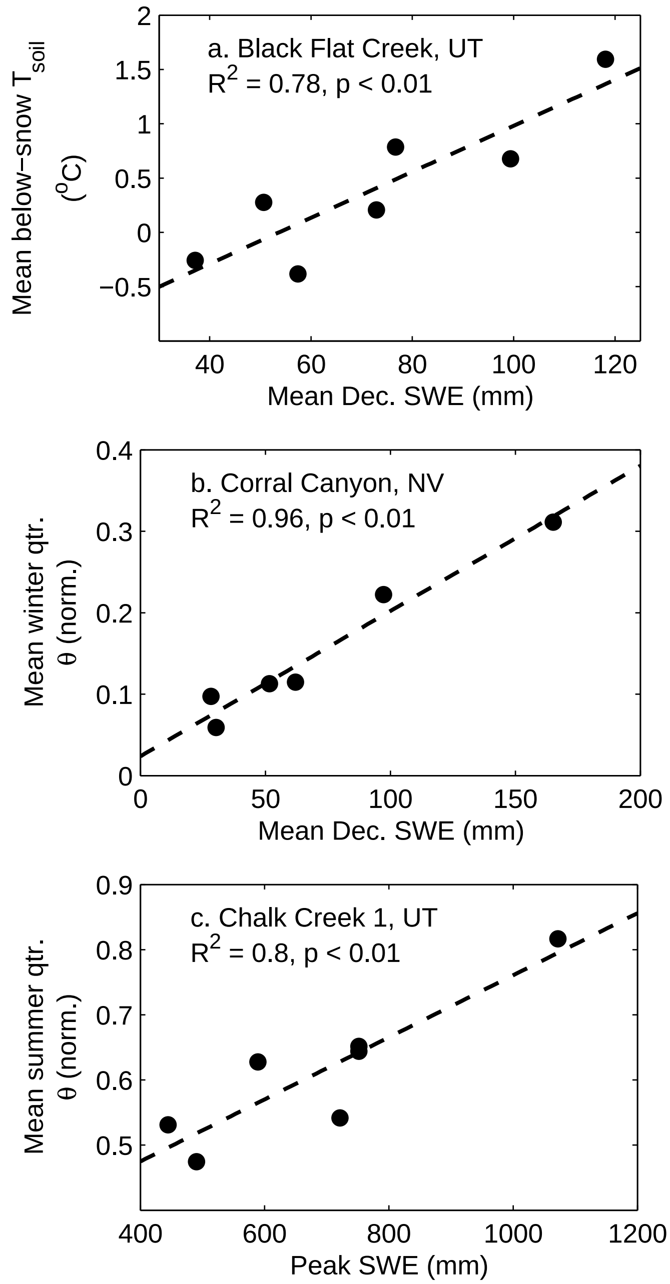

Figure 7: Simple linear regressions of (a) mean below-snow T_{soil} versus mean December SWE, (b) mean winter quarter (JFM) 20 cm θ versus December mean SWE, and (c) mean summer quarter (JAS) 50 cm θ versus peak SWE during different years (interannual variability) at individual SNOTEL sites. These are shown as examples of the regression results presented in Tables 2 and 4.

