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Two-Dimensional Liquid Water Flow through Snow at the Plot Scale in Continental Snowpacks: Simulations and Field Data Comparisons

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Abstract. Modelling the multi-dimensional flow of liquid water through snow has been limited in spatial and temporal scales to date. Here we present simulations using the iTOUGH2 model informed by the model SNOWPACK, referred to as SnowTOUGH. We use SnowTOUGH to simulate snow metamorphism, melt/freeze processes, and liquid water movement in two-dimensional snowpacks at the plot scale (20 m) on a sloping ground surface during multi-day observation periods at three field sites in northern Colorado, USA. Model results compare well with subalpine and alpine sites, but not a treeline site. Results show the importance of longitudinal (i.e. parallel to ground surface in the downslope direction) intra-snowpack flow paths, particularly during times when the snow surface (i.e. snow-atmosphere interface) is not actively melting. Simulations show that longitudinal flow can occur at rates orders of magnitude greater than vertically downward percolating water flow (a ratio of >250:1) as a result of hydraulic barriers.

1 Introduction

The presence, storage, and movement of liquid water within a snowpack has direct implications for land surface albedo (Dietz et al., 2012), wet-snow avalanches (Mitterer et al., 2011), streamflow generation (Hirashima et al., 2010; Wever et al., 2014), and rain-on-snow runoff generation (Würzer et al., 2016). During snowmelt and rain-on-snow events, the movement of liquid water through snow is a major factor in controlling the timing and magnitude of runoff (Brauchli et al., 2017; Colbeck, 1972; Musselman et al., 2018; Würzer et al., 2016). Although liquid water flow is typically thought of as acting primarily in the vertical direction, previous work has shown that intra-snowpack longitudinal flow can affect the timing, volume, and spatial patterning of runoff. We define intra-snowpack longitudinal flow as flow parallel to the ground surface in the downslope direction (sometimes referred to as lateral flow). Such intra-snowpack longitudinal flow has been shown to deposit runoff directly into streams, bypassing soil interaction (Eiriksson et al., 2013; Liu et al., 2004), and to create focused soil infiltration capable of altering runoff processes (i.e. produce infiltration excess; Webb et al., 2018d). Field observations have shown intra-snowpack flow paths to range in scale from centimetres up to tens of meters (Avanzi et al., 2017; Kattelmann, 1985; Schneebeli, 1995; Webb et al., 2018a; Williams et al., 2010). However, modelling of this spatio-temporally complex process has been limited to one-dimensional (i.e. vertical) or centimetre-scale simulations (e.g. Wever et al., 2014; Würzer et al., 2017).

Multi-dimensional numerical models simulating preferential flow (vertical and/or longitudinal) through snow have only been recently developed (Hirashima et al., 2019; Hirashima et al., 2017; Hirashima et al., 2014; Leroux and Pomeroy, 2017). These models apply long-understood soil physics using laboratory parameterization of snow properties (Calonne et al., 2012; Yamaguchi et al., 2010). As a result, these processes have been simulated primarily in centimetre-scale studies (e.g. Hirashima et al., 2019). However, there remains a need to understand these processes at the plot scale (multiple meters) to further understand the hydrological impacts. Processes to consider during water flow through snow include snow metamorphism, the melting of snow, and re-freezing of liquid water. These processes create temporally dynamic media properties, specifically snow grain size and porosity, creating a more complex environment relative to soil (Webb et al., 2018b). The layered characteristics of a snowpack and rapid metamorphism that occurs during melt (McGurk and Marsh, 1995; Marsh, 1987; Marsh and Woo, 1985) create temporary hydraulic barriers (Webb et al., 2018b) and thus temporally dynamic flow paths.

