Spatio-temporal variability of midwinter snowmelt generated by ground heat flux: implications to catchment hydrology

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Abstract

Introduction

Ground heat flux is largely ignored in modeling of snowmelt processes (reference), particularly among spatially-explicit models (reference). In models that account for ground heat flux processes, spatio-temporal variability of the processes is highly simplified and constrained (reference). The rationale for these simplifications is that snowmelt generation is often dominated by high-energy sources like solar radiation, long-wave radiation, and turbulent heat fluxes. In locations with cold soils, thin snowpacks, or transient snowpacks, few opportunities exist for ground heat to generate snowmelt making the simplifying assumptions reasonable. However, locations in temperate regions where soils freeze irregularly or for limited durations and where deep insulating snowpacks persist, substantial ground heat flux generated snowmelt (ground melt) may occur and may result in substantial snowpack loss over a winter period of several months.

Few empirical studies have reported the occurrence of ground melt, but most field-based snowmelt studies have not utilized methods that would permit observation of these processes. Continuous monitoring of snowpacks typically utilized snow pillows (reference) or snow depth sensors (reference). Neither can account for losses specifically at the base of the snowpack. Alternatively, snowmelt lysimeters directly measure outflow at the base of a snowpack, but in most studies that utilized snowmelt lysimeters, the lysimeter membranes were constructed with materials that would substantially reduce or inhibit heat transfer across the membranes (reference). Additionally, in regions with frequent midwinter snowmelt events generated by surface energy inputs, it can be difficult to accurately separate melt generated by ground heat flux from melt generated by other energy sources.

The current study monitored snow accumulation and melt processes through the winters of 2005/06 (2006), 2006/07 (2007), and 2007/08 (2008) for the purpose of investigating seasonal variation of runoff source area dynamics for a continental, forested, mountainous, snowmelt-dominated catchment in southeast British Columbia, Canada (figure). Snowmelt lysimeters with thin membranes were installed at six sites within the catchment in late October 2006 to monitor spring snowmelt for the purpose of calibrating a snowmelt runoff model. ground melt was recorded at all six sites throughout the 102 day midwinter season of 2007 with nearly continuous subzero air temperatures, even
during periods when daily maximum air temperatures barely exceeded -20°C. At one site, average melt exceeded 1 mm/day and accumulated melt was 108 mm, or 37% as much as the winter peak snow water accumulation (SWE) at that site. In contrast, negligible midwinter ground melt was recorded during the 2008 midwinter season due to early winter soil freezing and delayed snowpack development. The intention of the overall project was not to study ground melt processes. The ground melt observations were unanticipated, but suggest that ground heat should not be automatically discounted as an important source of energy for snowpack loss and soil wetting.

The objectives of the current study were to: (1) report the midwinter snowmelt results; (2) confirm that the midwinter snowmelt was generated by ground heat flux; (3) examine the dominant processes controlling the spatio-temporal variability of the midwinter ground melt; and (4) explore the implications of midwinter ground melt to catchment hydrology. The study hypothesis is that the occurrence and rate of ground melt are controlled by soil temperature, meteorologically driven snowpack heat gradient, and soil wetness.

Methods

Study Area

This study was conducted within the Upper Elk Creek (UEC) sub-catchment (49°21’28”N and 115°46’11”W) of the Cotton Creek Experimental Watershed (CCEW) near Cranbrook, British Columbia, Canada, approximately 540 km east of Vancouver. This study was a component of the CCEW project, which studies the effects of forest harvesting on runoff and sediment transport. The 3.5 km² UEC catchment is almost entirely forested with high density subalpine fir (Abies lasiocarpa) and Engelmann spruce (Picea engelmannii) stands, medium density lodgepole pine (Pinus contorta) and western larch stands (Larix occidentalis), and clearcuts.

The mean hillslope gradient within the UEC catchment is 30% ranging between nearly flat and >60%, and elevations range between 1436 and 1942 m. Upper Elk Creek and Cotton Creek drain westward directly into Moyie Lake approximately 30 km south of Cranbrook, BC. Mean annual precipitation is approximately 800 mm at the Upper Cotton climate station (UCCS; 1775 m elevation) in CCEW, approximately 700 m south of UEC. The hydrologic regime is snowmelt-dominated with solar insulation playing a dominant role in generating spring snowmelt. Snowpacks generally persist from October/November through May/June. Peak snowpack depth generally varies between 1 and 2 m.