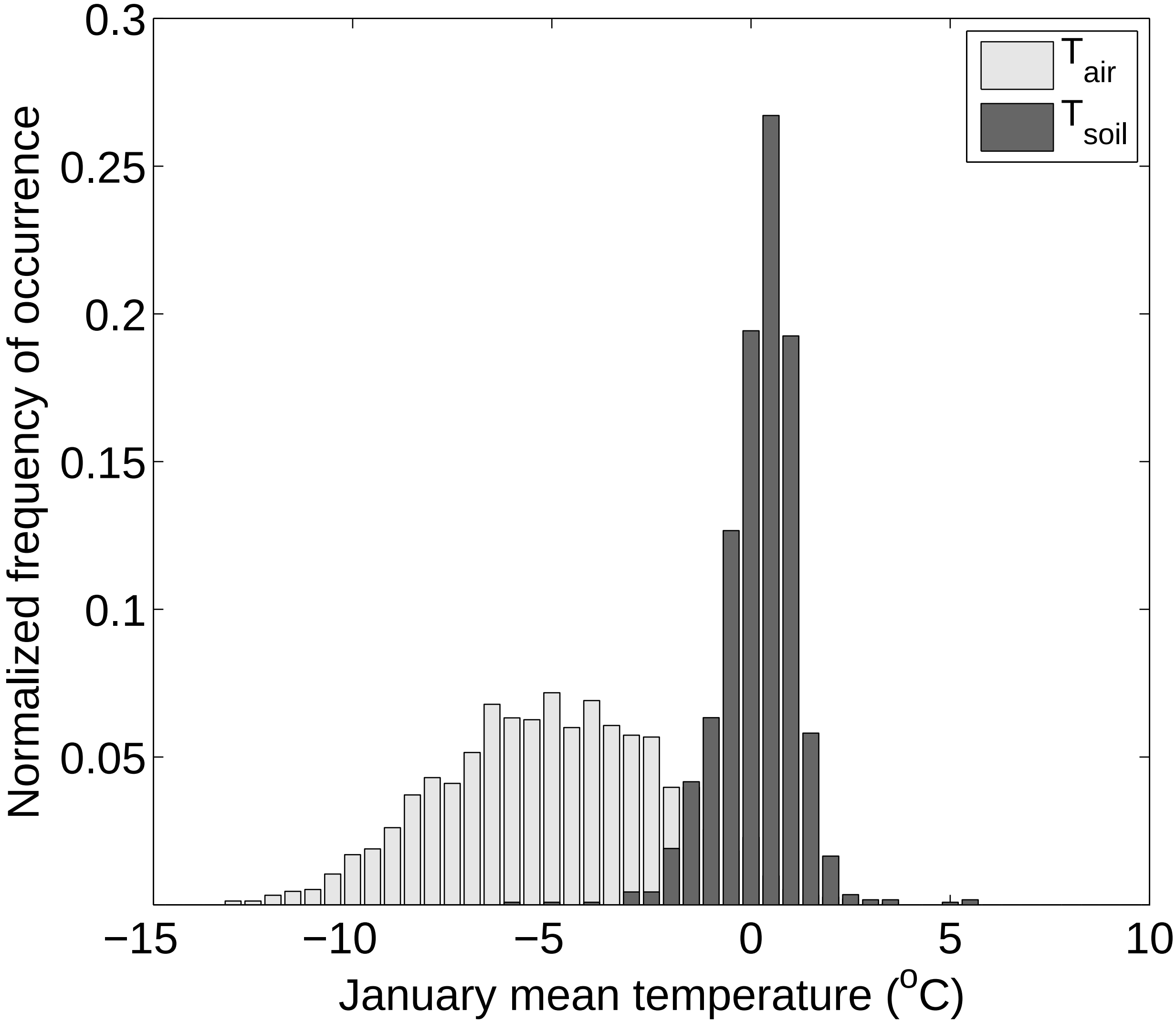

Figure 8: Frequency distributions of mean January soil (20 cm) and air temperature for all sites and all years of data (2001–2011). The histograms are standardized to show the fraction of data in each temperature bin.

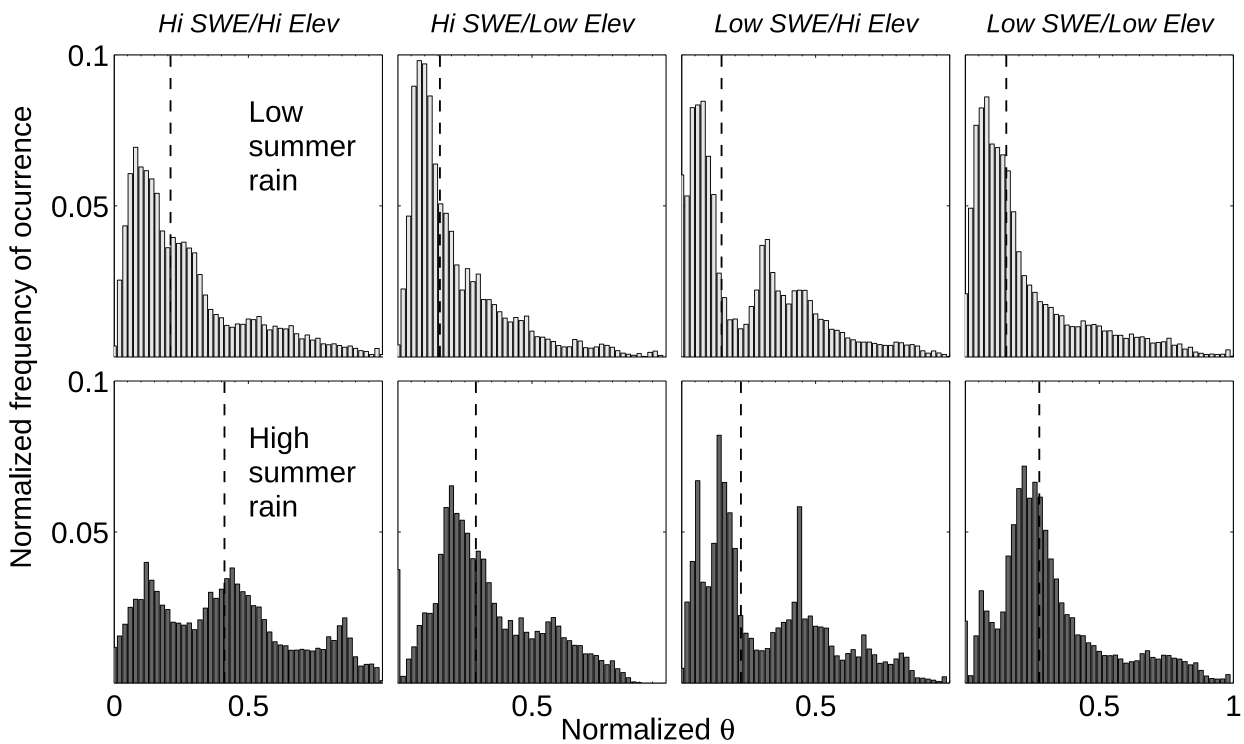

Figure 9: Frequency distributions of mean summer quarter θ (normalized 20 cm data for Jul., Aug., and Sep.) for subsets of soil sites with contrasting profiles of elevation, mean snowpack size, and summer precipitation. Sites in the top row received less than 20% of total annual precipitation in the 3 summer months. Sites in the lower row received greater than 20%. High and low elevation and SWE groups are defined in the text. The same 6 years of data, 2006–2011, are used in each group of sites. Median summer quarter soil θ for each group is plotted with a dashed vertical line.

Appendix A: Quality assurance and data exclusion procedures and examples

Introduction

The USDA/NRCS has installed depth profiles of Stevens Hydra Probe sensors (Hydra Probe I and II, Stevens Water Monitoring Systems, Inc., Portland, OR, USA) to provide soil temperature (T_{soil}) and soil water content (θ) data at selected sites in the SNOTEL network. Once deployed, sensor maintenance and quality assurance of data by the NRCS are fairly minimal. For this reason, we opted to create our own quality assurance procedures for this study. Using these procedures, we identified and excluded problematic data generated by these soil sensors.

Raw sensor responses (resistances or voltages) are converted to T_{soil} and θ data by the NRCS using calibration equations. For T_{soil}, the temperature-dependent resistance of the thermistor circuit is converted to soil temperature based on coefficients supplied by the thermistor manufacturer [*Bellingham and Fleming*, n.d.]. For θ, voltages returned by the sensor are converted to soil dielectric permittivity by manufacturer supplied software and this value can then be converted to soil water content using a number of calibration equations. The NRCS currently uses a multi-soil, loss-corrected equation tested and documented in Seyfried et al. [2005] but that is not customized for the soils at each individual SNOTEL site. We assume that in their new, pre-deployment state, T_{soil} and θ data reported by these sensors are reasonably accurate and precise in soil with characteristics similar to those in which the calibration equations were developed.

Several issues, however, may interfere with the collection of accurate and precise data at SNOTEL sites over the long term. First, placement of sensors into field soils is inherently problematic and the volume of soil in which an installed sensor makes a measurement may contain rocks, roots, drainage channels, or other physical irregularities. These irregularities may not represent average soil hydrologic or thermal properties of the site. Second, sensor response may drift as sensors age and weather in the field or as site soil and vegetation characteristics change over time. This may lead to directional changes in T_{soil} or θ data over time. Third, sensors fail and are periodically replaced by NRCS staff, which requires excavation and installation of new sensors. Data collected at a particular site and depth may therefore include data from multiple sensors in slightly different positions in the soil profile.