The goal of this study is to advance the understanding of the spatio-temporal scales of longitudinal intra-snowpack flow paths by simulating liquid water flow through a layered snowpack at the plot scale. The research objectives are: 1) use the model SNOWPACK (Bartelt and Lehning, 2002) to simulate snow metamorphism, melting, and re-freezing processes; 2) utilize enhancements to the TOUGH2 (Pruess et al., 2012) non-isothermal multiphase flow and transport model, as implemented in the iTOUGH2 simulation-optimization framework (Finsterle, 2018, 2007), to simulate water flow through a two-dimensional, temporally dynamic, layered snowpack at the plot scale; and 3) compare results to field observations under varying snowpack conditions.

2 Methods

We simulated liquid water flow through snow at three experimental plots, modelled as 20 m long two-dimensional domains with a hillslope angle of 10° (Fig. 1). Within this domain, the iTOUGH2 numerical model simulated the flow of liquid water with time-varying snow layer properties provided by the SNOWPACK model. It is important to note that the models were not fully coupled. For each iTOUGH2 time step, material properties were updated using output from SNOWPACK at that time step. For the remainder of this paper this soft coupling of SNOWPACK and iTOUGH2 will be referred to as SnowTOUGH. For SnowTOUGH testing, we limited the time domain of simulations to match field observations. We initiated the simulations during the first snow pit observations and ended them approximately three days later at the completion of experiments at each study plot.

2.1 SNOWPACK

The time-dependent material properties of the SnowTOUGH simulations were informed using the physically based SNOWPACK model (Bartelt and Lehning, 2002; Lundy et al., 2001). SNOWPACK discretizes the snow profile into layers, adding layers during accumulation events and consolidating them during compaction and melt. SNOWPACK closes the mass and energy balances at each time step and includes physically based routines for internal snowpack processes including energy exchange, snow grain metamorphism, and liquid water transport. SNOWPACK has been extensively validated in multiple environments and snow conditions (e.g. Jennings et al., 2018; Lundy et al., 2001; Meromy et al., 2015; Wever et al., 2016). Simulations were run at hourly timesteps with quality-controlled meteorological observations. For more information on SNOWPACK simulations, see Webb et al. (2020; 2018c).

Snow layer variables were calculated by SNOWPACK at hourly intervals, specifically snow grain diameter (d), bulk snow density (ρ_s), volumetric liquid water content (θ_w), and volumetric ice content (θ_i). The dry density of each snow layer (ρ_{ds}) was calculated by subtracting θ_w from ρ_s. The melt/freeze rate of each layer was determined by changes in θ_i. Van Genuchten parameters (Van Genuchten, 1980) of unsaturated flow and water retention (i.e. α and n) were determined from SNOWPACK output using equations developed by Yamaguchi et al. (2010):

$$\alpha = 4.4(10^{6})\left(\frac{\rho_{ds}}{d}\right)^{-0.98} \tag{1}$$

$$n = 1 + 2.7(10^{-3})\left(\frac{\rho_{ds}}{d}\right)^{0.61} \tag{2}$$

The intrinsic permeability (K) of each snow layer was defined using SNOWPACK output and the equation developed by Calonne et al. (2012):

$$K = 3.0 r_{es}^{2} exp(-0.013\theta_i\rho_i) \tag{3}$$

where r_{es} is the equivalent sphere radius and ρ_i is the density of ice (917 kg m^{-3}).

2.2 iTOUGH2

iTOUGH2 is a simulation-optimization framework for the TOUGH suite of numerical models that have been utilized and validated for a range of processes in porous media (e.g. Fujimaki et al., 2008; Hannon and Finsterle, 2018; Ho and Webb, 1998; Kechavarzi et al., 2008; Lippmann and Bodavarsson, 1983). For this study we used the equation of state module 9 (EOS9), applying Richards' equation (Richards, 1931) for the transport of liquid water only and does not consider energy transport (Pruess et al., 2012). We used new enhancements to the iTOUGH2 code (Finsterle, 2018) that allow for time-dependent material properties and time-dependent material-related source/sink terms to simulate the snow metamorphism and melt/freeze processes in a layered snowpack. The layered snowpack was modelled above a 10–30 cm deep soil, increasing in depth under deeper snow, with a drain at the downslope end. The model was discretized into elements 50 cm in length and 1 cm in height (Fig. 1). Initial conditions were provided through manual snow pit observations (Webb et al., 2020; Webb et al., 2018c).