Soils are deep glacial tills dominated by sands and silts with abundant coarse fragments. Riparian soils incorporate some organics. By volume, soils average 42% pore space, 3% organics, 38% fines, and 17% coarse fragments. These values likely under-represent coarse fragments, as large particles were excluded from grain-size analysis respective of the sample sizes. Fines average 45% sand, 50% silt, and 5% clay; although, the clay-size
fraction is mostly fine-ground silt rather than true clay minerology. Surficial bedrock exists infrequently in isolated outcrops.

Sample Design

Fifty hillslope monitoring sites were established (33 in October 2005 and 17 in July 2006) at random locations throughout the UEC catchment. Each site incorporated automated measurement of water table elevation and manual measurement of soil saturation, SWE, snow depth, and snow temperature. Access tubes extended through the snowpack to facilitate manual soil saturation measurements throughout winter and spring. At 6 of the 50 hillslope sites, additional automated infrastructure was established in October 2006 to study hydrologic processes in greater detail. These measurements included volumetric soil water content, soil temperature, air temperature, and water input (i.e. snowmelt/rainfall) depth using snowmelt lysimeters. These 6 sites are referred to as lysimeter sites; whereas, all 50 sites that monitor hillslope runoff processes (including the 6 lysimeter sites) are referred to as hillslope sites. Additional details of the data collection infrastructure at the lysimeter sites are provided in table ?.

Seven nested stream discharge stations were installed (3 prior to this study in 2004 and 4 in July 2006). During each field visit, snowcover extent and locations of overland flow were manually mapped. Additional climate data were obtained from 5 automated climate stations that were previously established within CCEW. One is within the UEC catchment and four are between 700 and 1400 m from the UEC catchment boundary. These climate stations acquired a range of meteorology data (e.g. precipitation, air temperature, relative humidity, net radiation, wind speed and direction). Continuous SWE data from the Moyie Mountain snow pillow (BC Ministry of Environment station ID# 2C10P) located at 22 m elevation and approximately 22 km north of UEC catchment were also utilized for this study.

Analysis

Commencement of each midwinter period was defined as the first day of subzero air temperatures following the last occurrence of water input generated by a climatic event in the November/December period. Termination of each midwinter period was defined as the last day of consecutive subzero air temperatures prior to the first occurrence of multiple days of water input at most sites that was generated by a climatic event. This resulted in the 2007 and 2008 midwinter periods being defined as November 22, 2006 to March 3, 2007 (102 Days) and December 10, 2007 to April 1, 2008 (114 Days), respectively.

Hourly data were aggregated to daily intervals for analysis, as the frequency of lysimeter tipping bucket tips was too low to substantiate analysis of hourly data. Exceptions were made for analyzing certain air temperature statistics (e.g. daily maximum).

Soil saturation calibration and re-scaling
A multivariate analysis of the daily ground melt results from the 2007 midwinter period was conducted to investigate the dominant process controls on daily variability in ground melt. The analysis was applied separately for each of the six lysimeter sites. The initial predictor variables considered included air temperature, soil temperature, and soil moisture at each site. Wind speed, vapor density, solar radiation, and snow depth recorded at UCCS were considered as proxy variables. It is acknowledged that the proxy variables do not necessarily represent the conditions at each site equally, but were incorporated in the absence of similarly measured data from each site to quantify the approximate conditions and relative changes in the catchment from day to day.

Autocorrelation and partial autocorrelation functions (ACF and PACF, respectively) were calculated for ground melt at each site to evaluate the strength and persistence of autoregressive memory in the ground melt time series, as any memory needed to be addressed in the multivariate analysis. Cross-correlation functions (CCF) of ground melt with the potential predictor variables were calculated beforehand to gain a better understanding of the variables that might be most suited to predicting ground melt and at what time lags the correlations were strongest. It was possible for soil temperature and soil saturation to both lag and lead ground melt due to the potential for a feedback response loop (discussed below), but any leading correlations were ignored in this analysis for the purpose of ground melt prediction. Further cross-correlation analysis of air temperature with ground melt using a 30-day moving window to investigate whether any ground melt response delay varied through the winter.