Quality assurance procedures and results

Because of the limited maintenance and quality assurance of sensors and data in the SNOTEL network, we implemented our own extensive quality assurance and data exclusion procedures for this project. We began with uncorrected hourly data from each sensor at all SNOTEL sites. We then screened each sensor time series using four methods and excluded all data with errors and irregularities in the long-term T_{soil} and θ record from further analysis. These four data exclusion methods are described below with examples of excluded data provided in the referenced figures.

1. Incomplete data files were removed using an automated script that treated each sensor time series identically. Incomplete data files were defined as those having less than a full month of data, or those with irregular measurement frequencies (greater or less than hourly/daily measurements). See Figure A.1. for an example.

2. Measurement errors were also removed using an automated script. Some of these were measurements automatically flagged as errors by the datalogger. We also assigned a range of reasonable values for T_{soil} (> -30 and < 50 °C) and θ (≥ 0 and < 45 %) given our knowledge of the sensors and their calibration ranges. Data outside of these ranges were removed. See Figures A.1, A.2 and A.3 for examples.

3. We plotted and visually inspected the T_{soil} and θ timeseries from each soil sensor at all sites used in the analysis (n = 756, three T_{soil} and θ time series at each site). We identified and removed the entire water year of data if there were large amounts of obvious errors in the data, changes in the sensor response shape, or otherwise unusual patterns (Figure A.3). These included time periods in which the baseline of the time series abruptly shifted above or below surrounding data, likely indicating a sensor change (Figures A.1 and A.2). In such cases, all data prior to the sensor change were excluded. We also removed periods with θ data at maximum (~45% VWC) or minimum (0% VWC) values for unusually long periods, indicating that sensor responses were outside the calibration equation range (Figure A.3).
4. Statistical outliers (spikes) in the data were removed from each timeseries if they were more than 3 standard deviations from the 24 h moving window average of the timeseries (Figures A.1, A.2, and A.3). This was done using an automated script.

Only the data that remained after these four quality assurance steps were used in further analyses in this study. For some analyses we compared θ data across sites which vary greatly in soil textural and hydraulic properties. To do this we normalized the θ time series from each sensor according to its full observed range of values in the included water years. The lowest θ value was set to 0, the highest to 1, and all other data were linearly scaled (based on sensor response) between these values. Many of the data analyses presented in the text required the calculation of summary data, including monthly or other periodic averages, from this quality-assured data. To avoid potential issues with missing data when making these summary calculations, time periods missing more than 5% of data were discarded.

We excluded a large proportion of all T_{soil} and θ data with our quality assurance procedures. Between 57 and 67% of all soil sites (n=252) had some data excluded from analysis and 23–32% of all available water years of data were excluded (Table A.1). The proportion of data excluded was greater for θ, particularly at lower soil depths (Table A.1). We removed a large amount of irregular θ data due to sensor drift or malfunction, which may explain some of this difference (as in Figure A.3, for example). Older data was also removed at a higher percentage than recent data (Table A.1) and there are two potential reasons for this. First, when we found an apparent sensor change at a site we preferentially excluded older data. Second, data reported immediately after sensor installation may have been subject to more problems than recent data. After all data exclusion steps were complete, 28% of the T_{soil} and θ summary calculations needed for this analysis were missing enough data (> 5%) to be discarded.

Though a large amount of data was removed, some potential errors may remain. Sensors are periodically replaced after they fail and the NRCS provides information about these changes as metadata. Though we tried to remove sensor data with this problem, we did not explicitly use the NRCS metadata when excluding data for our study. We may thus be examining inter-annual variability in time series data derived from more than one sensor. Though we were able to exclude some uncertainty due to instrumentation changes, drift, and malfunction, there are likely site-specific influences on these instruments that are difficult quantify. Exogenous changes at SNOTEL sites, such as the growth of vegetation, may have influenced the long-term T_{soil} and θ record at some sites. Additionally, we did not account for site differences in soil texture, vegetation cover, slope, aspect, and the location of sensors relative to other measurements (SWE, precipitation, T_{air}, etc.) in our analyses. Such site-specific factors certainly influenced T_{soil} and θ and introduced some uncertainty into our analysis of across-site variability.

Because soil temperature and soil moisture are fundamental biophysical drivers of ecosystem processes, the USDA/NRCS SNOTEL network offers great potential to inform ecosystem studies in the western U.S. Though quality issues make this data difficult to work with, we are confident that the quality assurance procedures described here were rigorous enough to remove the majority of problematic data. Future studies could improve upon this analysis in a number of ways. It may be sensible to more effectively use the metadata provided by the NRCS to limit examination of interannual variability to individual sensors if replacement is an issue at a site. The NRCS currently provides some data on soil properties at SNOTEL sites. In future studies, addition of this and other site metadata may allow better quality assurance and explain a large amount of variability in T_{soil} and θ data.

Table A.1: Summary table of the amount of T_{soil} and θ data excluded from this analysis.

	T_{soil}			θ		
	5 cm	20 cm	50 cm	5 cm	20 cm	50 cm
Sites affected (n)	146	147	144	165	169	167
Sites affected (%)	58	58	57	65	67	66
Water years removed (n)	365	394	373	426	456	512
Water years removed (%)	23	25	23	27	29	32
2001 data removed (% of sites)	45	45	36	45	55	55
2002	57	62	52	62	71	62
2003	56	58	56	59	59	61
2004	42	46	46	44	46	50
2005	27	29	30	31	35	45
2006	29	31	32	32	37	42
2007	12	15	13	18	19	22
2008	14	16	13	20	19	22
2009	19	20	18	22	22	25
2010	17	16	16	19	20	24
2011	16	18	16	22	24	26