The material properties that we defined to vary through time were permeability, the van Genuchten m term (m=1-1/n), and van Genuchten α term. The time-dependent source/sink terms were used to simulate the melt/freeze processes. The melt rate of snow and re-freezing of liquid water, determined from SNOWPACK, was used to quantify time-dependent source terms for liquid water introduction via snowmelt and as corresponding sink terms for re-freezing of water. The movement of liquid water simulated by SnowTOUGH was then compared to field observations at three study plots

3 Field Sites

Field observations of snowpack θ_w, stratigraphy, and longitudinal flow paths were conducted at three locations in the Colorado Rocky Mountains using a combination of dye tracer experiments and ground-based remote sensing. These sites ranged in elevation from a subalpine site at 2700 masl, a treeline site at 3350 masl, and an alpine site at 3500 masl. Each site had continuous observations of snow depth and air temperature with additional meteorological stations at the alpine and subalpine sites. All sites had a ground surface slope of ~10°. For more information on site descriptions and meteorological data, see Webb et al. (2020; 2018c).

During observation periods, which we timed to occur near peak snow water equivalent (SWE), a dye tracer (Rhodamine WT) was applied at each of the study plots immediately prior to the first snow pit observation. This was the time of initiation for SnowTOUGH simulations. The dye tracer was subsequently allowed to move into and through the snow undisturbed for at least two full days prior to a second set of snow pits being dug downslope of application. These snow pits allowed us to observe locations of longitudinal flow paths that transported the dye tracer. For further information concerning the dye tracer experiments see Webb et al. (2020).

Additionally, ground-based remote sensing techniques were used to estimate the plot-scale distribution of θ_w multiple times throughout the observation periods. Snow depths derived from terrestrial LiDAR scanning were collected in combination with ground penetrating radar surveys to obtain spatially distributed dielectric properties of the snowpack that were used to estimate the spatial distribution of bulk snowpack θ_w. For further details of these ground-based remote sensing methods see Webb et al.(2018c).

4 Results

4.1 SNOWPACK

SNOWPACK output shows the progression of liquid water development, snow layer metamorphism, and melt/freeze processes at our three sites (Fig. 2). The timing of our observations was such that we captured a period early in the melt season

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for each plot. Spring snowmelt, defined to begin on the first simulated day of persistent liquid water in the snowpack, began on March 3, March 18, and May 4 for the subalpine, treeline, and alpine study plots, respectively (Fig. 2a). The first day of the intensive observation period for each plot was March 5, April 12, and May 15 for the subalpine, treeline, and alpine study plots, respectively. The subalpine plot was the only site that was not actively melting and releasing liquid water immediately prior to our observation period while the treeline site was melting for the longest time immediately prior to our observations (Fig. 2a). The observation period at the alpine site captured the onset of a storm and re-freezing of the snow surface. Thus, these three sites and observation periods captured varying stratigraphy and conditions that occur within any given melt season in mountainous environments.

4.2 SnowTOUGH

SnowTOUGH incorporated the melt/freeze processes and temporally dynamic snow layer variables into a two-dimensional plot-scale model. At the alpine and treeline sites, SnowTOUGH simulated the presence of multiple hydraulic barriers, holding vertically percolating water and transporting it longitudinally downslope (Fig. 3). Conversely, the subalpine simulations did not simulate longitudinal liquid water flow, though increased water retention in specific layers did occur as a result of the layer water retention properties. These simulations display the higher occurrence of hydraulic barriers as a result of the more complex stratigraphy of higher elevation snowpacks (Fig. 2, 3).