Using the cross-correlation and autocorrelation analyses for direction, predictor variables were sequentially added to a regression model for each site to predict ground melt. After adding each variable, the Akaike information criterion (AIC) (reference) was used for model evaluation and for selecting the final model. The ACF, the PACF, and the Durbin-Watson (reference) test statistic were calculated from the model residuals after adding each variable to evaluate the significance of any remaining serial correlation. A plot of the residuals against time was also used for diagnostic purposes.

For each site, AR1, AR2, and AR3 terms were added to the model first and clipped according to the AIC results. Next, air temperature with lags of 0 through 4 were added and clipped accordingly. The square of air temperature was also included in the model selection due to non-linearity in the residuals consistent with multi-day air temperature patterns. The CCF results were used to determine the sequence for adding additional predictor variables after inclusion of air temperature. For soil temperature and soil saturation, lags of 0 (i.e. same-day responses) were excluded from model selection due to the potential for soil temperature and soil saturation to respond to ground melt inputs (i.e. feedback response patterns). For sites 24, 2006, and 4004, the time series were subset for model development due to data gaps (sites 24 and 4004) and due to difficulties in fitting models to melt generated by climatic events (sites 2006 and 4004) (table).
Additional regression models were developed to predict the responses of daily soil temperature and daily soil saturation to ground melt inputs. For both model types, potential predictor variables were limited to relevant autoregressive terms and to ground melt inputs. For soil temperature models, air temperature, snow depth, solar radiation, wind speed, and vapor density were also evaluated as potential predictor variables due to their potential to permeate the snowpack and influence soil temperature. Otherwise, model selection followed a similar procedure as for the ground melt prediction models.

Results

Winter Weather and Snowpack Conditions

The midwinter weather and snowpack conditions for 2007 and 2008 were generally similar, as recorded at UCCS. The average midwinter temperature was slightly colder in 2007 than in 2008 (-7.5°C and -7.0°C, respectively) with slightly lower accumulated precipitation (297 mm and 312 mm, respectively) and slightly lower maximum snowpack depth (1.48 m on February 21 and 1.54 m on March 30, respectively). Through both midwinter periods, air temperatures cycled between multiday periods of cold weather and multiday periods of only slightly subzero weather. In both years, the weather remained only slightly subzero after early February until the onset of active melt, which began in early March in 2007 and in early April in 2008.

Although the midwinter conditions were similar between the two years, the pre-winter conditions were sufficiently different to establish very different antecedent soil hydrothermal conditions. The 2007 pre-winter period (i.e. November 2006) experienced early snowpack development with air temperatures remaining around freezing. Several rainstorm/snowmelt events occurred that did not eliminate the established snowpack, but did generate soil wetting. The early development of a deep insulating snowpack preserved the relatively wet and unfrozen soil conditions in a quasi-static state for the remaining winter.

In contrast, the 2008 pre-winter period (i.e. November and early December 2007) experienced delayed snowpack development with an approximately 2-week period of severely cold weather. The cold weather was followed by a brief warming event and a sudden return to severely cold weather. Rapid snowpack development began after the return to cold weather. The delayed snowpack development and cold weather led to extensive soil freezing and drier soils compared to pre-winter 2007, and were preserved in a quasi-static state for the remaining winter by the subsequent snowpack development.

These differences in antecedent soil conditions were important in controlling ground melt processes through the respective midwinter periods, as discussed below. The remaining sections focus on results from the 2007 and 2008 midwinter periods.
Midwinter snowmelt

Snowmelt was recorded at all 6 lysimeter sites throughout the 102 day midwinter period of 2007. Midwinter melt at the 6 sites averaged 0.46 mm/day and ranged between 0.11 mm/day (site 2013) and 1.06 mm/day (site 6003). The maximum SWE measured manually at the 6 sites in 2007 averaged 266 mm and ranged between 180 mm and 394 mm (figure). The ratio of the accumulated midwinter melt to the maximum SWE for each site averaged 0.18. At site 6003, the accumulated midwinter melt was 108 mm and the maximum SWE was 294 mm, which suggests that approximately 27% (108 mm / (108 mm + 294 mm)) of the accumulated snow was lost to melt at the base of the snowpack, not accounting for atmospheric losses. Moreover, 108 mm of snow loss via ground melt represents approximately 14% of the mean annual precipitation. In contrast, snowmelt recorded throughout the 114 day midwinter period of 2008 averaged only 0.06 mm/day. The melt occurred during the latter relatively warm period of midwinter 2008 and primarily at one location (site 4004).