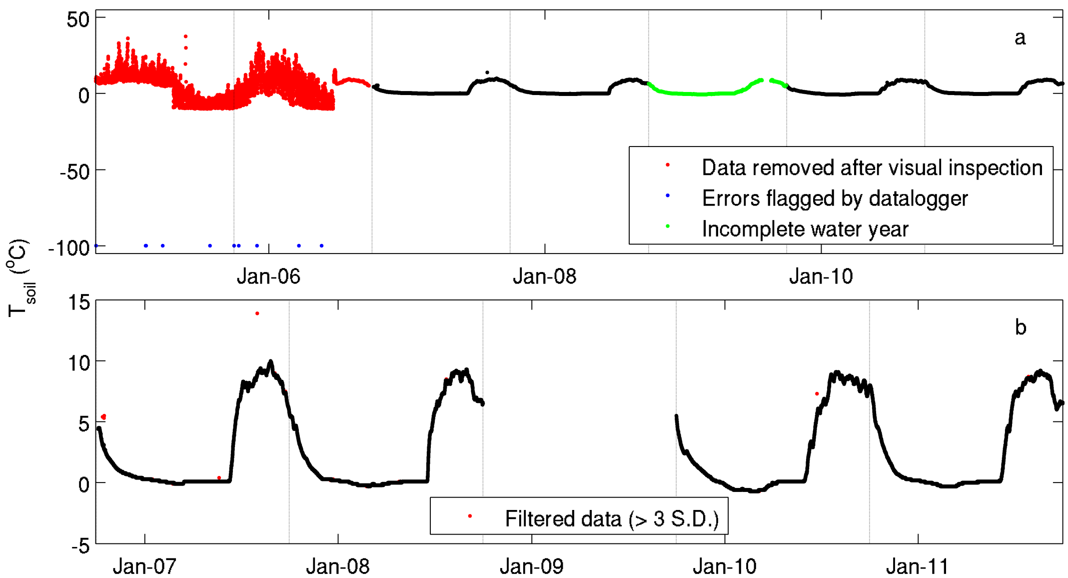

Figure A.1: Soil temperature data from the Slumgullion, CO SNOTEL site. The entire T_{soil} record to 2011 is shown in panel (a), with colors indicating bad data flagged by the datalogger (blue), incomplete water years (green), and data manually excluded due to the change in the sensor response and baseline relative to subsequent data (red). The incomplete water year data (green) was removed because more than 5% of all days did not have hourly measurements. In panel (b), the remaining data are plotted, and red points indicate data that were subsequently excluded because they were more than 3 standard deviations away from the 24 hour running mean. Dashed vertical lines are plotted at the start of each water year (Oct 1).

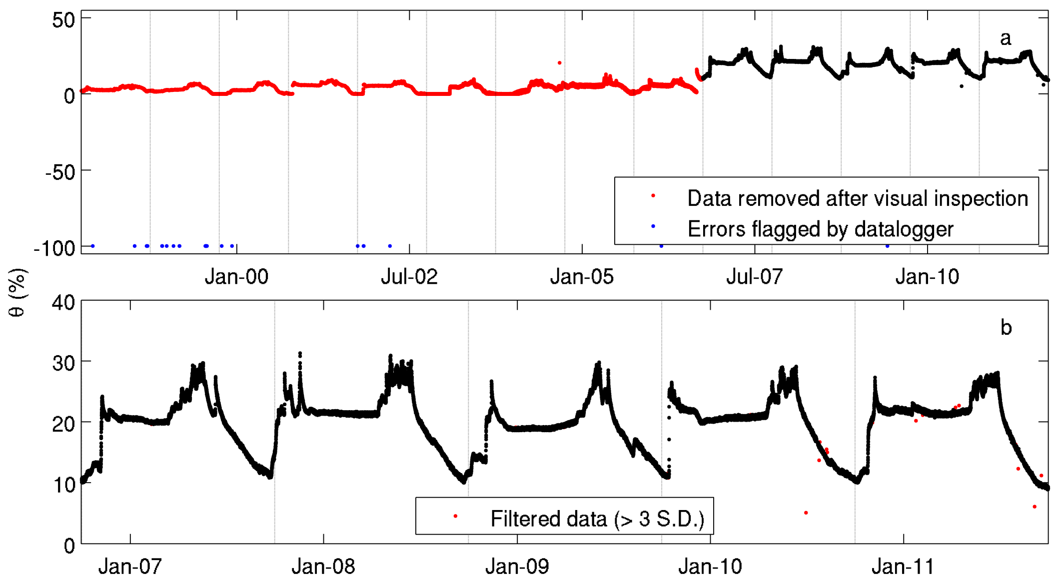

Figure A.2: Soil water content data from the Jackson Peak, ID SNOTEL site, with excluded data highlighted in color, as in Figure A.1.

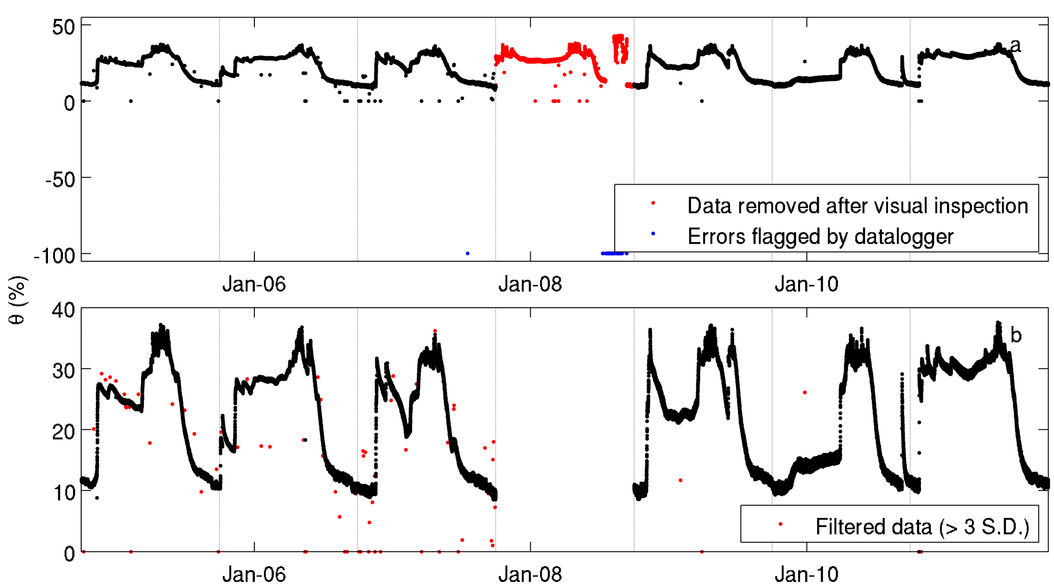

Figure A.3: Soil water content data from the Buckskin Lower, NV SNOTEL site, with excluded data highlighted in color, as in Figures A.1. and A.2.