For the treeline site, at a simulation time of 40 hours, when peak longitudinal flow occurred, total simulated intra-snowpack longitudinal flow rate was 0.0058 kg s^{-1} (5.8 ml s^{-1}) per meter width of the study plot. This occurred within a single longitudinal intra-snowpack flow path at the snow-soil interface. The longitudinal intra-snowpack flow rate of 0.0058 kg s^{-1} (5.8 ml s^{-1}) occurred in a profile where vertically downward moving liquid water had a flow rate of 0.0043 kg s^{-1} (4.3 ml s^{-1}).

The alpine site had unique meteorological conditions during the observation and simulation period relative to the other sites. An incoming storm resulted in all surface melt halting during the first day of the three-day simulation period (Fig. 4). The snow surface temperature later warmed back to 0°C for a two-hour period, but no surface melt was simulated to occur during this brief time. Though surface melt stopped, liquid water continued to flow for the entirety of the simulation. SnowTOUGH simulations of the alpine site had three longitudinal intra-snowpack flow paths. At a simulation time of 7 hours, when peak longitudinal flow occurred, the flow rates of individual flow paths were as high as 0.05 kg s^{-1} (50 ml s^{-1}) and total longitudinal flow (i.e. all flow paths combined) was 0.265 kg s^{-1} (265 ml s^{-1}) per meter width of the study plot (Fig. 3). These flowrates occur in a profile where vertically downward moving liquid water was only 6.22×10^{-4} kg s^{-1} (< 1 ml s^{-1}) (Fig. 3). The simulated number of intra-snowpack longitudinal flow paths for the alpine and subalpine sites were equal to field observations whereas the treeline site simulations did not match well with field observed locations of the dye tracer during experiments described in Webb et al. (2020).

4.3 Comparison to Field Data

Field observations compare well to simulations for the alpine and subalpine sites, but not the treeline site (Fig. 3). The number of intra-snowpack flow paths shown in the SnowTOUGH simulations were similar to those shown from dye tracer experiments at the alpine and subalpine sites presented in Webb et al. (2020) though the depths of these flow paths beneath the snow surface differed slightly. The field-observed dye tracer locations that were not simulated as longitudinal flow paths for some instances still display increased liquid water retention or ice lens formation (Fig. 4). Additionally, simulation results suggest increasing longitudinal downslope flux of liquid water with elevation that was similarly observed at these sites (Webb et al., 2020).

The largest discrepancy between simulations and field observations occurred at the treeline site where only one intra-snowpack flow path was simulated using SnowTOUGH and three were observed in the field at different depths beneath the snow surface (Fig. 4). The alpine study plot simulated three longitudinal flow paths and three were observed in the field, though at slightly different vertical depths in the snow profile. Field observations showed one near the snow surface and two near the snow-soil interface. SnowTOUGH simulations of the alpine plot resulted in three flow paths near the snow-soil interface. At the subalpine site both field observations and SnowTOUGH simulations resulted in no longitudinal flow paths.

4 Discussion

This is the first study, to our knowledge, that has simulated the two-dimensional flow of liquid water through a snowpack at the experimental plot scale. Our simulations show the presence of hydraulic barriers that divert liquid water longitudinally via preferential flow paths at the two upper elevation sites (alpine and treeline) that were also present in field observations.

SnowTOUGH simulations produced the greatest rates of longitudinal flow at the highest elevation site, the alpine plot, similar to field observations using dye tracer experiments and ground-based remote sensing techniques (Webb et al., 2020). The number of longitudinal flow paths observed in the field at this site were equal to simulations. The depths of these flow paths beneath the snow surface however, differed slightly between field observations and simulations. This is likely a result of SnowTOUGH simulations not accounting for snow depth variability across the plot and natural snowpack layer heterogeneity (Leroux and Pomeroy, 2017; Marsh and Woo, 1985; Molotch et al., 2016). Some of the field-observed dyed flow paths were observed as dyed ice lenses at the treeline plot (Webb et al., 2020) where SnowTOUGH simulated liquid water storage increased and ice lenses formed with no longitudinal flow. This may result in a longitudinal flow path during later melt events, though further experiments with longer observation periods are necessary. The natural heterogeneity of snowpack stratigraphy would be difficult to characterize at this scale without disturbing the snow at the location of the dye tracer experiment. Maintaining undisturbed conditions is essential to study natural transport of the dye. Additional studies are necessary to characterize the horizontal heterogeneity of stratigraphy in varying snowpack conditions. Previous snow studies have suggested that the discontinuity of layers (such as ice lenses) can be a major factor in flow path continuity (Eiriksson et al., 2013; Kattelmann and Dozier, 1999; McGurk and Marsh, 1995; Schneebeli, 1995; Yamaguchi et al., 2018). However, previous studies of capillary barriers at the interface between soil layers have shown that homogenous layer assumptions, as those made in the present SnowTOUGH simulations, capture the average of randomized heterogeneous simulations (Ho and Webb, 1998). The validity of this assumption for snow should be further studied.