These results indicate that melt was widespread and comprised a substantial portion of the total snow accumulation during midwinter 2007, but was very limited during midwinter 2008. An important determination is whether or not the midwinter snowmelt was generated by ground heat flux or by other energy sources (i.e. climatic events).

Figure 2 illustrates that snowmelt occurred at some sites through all weather conditions during midwinter 2007 including extended periods of extreme cold conditions (e.g. late November and mid-January). At site 6003, the snowmelt rate maintained at least 0.5 mm/day at all times, even on days when the daily maximum air temperature barely exceeded -20°C. The other sites with less snowmelt also experienced melt through extreme cold conditions, but four sites did experience a break in melt when daily mean air temperatures dropped below approximately -20°C. In contrast, site 4004 (a southwest aspect, low elevation, clearcut site) experienced melt only on days when the daily maximum air temperature exceeded -5°C. The relationship between daily melt and daily mean air temperature was approximately linear for all sites in 2007, but non-linear for site 4004 in 2008 (figure). Moreover, the maximum daily snowmelt at site 4004 was approximately three times higher in 2008 than in 2007.

An energy balance determination for the base of the snowpack suggested that the portion of the total ground heat flux that would have been required to generate the 2007 midwinter snowmelt ranged between 2% and 13% for the 6 sites, in terms of winter averages (table). The most limiting condition occurred on February 10, 2007, at site 6003 when approximately 22% of the available ground heat flux would have been required to generate the daily melt of 1.44 mm. During field investigations on February 11, 2007, the lower portion of the 94 cm deep snowpack at site 6003 was wet and water was observed dripping from the base of the snowpack in a melted air pocket. This was observed in the early afternoon while the air temperature was -2°C after rising from a nightly low of -8°C, and while the snowpack internal and surface temperatures were -4.3°C and -2.0°C, respectively.
The combination of the energy balance results, the field observations on February 11, 2007, and the severity of the cold weather with continued snowmelt in 2007 substantiate the conclusion that the 2007 midwinter snowmelt was generated primarily by ground heat flux. Two notable exceptions occurred when substantial snowmelt energy was contributed by other sources: January 1-2 at site 2006 when approximately 7 mm of additional melt was contributed by a lower elevation forest canopy melt event generated by turbulent heat fluxes, and February 5-8 at site 4004 when at least 3 mm of additional melt was generated by radiation energy fluxes. The data logger at site 4004 was removed for maintenance February 6-11, so snowmelt was not recorded on those days. Other energy sources (i.e., climatic events) were likely responsible for generating most of the snowmelt in 2008.

Processes Controlling Ground Melt

Several processes appeared to control the occurrence, timing, and rate of ground melt throughout the midwinter periods of 2007 and 2008 including variability in soil temperature, meteorologically driven snowpack heat gradients, and soil wetness. The following four sections investigate these process controls.

Soil Temperature

The mean soil temperature at 10 cm depth among all sites was 1.7 °C at the start of the 2007 midwinter period (i.e., November 22, 2006) compared to 0.2 °C at the start of the 2008 midwinter period (i.e., December 10, 2007). As the 2007 midwinter period progressed, the soils cooled at 5 of 6 sites (figure) and functioned as heat sources with vertical heat loss to the overlying snowpack. In contrast, the soils warmed through the midwinter period of 2008 and functioned as heat sinks while gaining heat from deeper soils and potentially the snowpack, depending on the direction of the snow/soil interface heat gradient. These soil temperature patterns were likely representative of the widespread conditions in each year, as soils at most of the 50 hillslope monitoring sites were unfrozen and wet during snowpack surveys in February 2007; whereas, soil freezing was present at most of the 50 sites during snowpack surveys in February 2008.