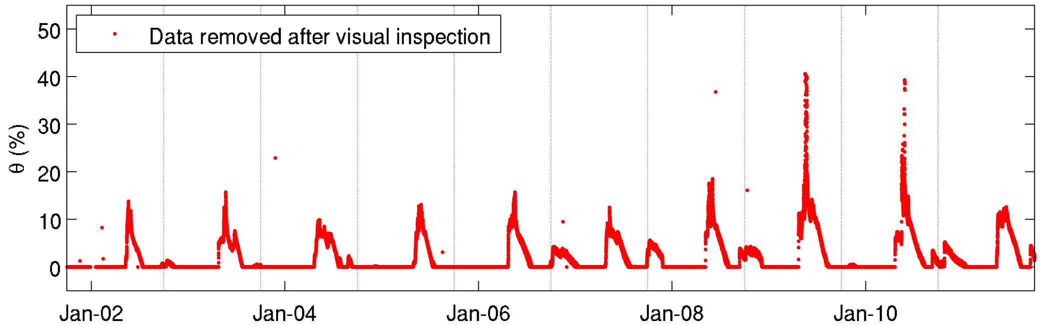

Figure A.4: Soil water content data from the Big Sandy Opening, WY SNOTEL site. All data from this sensor were excluded because the majority of data reported is at 0 % water content. The sensor response may have been out of the range of the calibration equation used by NRCS. Dashed vertical lines are plotted at the start of each water year (Oct 1).

Appendix B: Principal component analysis of climate and soil data from the SNOTEL network

Introduction

In our study of data from 252 SNOTEL sites around the western U.S., we found high intersite variability in below-snow soil temperature (T_{soil}), winter quarter soil water content (θ), and summer quarter soil θ. To test whether this variability in the soil environment was related to snowpack and other climatic variables across these study sites, we used multiple regression analysis with PCA scores as the explanatory variables. This analysis complements our examination of interannual variability in soil temperature and moisture and adds support to hypotheses tested using simple linear regression in the main body of the article. The following sections describe the methodology and results of this analysis.

Methods

We performed principal components analysis (PCA) using two multivariate datasets. These were constructed as matrices with each row containing observations from one individual site in 1 year and columns containing the explanatory variables observed at those sites and in those years. The first dataset contained variables relevant to the below-snow soil environment (snowpack metrics, Oct.–May mean monthly T_{air} and SWE, presnowpack temperature and θ, and below-snow means). The second dataset contained variables relevant to the warm season soil environment (snowpack metrics, May–Sept. mean monthly T_{air} and precipitation, JJA T_{air} and precipitation means, and JFM T_{soil} and θ). Below-snow T_{soil}, winter quarter (JFM) θ, and summer quarter (JJA) θ were the variables examined for dependence on these datasets. Principal components analyses were run for both datasets, which generated a number of new orthogonal axes (principal components). Each new axis was weighted with a loading value for every explanatory variable in the original dataset, signifying the importance of the explanatory variable on the axis. All observations in the dataset received scores indicating their placement along each new axis.

From each set of principal components, we rejected all axes that explained less than 100/N percent of the variance in the dataset, where N was the number of explanatory variables in the dataset. We used the remaining axes to test our hypotheses using multiple regression. The explanatory variables with the three highest loadings were assumed to be the most important for each axis, and we used them to assist in interpreting the multiple regression results. This condensed all correlated environmental quantities down to a few orthogonal, composite variables that could be used in multiple regression analysis.

We chose mean below-snow T_{soil}, winter quarter mean θ, and summer quarter mean θ as the dependent variables for multiple regression analysis because these were the most suitable values for testing our hypotheses. The generalized regression model used was

$$y = PC1 + PC2 + PC3 + PC4$$

where y was the dependent variable (snow-cover period T_{soil} , winter quarter θ, or summer quarter θ), and PC1–4 are the scores for principal component axes 1–4. We ran each PCA and performed the multiple regression analysis with all years of data and then separately for 2007, 2009, and 2011 data.

Below-snow results

We retained the first four principal component axes from the below-snow PCA. These four principal components explained 78% of the variance in the dataset for all years, and 86, 86, and 88% for the 2007, 2009, and 2011 subsets, respectively (Table B.1). The explanatory variable loadings on these axes were fairly consistent in all years (Table B.2), and we used these loadings to characterize the axes. We termed below-snow PC1 the spring snowmelt axis because total snow-covered days, snow-free date, and spring SWE and T_{air} (April and May) were the most important explanatory variables (had the highest loadings) on this axis. We termed PC2 the winter temperature axis because mean T_{air} during the snow-cover period was most important. January through March SWE were also important in the 2007, 2009, and 2011 PC2 axes. We termed PC3 the snowpack start temperature axis because presnowpack T_{soil}, T_{air}, and snowpack start day were most important. Below-snow PC4 was termed the fall snow/soil axis because fall SWE (Oct. and Nov.), presnowpack θ, and presnowpack T_{soil} were most important. Observation scores along these axes were used as explanatory variables in multiple regression analysis of snow-cover period T_{soil} and winter quarter θ (see Tables B.3 and B.4).

In multiple regression tests, mean below-snow T_{soil} was significantly dependent on the winter temperature (PC2) and snowpack start temperature (PC3) axes in all years tested (Table B.3). Below-snow T_{soil} was higher at sites with warmer winter T_{air} (PC2), suggesting that soils were not fully insulated from the thermal environment above the snowpack. Below-snow T_{soil} was cooler at sites that had lower presnowpack T_{soil} and T_{air}, and these sites tended to have a later snowpack start date (PC3). Below-snow T_{soil} was also warmer at sites with greater early-winter SWE (PC1 & 4), though this relationship was not significant in one of the individual years tested. In some years, soils were warmer at sites with higher presnowpack soil moisture (PC4), perhaps indicating an effect related to the high heat capacity of water or latent heat release during soil freezing. Relationships with the spring snowmelt axis (PC1) were generally weak and inconsistent between the years tested.