The continued flow of liquid water after surface melt ceased at the alpine site provides insights towards the movement of liquid water during the melt season. The flow paths continued to direct liquid water longitudinally downslope 40 hours after surface melt ceased (Fig. 4) and was confirmed during dye tracer collection and ground-based remote sensing observations. The dyed flow paths still contained liquid water at the time of observations, implying that further longitudinal flow would have likely occurred for an uncertain time and distance. During this time of no surface melt, little vertical movement of water towards the ground surface occurred in the SnowTOUGH simulations and the dominant flow direction was parallel to the ground surface as a result of hydraulic barriers. The simulated longitudinal movement of water through the snowpack was orders of magnitude greater than vertical downward movement of meltwater (>250:1) with peak longitudinal fluxes reaching 265 ml s^{-1} (0.95 m^3 hr^{-1}) per meter width of hillslope in the alpine site simulation (Fig. 3). This suggests that during regular diurnal melt cycles in the spring snowmelt season, meltwater may continue flowing downslope overnight or during cold periods, accumulating at downslope convergent locations. For the alpine plot, this location is where the ground surface and snow surface slope gradients decrease as was observed to accumulate liquid water in the ground-based remote sensing observations (Webb et al., 2020, 2018c) and produced large variability in snowmelt lysimeter discharge in previous years (Rikkers et al., 1996). This process also has implications for SWE distribution during mid-winter melt events. Mid-winter melt events may initiate flow paths that divert liquid water along longitudinal flow paths with no infiltration across the snow-soil interface. This meltwater may flow downslope for many hours due to the relatively slow re-freezing process, with accumulating flow at convergent locations prior to re-freezing. As a result, the distribution of SWE may be such that increased bulk density occurs at downslope locations of convergent flow paths with no obvious increase in depth, and potentially a decrease in depth. For example, Webb et al. (2018a) observed a 170% increase in SWE with a decrease in snow depth as a result of increased liquid water content from upslope locations.

The SnowTOUGH simulations bring new modelling capabilities of two-dimensional liquid water flow through snow. To date, multi-dimensional modelling has been limited to the centimetre scale (e.g. Hirashima et al., 2017; Leroux and Pomeroy, 2017). For simulations at the scale of meters to tens of meters, as presented in the current study, variable parameterization remains a challenge. Current hydraulic variables for snow layers have been developed at the centimetre scale in controlled laboratory environments (Calonne et al., 2012; Yamaguchi et al., 2010) and shown improvement for one-dimensional (vertical) models on flat terrain (e.g. Wever et al., 2016; Wever et al., 2014). However, difficulties arise with layer heterogeneity as previously mentioned, sloping terrain as presented in this study, and if snow grain types vary (Yamaguchi et al., 2012). While these variable parameterizations worked well for the subalpine and alpine study plots, the treeline site simulations did not match field observations well, indicating the variables do not work as well when hydraulic barriers of lesser strength are present (i.e. smaller differences in layer properties across interfaces). Future studies at the plot scale may improve effective parameterization of specific layer variables through the application of snowmelt lysimeters and inverse modelling techniques. Improved parameterization of snow variables for modelling liquid water flow through snow would likely improve the modelling accuracy for hydraulic barriers that dominate liquid water transport during times of little or no surface melt (Fig. 4). These hydraulic barriers cause the longitudinal flow paths at the plot scale and control the storage and release of liquid water. A logical next step for future studies aiming to model this process is to develop a fully coupled two-dimensional model and build upon parameterization of variables to determine effective properties at the plot to hillslope scales.