Midwinter mean daily ground melt in 2007 varied positively with soil temperature at the start of the midwinter period; whereas, soil freezing at the start of midwinter 2008 appeared to inhibit subsequent ground melt (figure). With greater soil temperature, the heat gradient between the soil and the snowpack would have been greater leading to increased rates of vertical heat flux and more energy for snowpack warming or snow melt. Moreover, greater soil temperature at the start of the midwinter period would have resulted in greater heat storage and release for ongoing upward flux throughout the remaining winter.

The overall pattern in figure suggests that a minimum soil temperature threshold of 1 °C was required for ground melt to occur, which reflects that soil temperature was measured at 10 cm depth. In reality, an ongoing threshold of 0 °C at the soil surface would determine whether or not ground melt is possible.
Meteorologically Driven Snowpack Heat Gradient

Ground melt rates were not constant through midwinter 2007 at any of the sites. Rather, daily ground melt varied with air temperature through the entire range of subzero temperatures. At four sites, ground melt stopped when air temperatures were at their lowest values and then re-started when air temperatures increased. At the site with the greatest melt (site 6003), ground melt varied between 0.48 mm/day and 1.74 mm/day (figure). At the site with the lowest melt (site 2013), ground melt varied between 0 mm/day and 0.48 mm/day. A cross-correlation analysis of daily ground melt and daily air temperature for the midwinter period of 2007 showed that the greatest correlations for individual sites ranged between ?? (site ?) and ?? (site ?), and melt lagged air temperature by ?? days (site ?) to ?? days (site ?), respectively. A plot of daily ground melt lagged 3 days on daily air temperature for sites 6003 and 2013 illustrated a clear delayed meteorological control on ground melt for both high melt and low melt sites (figure). The results also suggested that a minimum air temperature threshold exerted control over the occurrence of ground melt at site 2013—the low melt site. At similarly low air temperatures, however, ground melt continued at the high melt site suggesting that other processes were also responsible for controlling the overall melt rates.

A closer investigation of the response of ground melt to varying daily air temperature at site 6003 showed a marked hysteresis behavior likely controlled by the rate of snowpack heat conduction (figure). Ground melt was comparatively greater (given equal air temperatures) through cooling phases than through warming phases. A cross-correlation analysis using a 30-day moving window showed that the ground melt response delay was greater through the middle portion of the midwinter and varied negatively with air temperature—i.e. ground melt was more responsive to air temperature variation when overall air temperatures were greater (figure).

An examination of midwinter mean daily snowmelt for the six sites showed that ground melt increased linearly with midwinter mean air temperature in 2007, but was negligible in 2008 (figure). One outlier was present in the 2007 data likely resulting from the combination of high soil temperature (discussed previously) and high soil wetness (discussed below).

The above results indicate that meteorology and snowpack heat conduction processes exerted substantial control over ground melt rates on a daily basis and as a seasonal accumulation in 2007. Air temperature would have strongly influenced the magnitude of the heat gradient through the snowpack. A stronger heat gradient would have resulted in greater upward heat flux through the snowpack leaving less heat for ground melt, and vice versa for a weaker heat gradient.

Soil Wetness

Midwinter mean daily ground melt in 2007 varied positively with the level of soil saturation at the start of the midwinter period (figure). Water has greater thermal
conductivity and heat capacity than air; therefore, as soil saturation increases and water replaces air in pore space, the thermal conductivity and heat capacity of the soil increases (reference). It appeared likely that sites with greater soil wetness experienced greater conduction of heat to the snowpack through the midwinter period resulting in greater rates of ground melt.

Prediction of Daily Ground Melt From the 2007 Midwinter Period

From the ACF/PACF analysis of daily ground melt form the midwinter period of 2007, first-order autoregressive (AR1) memory was strongly significant at all sites, and second- or third-order (AR2 or AR3, respectively) memory was slightly significant at colder and/or higher melt sites. From the CCF analysis, air temperature was strongly correlated with ground melt at all sites and lags varied from ?? to ?? days. Variables that were slightly to moderately correlated with ground melt included soil temperature, soil saturation, snow depth, wind speed, and vapor density; although, these variables were not significantly correlated at all sites. Lags were apparent at some sites for vapor density, wind speed, and snow depth. Cross-correlation analysis of air temperature with ground melt using a 30-day moving window showed that the ground melt response delay varied through the winter at all sites, and that the response delay was greatest at lower air temperatures.