Mean winter quarter θ was significantly dependent on winter temperature (PC2) and fall snowpack/soil (PC4) axes in all years tested (Table B.4). Winter quarter θ was higher at sites where winter T_{air} was warm (PC2). This may suggest that winter and early spring melt events recharged soil moisture, but a relationship between elevation and soil water content is also a possibility. Winter quarter θ had a positive relationship to the fall snowpack/soil axis (PC4), indicating that winter soil moisture was higher at sites with either greater October and November SWE or higher presnowpack θ, depending on the years of data used in the model. In some of the years tested, winter quarter θ was lower at sites where presnowpack T_{soil} and T_{air} were high (PC3). These results suggest that a combination of precipitation and temperature conditions during the fall and early-winter are important determinants of winter quarter θ.

Warm season results

We retained the first three principal component axes from the warm-season PCA. These four principal components explained 67% of the variance in the dataset for all years, and 75, 73, and 76% for the 2007, 2009, and 2011 subsets, respectively (Table

B.5). We termed warm season PC1 the summer T_{air} axis because summer quarter T_{air} was the most important explanatory variable (Table B.6). We termed PC2 the spring snowmelt/summer precip axis because summer quarter precipitation was the most important explanatory variable for all years, and peak SWE, snow-free date and spring precipitation were most important in the axes for 2007, 2009, and 2011. We termed PC3 the winter T_{soil} axis because winter quarter T_{soil} was most important for all axes except the 2011 axis, in which May precipitation loaded the highest. Overall, the importance of explanatory variables for the warm-season PCA axes changed between years more than for the below-snow PCA axes. Observation scores along these axes were used as explanatory variables in multiple regression analysis of summer quarter θ (see Table B.7).

Mean summer quarter θ was significantly dependent on the summer T_{air} axis (PC1) in all years tested, but precipitation and snowpack were also important explanatory variables in some years (Table B.7). Summer quarter θ was lower at sites with higher summer T_{air} (PC1), suggesting greater rates of warm-season evapotranspiration. Summer quarter θ could be higher at sites with greater warm season precipitation, higher peak SWE, and later snow-free date (PC2 & 3), but these relationships did not hold for all years that we tested. Interestingly, winter T_{soil} also appeared to influence summer quarter θ in some of our multiple regression tests. Though the statistical relationships between summer quarter θ and our explanatory variables were inconsistent between years, they do indicate that warm season T_{air}, warm season precipitation, and snowpack characteristics were responsible for intersite differences in summer soil moisture during some years.

Tables

Table B.1: Standard deviation and variance explained (percent and cumulative) by the first four principal component axes for the below-snow PCA analyses. The results of four separate PCA analyses are shown, PCA using observations from all years together, and using 2007, 2009, and 2011 subsets of the observations.

	PC 1				PC 2				PC 3				PC 4			
	All	2007	2009	2011	All	2007	2009	2011	All	2007	2009	2011	All	2007	2009	2011
Std. Deviation	3.16	3.47	3.42	3.53	2.39	2.43	2.56	2.50	1.51	1.46	1.44	1.54	1.19	1.20	1.01	0.93
% Var. Explained	0.40	0.48	0.47	0.50	0.23	0.24	0.26	0.25	0.09	0.09	0.08	0.09	0.06	0.06	0.04	0.03
Cum. Var. Explained	0.40	0.48	0.47	0.50	0.63	0.72	0.73	0.75	0.72	0.80	0.81	0.84	0.77	0.86	0.85	0.88

Table B.2: Explanatory variables used in the below-snow PCA analyses and their loading values on each of the first four principal component axes. Again, the results of four separate PCA analyses are shown (all years, 2007, 2009, and 2011). The highest loadings for each column were assumed to be the most important variables for the respective axis. Loading values ≥ |0.25| are shown in boldface type.