5 Conclusions

Through the soft coupling of SNOWPACK and iTOUGH2, we successfully simulated the two-dimensional movement of liquid water through a layered snowpack, including snow metamorphism and melt/freeze processes in our SnowTOUGH modelling framework at spatial scales previously unstudied. The simulations compared well with field data at two of the three field sites. Results show the importance of longitudinal intra-snowpack flow paths, particularly during times when the snow surface re-freezes. We show the importance of longitudinal flow paths at the multiple meter scale and for temporal scales beyond regular diurnal fluctuations. At the alpine study site, the longitudinal flow was orders of magnitude greater than vertically downward percolation of water (>250:1). This study shows the increasing influence of longitudinal intra-snowpack flow paths at higher elevations, where a snowpack develops a more complex and persistent stratigraphy. Locations where the snowpack stratigraphy has smaller differences in layer properties across interfaces show a need for future improvement of variable parameterization.

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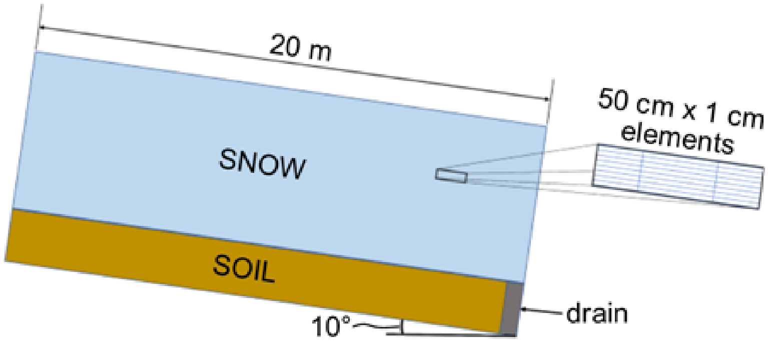

Figure 1: Conceptual diagram of the model domain showing the snowpack above soil, the location of the drain in the soil, and element discretization. Figure not to scale.