All of the final regression models were significant at predicting ground melt and all variables in the models were significant. The amount of ground melt variance explained by the models ranged from approximately 80% to approximately 95%, and no significant serial correlation remained in the model residuals. The Kendall test (reference) and the Shapiro-Wilk test (reference) indicated that no trend remained in the model residuals and the model residuals were normally distributed, respectively, for all sites.

All of the final models included snowmelt, air temperature, and snow depth terms. Models for sites 2013 and 6501 included lag 2 terms for ground melt and air temperature. Models for sites 4004 and 6003 included lag 1 and lag 2 soil temperature terms. Soil saturation and other meteorological variables were insignificant at predicting ground melt variability on a daily basis. In terms of the relevance to ground melt response, lagged snowmelt accounted for snowpack water storage effects, present-day (i.e. lag 0) air temperature accounted for short-term variability in meteorological heat inputs, lagged air temperature accounted for short-term snowpack heat storage effects, and present-day snow depth accounted for its long-term influence on the strength of the snowpack heat gradient. The average of the two lagged soil temperature terms accounted for long-term variability in soil heat flux; whereas, the difference between the two lagged soil temperature terms accounted for short-term variability in soil heat flux. It is likely that a portion of the ground melt response delay was associated with delayed measurement by the snowmelt lysimeter system.

Models for sites with relatively cold soils at the start of the midwinter period (e.g. sites 2013 and 6501) included terms with larger ground melt and air temperature lags, which suggests that ground melt responds more rapidly to meteorological changes when overall
ground heat flux inputs are greater. The inclusion of snow depth reflects that deeper snow leads to weaker vertical temperature gradients in the snowpack, holding air temperature constant, and, thus, more soil heat flux can be used for melt rather than for conduction upward through the snowpack.

Soil Temperature and Soil Wetness Response Processes

At most sites, occasions during the 2007 midwinter period with relatively high ground melt rates were accompanied immediately or shortly after by more rapid decreases in soil temperature and more rapid increases in soil saturation (figure). These patterns were particularly noticeable for the non-ground melt events that occurred at site 2006 on January 2 and at site 4004 in early February. To investigate the potential responses of soil temperature and soil wetness to ground melt inputs, regression models were developed to predict soil temperature and soil wetness using the daily data from the 2007 midwinter period.

Results from models???

Discussion

Synthesis of Results

The results from this study suggest that ground melt can represent a substantial portion of the annual water budget and a substantial loss from the winter snowpack; however, the results suggest that ground melt does not occur in all years and varies spatially and temporally in years when it does occur. The first order control on the occurrence of ground melt in any year is the occurrence of widespread soil freezing upon the establishment of a deep, insulating snowpack. With greater soil temperature, greater soil heat is stored and available for upward flux. As a minimum, the temperature of the soil surface must be 0 °C for snow adjacent to the soil to be warmed to its melting point. As illustrated by the 2008 data, it is possible for frozen soils to warm after snowpack development and eventually facilitate ground melt; however, the warming process is slow and could take longer than the duration of the midwinter period.

Provided that the early-winter soil temperature does not inhibit ground melt, spatial variability in the seasonal accumulation of ground melt is controlled by early-winter soil temperature and early-winter soil wetness, and by the mean midwinter air temperature. In effect, early-winter soil wetness and mean midwinter air temperature form second-order controls on ground melt. Soil heat capacity and soil thermal conductivity are positively associated with soil wetness; therefore, greater soil wetness results in greater soil heat storage and greater rates of upward ground heat flux. Greater air temperature results in a weaker snowpack heat gradient leaving more soil heat flux available for ground melt instead of upward heat flux through the snowpack.
Temporal variability in daily ground melt is controlled primarily by daily air temperature variability, which forms a third-order control on ground melt, but also by daily snow depth variability. Air temperature controls on the snowpack heat gradient can influence ground melt both spatially and temporally. Like air temperature, greater snow depth results in a weaker snowpack heat gradient, but by increasing the depth that the gradient acts over rather than by increasing the temperature differential.