	PC 1				PC 2				PC 3				PC 4			
Explanatory variables	All	2007	2009	2011	All	2007	2009	2011	All	2007	2009	2011	All	2007	2009	2011
Elevation	-0.14	0.17	-0.15	-0.13	-0.21	-0.19	0.16	0.20	-0.04	**-0.26**	0.17	0.11	0.06	**0.27**	0.11	**0.63**
Snow-covered days[a]	**-0.28**	**0.26**	**-0.26**	**-0.26**	-0.01	0.06	-0.07	-0.05	-0.14	-0.09	0.13	0.11	0.06	0.12	0.05	-0.14
Snow-free day	**-0.27**	0.17	**-0.25**	**-0.25**	0.03	0.12	-0.10	-0.08	-0.07	-0.11	0.05	0.06	-0.09	0.22	0.06	-0.19
Snowpack start day	0.19	-0.21	0.18	0.19	0.03	0.01	0.08	-0.02	**0.47**	**0.39**	**-0.49**	**-0.45**	-0.06	0.18	0.09	0.06
Peak SWE	-0.24	0.19	-0.20	-0.21	0.23	**0.29**	**-0.26**	**-0.25**	0.10	0.10	-0.12	-0.12	-0.17	-0.01	-0.03	0.04
Below-snow period T_{air}[b]	0.08	-0.10	0.12	0.11	**0.37**	**0.34**	**-0.33**	**-0.34**	-0.10	-0.14	0.03	0.08	0.06	0.18	0.12	0.06
Oct. Mean T_{air}	0.15	-0.24	0.23	0.19	**0.27**	0.21	-0.23	**-0.25**	0.11	0.03	-0.01	0.01	-0.07	-0.03	0.01	-0.22
Nov. Mean T_{air}	0.18	-0.24	0.23	0.22	0.18	0.16	-0.22	-0.24	-0.11	-0.17	-0.04	0.01	**-0.31**	0.00	0.06	0.00
Dec. Mean T_{air}	0.13	-0.20	0.24	0.21	**0.28**	0.24	-0.18	-0.21	0.06	-0.14	0.02	0.07	0.13	0.24	0.11	0.24
Jan. Mean T_{air}	0.13	-0.19	0.21	0.18	**0.26**	0.22	-0.21	**-0.26**	-0.15	-0.15	0.04	0.03	-0.04	**0.26**	0.11	-0.16
Feb. Mean T_{air}	0.21	**-0.25**	0.22	0.22	**0.25**	0.20	-0.24	-0.24	-0.06	-0.01	-0.03	0.02	0.03	-0.05	-0.02	-0.06
Mar. Mean T_{air}	0.21	-0.24	0.24	0.24	0.21	0.21	-0.17	-0.18	-0.02	-0.00	0.02	0.03	**0.25**	-0.06	-0.02	0.24
Apr. Mean T_{air}	0.24	-0.24	0.23	**0.25**	0.19	0.15	-0.19	-0.12	0.04	0.05	-0.09	0.01	0.21	**-0.25**	-0.05	**0.35**
May Mean T_{air}	0.22	-0.23	**0.25**	0.24	0.18	0.18	-0.16	-0.15	0.08	0.05	0.00	-0.05	0.14	-0.21	0.06	0.08
Oct. Mean SWE	-0.19	0.23	-0.17	-0.23	-0.01	0.03	-0.01	-0.03	-0.05	-0.17	0.03	0.09	**0.47**	0.01	**0.46**	0.16
Nov. Mean SWE	-0.22	0.24	-0.24	**-0.25**	0.07	0.15	-0.12	-0.08	0.09	0.06	-0.06	-0.03	**0.51**	-0.13	0.19	0.15
Dec. Mean SWE	-0.24	0.21	-0.23	-0.22	0.17	0.24	-0.18	-0.23	0.17	0.13	-0.11	-0.10	0.22	-0.17	-0.02	0.02
Jan. Mean SWE	-0.23	0.18	-0.18	-0.18	**0.25**	**0.28**	**-0.27**	**-0.27**	0.16	0.15	-0.15	-0.13	0.01	-0.13	-0.10	0.15
Feb. Mean SWE	-0.22	0.19	-0.17	-0.19	**0.25**	**0.28**	**-0.29**	**-0.26**	0.14	0.13	-0.12	-0.13	-0.13	-0.13	-0.08	0.16
Mar. Mean SWE	-0.23	0.20	-0.18	-0.19	0.24	**0.28**	**-0.28**	**-0.27**	0.13	0.11	-0.13	-0.13	-0.16	-0.04	-0.05	0.06
Apr. Mean SWE	**-0.26**	0.22	-0.22	-0.22	0.19	0.22	-0.23	-0.23	0.07	0.08	-0.09	-0.09	-0.22	0.14	-0.03	-0.04
May Mean SWE	**-0.26**	0.19	-0.22	-0.24	0.13	0.15	-0.18	-0.18	0.09	0.02	-0.18	-0.08	-0.07	0.22	0.15	0.01
Presnowpack θ[c]	0.01	0.07	-0.06	0.04	-0.05	-0.10	-0.00	0.00	0.20	0.15	-0.17	**-0.35**	**0.27**	**-0.44**	**-0.77**	**-0.27**
Presnowpack T_{soil}[c]	-0.05	0.02	-0.02	0.02	0.11	-0.01	-0.17	-0.12	**-0.53**	**-0.51**	**0.55**	**0.53**	0.04	**-0.45**	-0.18	0.00
Presnowpack T_{air}	-0.09	0.06	-0.03	-0.06	0.20	0.19	-0.23	-0.19	**-0.48**	**-0.52**	**0.49**	**0.50**	0.07	-0.10	-0.09	-0.18

[a] Yearly total
[b] Mean for below-snow period
[c] At 20 cm depth

Table B.3: Results of the multiple regression analyses using below-snow T_{soil} as the dependent variable and the below-snow principal component axes as explanatory variables. Results for four separate analyses are shown (all years, 2007, 2009, and 2011). Regression coefficients for each principal component axis are shown with their standard error (S.E.), p value, and significance as explanatory variables in the model (*** for $p < 0.001$; ** for $p < 0.01$; * for $p < 0.05$).

	All years			2007			2009			2011		
Explanatory vars.	Coeff.	S.E.	p	Coeff.	S.E.	p	Coeff.	S.E.	p	Coeff.	S.E.	p
(Intercept)	0.743	0.023	0.000 ***	0.671	0.052	0.000 ***	0.568	0.059	0.000 ***	0.884	0.035	0.000 ***
PC 1	-0.023	0.007	0.002 **	0.007	0.015	0.617	-0.012	0.017	0.472	0.031	0.010	0.002 **
PC 2	0.141	0.010	0.000 ***	0.081	0.022	0.000 ***	-0.142	0.023	0.000 ***	-0.115	0.014	0.000 ***
PC 3	-0.038	0.015	0.011 *	-0.073	0.036	0.043 *	0.123	0.041	0.003 **	0.080	0.023	0.001 **
PC 4	0.128	0.019	0.000 ***	-0.248	0.045	0.000 ***	-0.157	0.059	0.008 **	0.015	0.038	0.698
Model adj. R^2		0.226			0.272			0.263			0.330	

Table B.4: Results of the multiple regression analyses using winter quarter θ as the dependent variable and the below-snow principal component axes as explanatory variables. Results for four separate analyses are shown (all years, 2007, 2009, and 2011).Regression coefficients for each principal component axis are shown with their standard error (S.E.), p value, and significance as explanatory variables in the model (*** for $p < 0.001$; ** for $p < 0.01$; * for $p < 0.05$).

	All years			2007			2009			2011		
Explanatory vars.	Coeff.	S.E.	p	Coeff.	S.E.	p	Coeff.	S.E.	p	Coeff.	S.E.	p
(Intercept)	0.462	0.007	0.000 ***	0.487	0.016	0.000 ***	0.439	0.015	0.000 ***	0.571	0.014	0.000 ***
PC 1	0.004	0.002	0.102	-0.005	0.005	0.300	0.008	0.004	0.070	0.017	0.004	0.000 ***
PC 2	0.045	0.003	0.000 ***	0.022	0.007	0.001 **	-0.045	0.006	0.000 ***	-0.044	0.006	0.000 ***
PC 3	0.014	0.005	0.003 **	0.046	0.011	0.000 ***	-0.011	0.010	0.266	-0.012	0.009	0.196
PC 4	0.041	0.006	0.000 ***	-0.095	0.014	0.000 ***	-0.094	0.015	0.000 ***	-0.077	0.015	0.000 ***
Model adj. R^2		0.239			0.364			0.417			0.378	

Table B.5: Standard deviation and variance explained (percent and cumulative) by the first three principal component axes for the warm season PCA analyses. The results of four separate PCA analyses are shown, PCA using observations from all years together, and using 2007, 2009, and 2011 subsets of the observations.