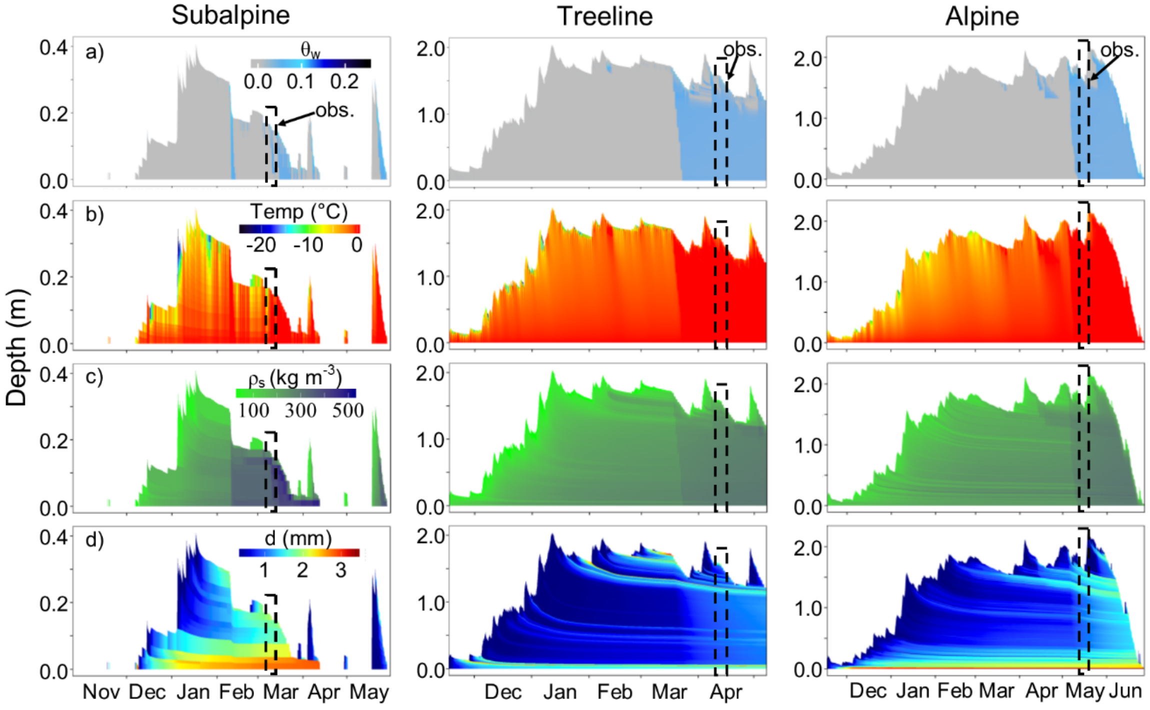

Figure 2: Results of SNOWPACK simulations for the subalpine, treeline, and alpine study sites. Results shown are a) volumetric liquid water content (θ_w), b) snow temperature, c) snow density (ρ_s), and (d) grain diameter with the observation (obs.) and SNOWTOUGH simulation period highlighted in the dashed box. Note that the axes have different scales for each site.

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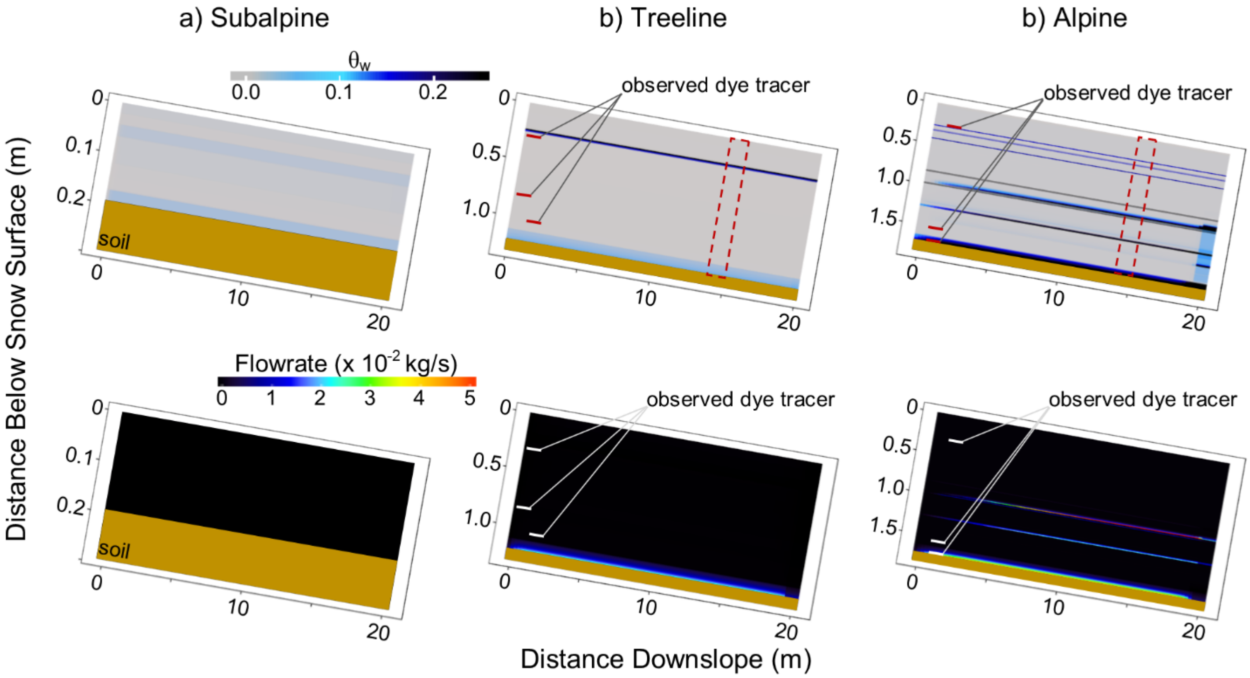