Feedback Response Loops

The results of this study suggest that greater soil wetness at the start of the midwinter period promotes greater midwinter ground melt via greater soil thermal conductivity, and that soil wetness responds positively to ground melt inputs. Collectively, these results suggest that soil heat flux and ground melt might form a positive feedback response loop, as they reinforce each other through the influence of soil wetness on soil thermal conductivity. In contrast, greater soil temperature at the start of the midwinter period promotes greater midwinter ground melt (or vice versa for lower soil temperature at the start of the midwinter period), but soil temperature responds negatively to ground melt inputs; hence, soil temperature and ground melt might form and negative feedback response loop. As a result, the potential for both positive and negative feedback response loops constrain each other.

It is uncertain whether any changes in soil wetness or soil temperature with the addition of ground melt inputs could be sufficient to cause either feedback responses to significantly impact ground melt patterns. Furthermore, it is uncertain which feedback response loop might dominate. Detailed physical modeling of the ground melt processes is necessary to further investigate this issue.

Implications to Catchment Hydrology

During the midwinter period of 2007, the greatest amount of ground melt occurred at the site with the highest early-winter soil wetness and the highest pre-winter soil temperature, and resulted in soil wetness being maintained or enhanced through the midwinter period (figure). In contrast, the least amount of ground melt occurred at the site with the lowest early-winter soil wetness, the lowest midwinter mean air temperature, and nearly the lowest early-winter soil temperature and resulted in static soil wetness. Sites with intermediary ground melt inputs experienced soil drying through the winter. As discussed previously, under the right conditions, a positive feedback response loop might be formed between ground heat flux and ground melt via increasing soil wetness, not withstanding the potential limitations caused by soil temperature response. In other words, greater fall soil wetness might cause increased midwinter ground melt causing greater spring soil wetness. As also discussed previously, detailed physical modeling of the ground melt processes is necessary before the potential occurrence of any feedback response loop can be determined more concretely.

Regardless of the merits of a positive feedback response loop between ground heat flux and ground melt, the implications of the midwinter ground melt results to catchment
hydrology are substantial. Locations that start the midwinter period with higher soil wetness receive more ground melt inputs, which leads to a reinforcement of any pre-existing spatial soil wetness patterns. If soil wetness and ground melt inputs are spatially organized, then hillslope hydrologic connectivity would likely be enhanced, which would subsequently enhance catchment hydrologic responsiveness during early spring runoff.

Propensity for Midwinter Ground Melt

It is important to put the midwinter ground melt results in perspective by considering how frequently widespread ground melt is likely to occur. Although only additional midwinter snowmelt monitoring at UEC catchment can determine with certainty the propensity for midwinter ground melt, data from the Moyie Mountain snow pillow were utilized to investigate this issue. Mean air temperature for a 7 day moving window was plotted against SWE at the end of the 7 day window for the October through December period of each year within the 1998-2009 period of record (figure). The results show that air temperatures in 2007 (i.e. autumn 2006) were approximately average up to a SWE of 75 mm and then higher than average between 75 mm and 125 mm. In contrast, air temperatures in 2008 (i.e. autumn 2007) were approximately average up to a SWE of 25 mm and then lower than average for most of the snowpack development between 25 mm and 125 mm. The midwinter period commenced each year of 2007 and 2008 by the time 125 mm of SWE had accumulated at the Moyie Mountain snow pillow (figure); hence, the status of soil temperature as a first-order control on the occurrence of midwinter ground melt was determined by the time 125 mm of SWE had accumulated. On this basis an based on the snowpack/air temperature patterns in figure, it appears likely that the 2007 ground melt results are more common than the 2008 results.

Future Research

Detailed 1-D modeling of surface and subsurface processes at multiple sites is necessary to better understand the processes controlling ground melt, any interactions between the processes, and any potential influences on catchment hydrology. For instance, since forest cover removal alters soil temperature, soil wetness, snow accumulation, and meteorology, it should also influence ground heat flux dynamics and the occurrence and rate of ground melt. Moreover, it is possible that the polyethylene sheeting used to construct the lysimeter liners could have altered sensible and latent heat fluxes between the soil, snowpack, and atmosphere. The liners likely limited upward vertical transfer of heat and vapor from the soil to the snowpack during the snow cover season, and may have retained heat in the soil during and after the warm snow-free period. The former would have decreased the amount of ground melt; whereas, the latter would have increased the amount of ground melt. The liners were installed in October 2007 upon the commencement of snowfall, so the latter effect likely was not a concern for the 2007 midwinter season; however, the former might have been. Nevertheless, detailed 1-D modeling is necessary to better understand any influences on ground melt.