	PC 1				PC 2				PC 3			
	All	2007	2009	2011	All	2007	2009	2011	All	2007	2009	2011
Std. Deviation	2.75	3.13	3.05	2.88	1.92	1.74	1.80	2.12	1.48	1.48	1.38	1.57
% Var. Explained	0.38	0.49	0.46	0.41	0.18	0.15	0.16	0.22	0.11	0.11	0.09	0.12
Cum. Var. Explained	0.38	0.49	0.46	0.41	0.56	0.64	0.63	0.64	0.67	0.75	0.72	0.76

Table B.6: Explanatory variables used in the warm season PCA analyses and their loading values on each of the first three principal component axes. Again, the results of four separate PCA analyses are shown (all years, 2007, 2009, and 2011). The highest loadings for each column were assumed to be the most important variables for the respective axis. Loading values ≥ |0.25| are shown in boldface type.

	PC 1				PC 2				PC 3			
	All	2007	2009	2011	All	2007	2009	2011	All	2007	2009	2011
Elevation	**-0.28**	**0.28**	**-0.26**	**-0.26**	0.16	0.07	-0.16	-0.21	0.03	0.01	-0.08	-0.05
Total snow-covered days	**-0.26**	0.23	-0.24	-0.24	**-0.27**	**-0.33**	**0.32**	**0.26**	0.17	0.08	-0.04	-0.18
Snow-free day	-0.23	0.14	-0.21	-0.22	**-0.31**	**-0.37**	**0.38**	**0.29**	0.19	0.22	0.01	-0.20
Peak SWE	-0.11	0.09	-0.09	-0.11	**-0.32**	**-0.41**	**0.45**	**0.30**	**0.33**	0.24	-0.10	**-0.33**
Below-snow period T_{air}	0.22	-0.17	0.21	0.23	-0.15	-0.23	0.23	0.08	**0.29**	0.17	**-0.25**	**-0.34**
Summer quarter mean T_{air}	**0.34**	**-0.31**	**0.32**	**0.33**	-0.11	-0.01	0.08	0.10	0.05	0.08	0.01	-0.08
Apr. Mean T_{air}	**0.30**	**-0.30**	**0.31**	**0.28**	0.19	0.12	0.02	-0.24	0.13	0.09	-0.10	-0.08
May. Mean T_{air}	**0.28**	**-0.31**	**0.30**	**0.31**	0.17	0.06	-0.11	-0.14	0.07	0.09	-0.12	-0.03
Jun. Mean T_{air}	**0.27**	**-0.28**	**0.31**	**0.25**	0.22	0.15	-0.00	**-0.27**	0.12	0.14	-0.14	-0.13
Jul. Mean T_{air}	**0.33**	**-0.31**	**0.32**	**0.32**	-0.03	-0.06	0.03	0.04	0.06	0.03	-0.03	-0.09
Aug. Mean T_{air}	**0.32**	**-0.31**	**0.32**	**0.32**	-0.11	-0.02	0.05	0.11	0.08	0.08	-0.05	-0.10
Sep. Mean T_{air}	**0.29**	**-0.29**	**0.30**	**0.32**	-0.16	0.09	0.16	0.14	-0.01	0.16	0.09	-0.05
Summer quarter precip.	-0.15	0.21	-0.18	-0.15	**0.36**	**0.31**	-0.12	**-0.33**	**0.36**	**0.31**	**-0.46**	**-0.32**
May precip.	-0.09	0.15	-0.07	-0.08	**-0.34**	-0.11	**0.34**	**0.27**	0.20	**0.30**	-0.09	**-0.37**
Jun. precip.	-0.01	-0.08	-0.06	-0.01	**-0.25**	**-0.39**	**0.36**	**0.34**	-0.01	0.19	0.20	0.02
Jul. precip.	-0.12	0.16	-0.09	-0.15	**0.31**	**0.30**	-0.14	**-0.30**	0.20	0.17	**-0.42**	-0.20
Aug. precip.	-0.14	0.20	-0.07	-0.14	0.22	**0.27**	0.18	-0.21	**0.25**	0.18	-0.02	**-0.29**
Sep. precip.	-0.07	0.15	-0.17	-0.08	0.24	0.17	-0.19	**-0.29**	**0.33**	**0.39**	**-0.34**	**-0.33**
Winter quarter 5 cm T_{soil}	0.06	-0.06	0.03	0.09	-0.03	0.13	0.16	0.04	**0.42**	**0.46**	**-0.46**	**-0.33**
Winter quarter 20 cm θ	0.12	-0.09	0.12	0.16	-0.12	-0.03	0.21	0.09	**0.37**	**0.36**	**-0.31**	**-0.26**

Table B.7: Results of the multiple regression analyses using warm season θ as the dependent variable and the warm season principal component axes as explanatory variables. Results for four separate analyses are shown (all years, 2007, 2009, and 2011). Regression coefficients for each principal component axis are shown with their standard error (S.E.), p value, and significance as explanatory variables in the model (*** for $p < 0.001$; ** for $p < 0.01$; * for $p < 0.05$).

	All years			2007			2009			2011		
Explanatory vars.	Coeff.	S.E.	p	Coeff.	S.E.	p	Coeff.	S.E.	p	Coeff.	S.E.	p
(Intercept)	0.271	0.005	0.000 ***	0.225	0.012	0.000 ***	0.268	0.012	0.000 ***	0.333	0.013	0.000 ***
PC 1	-0.022	0.002	0.000 ***	0.025	0.004	0.000 ***	-0.013	0.004	0.001 **	-0.025	0.005	0.000 ***
PC 2	0.010	0.003	0.000 ***	0.024	0.007	0.000 ***	-0.001	0.007	0.897	-0.009	0.006	0.169
PC 3	0.027	0.003	0.000 ***	0.011	0.008	0.180	-0.017	0.009	0.044 *	-0.025	0.008	0.003 **
Model adj. R^2		0.189			0.307			0.084			0.184	

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