375 **Figure 3: Results of SnowTOUGH simulations for the study sites at peak longitudinal flow: a) subalpine at time = 16 hours, b) treeline at time = 40 hours, and c) alpine at time = 7 hours. Results shown are (top) volumetric liquid water content (θ_w) distribution and (bottom) liquid water mass flowrates in the longitudinal (i.e. parallel to ground surface) direction. The soil elements within the model domain are shown as solid brown to focus results on intra-snowpack distributions. Dashed red boxes in the θ_w plots indicate the profile of model elements used for flowrate calculations.**

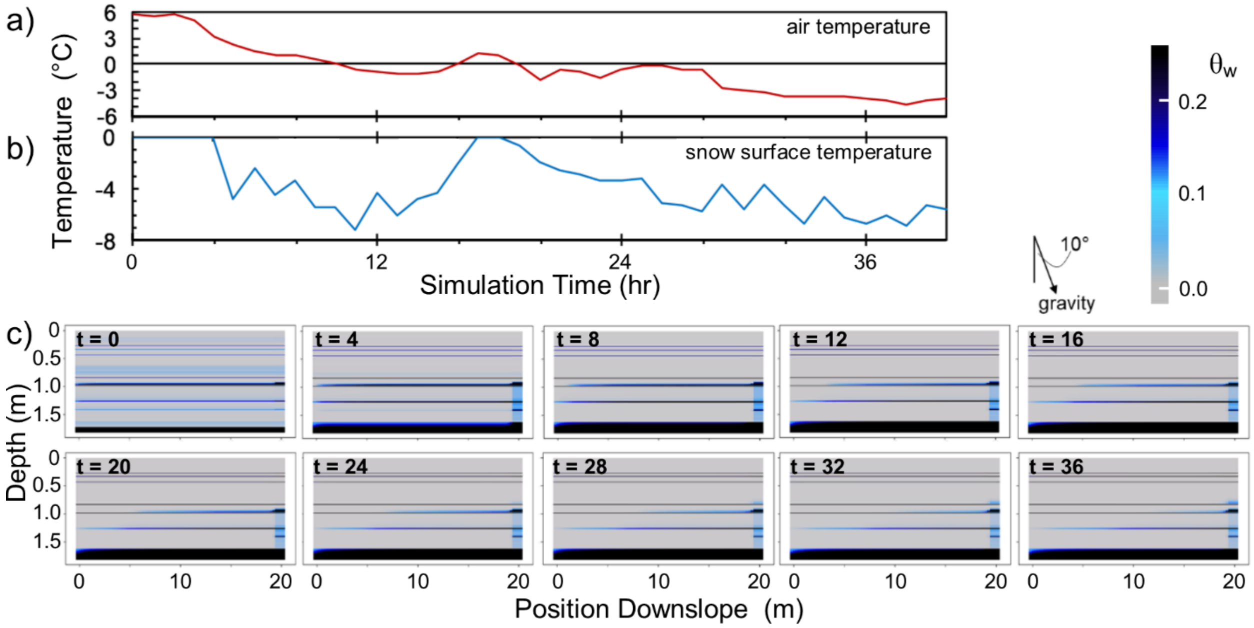

Figure 4: Time series results of SnowTOUGH simulations for the alpine site showing: a) measured air temperature, b) simulated snow surface temperature, and c) volumetric liquid water content (θ_w) distribution at 4-hour intervals (simulation time (t) is identified for each distribution shown). Simulation t = 0 hrs corresponds to May 15, 16:00.