Conclusions
Ground melt can make up a substantial portion of the annual snowmelt budget. Ground melt varies with meteorology and soil temperature. Soil wetness and ground melt form a positive feedback response loop. Pre-winter soil hydro-thermal dynamics and midwinter ground melt might influence spring runoff response. Importance of ground melt not reflected in literature.

Acknowledgements


Literature Cited

Tables

Table 1. Data collection infrastructure.

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Data Frequency</th>
<th>Equipment</th>
<th>Additional Details</th>
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<tr>
<td>Water input rate</td>
<td>Hourly</td>
<td>Snowmelt lysimeter with tipping bucket gauge</td>
<td>4 m² lysimeter, 10 mil polyethylene membrane, 0.06 mm water depth per tip</td>
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<tr>
<td>Air temperature</td>
<td>Hourly</td>
<td>ECH20 temperature probe</td>
<td>2 m above soil surface</td>
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<tr>
<td>Soil temperature</td>
<td>Hourly</td>
<td>ECH20 temperature probe</td>
<td>10 cm depth</td>
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<td>Soil moisture (automated)</td>
<td>Hourly</td>
<td>ECH20 soil moisture probe</td>
<td>20 cm and 40 cm depths</td>
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<td>Soil moisture (manual)</td>
<td>Weekly to bi-monthly</td>
<td>AquaPro capacitance soil moisture probe</td>
<td>10 cm depth intervals</td>
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<tr>
<td>SWE and snow depth</td>
<td>Weekly to bi-monthly</td>
<td>Federal snow sampler</td>
<td>5 samples at 4 m intervals on linear transect across hillslope at 5 m upslope from groundwater well</td>
</tr>
</tbody>
</table>
Water table elevation | Hourly | Ground water well & Odyssey capacitance water level recorder | Screened to ~5 cm below soil surface

Table ?
Need a table showing physiographic information for each of the six sites.

Table ?
Need to research thermal conductivities and include in analysis

Energy Balance at Base of Snowpack:
Winter mean, 2007

<table>
<thead>
<tr>
<th>Site</th>
<th>Heat flux density (W/m²)</th>
<th>Portion of Q₀ used for melt (%)</th>
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<tbody>
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<td>Soil, Qₛ</td>
<td>Melt, Qₘ</td>
</tr>
<tr>
<td>24</td>
<td>13.7</td>
<td>1.1</td>
</tr>
<tr>
<td>2006</td>
<td>11.7</td>
<td>1.7</td>
</tr>
<tr>
<td>2013</td>
<td>6.0</td>
<td>0.4</td>
</tr>
<tr>
<td>4004</td>
<td>9.4</td>
<td>2.6</td>
</tr>
<tr>
<td>6003</td>
<td>19.2</td>
<td>4.0</td>
</tr>
<tr>
<td>6501</td>
<td>15.6</td>
<td>0.9</td>
</tr>
</tbody>
</table>

\[ Q₀ = Qₛ + Qₑ (W/m²) \]
- \( Qₛ \) = soil heat flux density
- \( Qₘ \) = heat flux density to melt water
- \( Qₑ \) = excess heat flux density lost to storage in snowpack and atmosphere

Table ?
Include table of the CCF, ACF, PACF results

Table ?
Include table of the results from the multivariate analysis
Model coefficients, residual standard error, adjusted r², overall p-value

Figures
Figure 7
Figure?
How to change x-axis to have common dates? Use xlim command, min = 2007.begin date (2007/11/1)
Or change x-axis label to “Date” Write 2007 or 2008. Note hourly data
Figure ?

Figure ?

Figure ?
Figure?
Figure?

**Snowmelt (3 day lag) (mm/d)** vs **Daily Mean Air Temperature (°C)**

Site
- 6003
- 2013
Figure

Plot of ground melt response delay on time from 30-day moving window.
Figure 1: Change in Soil Saturation (%) vs. Mean Daily Snowmelt (mm/d).

Figure 2: Change in Soil Saturation (%) vs. Soil Saturation at Start of Midwinter Period (%).