Interactive comment on "Observations and simulations of the seasonal evolution of snowpack cold content and its relation to snowmelt and the snowpack energy budget" by Keith S. Jennings et al.
Anonymous Referee #1
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The authors present a study that uses a long term observational data set to validate simulated snowpack cold content. The authors attribute the largest increase in cold content to new precipitation mass. Validating a complex, multi-layer snowpack model that is frequently used in the literature is a substantial contribution, especially given the uniqueness of the long-term snow pit data. However, as currently presented, this manuscript needs substantial revision and polish. Below I explain my reasoning for this, and I hope the authors can use it to improve this manuscript into the contribution that is hiding under the surface. As is, I recommend accept pending major revisions.

Thank you for the detailed, critical review and the suggestion to publish pending the revisions. In the below response, our comments are in blue text.

My first issue is that these conclusions are specific to a deep snowpacks in a warmer climate. Thin, shallow snowcovers have a long record in the literature as being difficult to simulate due to the substantial radiative cooling of the snowpack resulting in sharp gradients and maximum cold content being exceeded. It is important that all these results are very clearly stated to apply to the deep snowpacks herein.

Given our geographic setting (Colorado Rocky Mountains), we framed this work in the context of western US snowpacks, which are essential to regional water resources. In this regard, the alpine and subalpine snowpacks are considered shallow and cold relative to the deep, warm snowpacks of the Sierra Nevada and Cascade mountains (Armstrong and Armstrong, 1987; Serreze et al., 1999; Trujillo and Molotch, 2014). We note in the discussion section of the original manuscript that these results are specific to the studied sites:

> "Firstly, we have only presented results from two sites within a single snow-dominated research catchment. Seasonal snow cover in the western United States spans a large elevational gradient and includes both maritime (e.g., the Cascades and Sierra Nevada) and continental (e.g., the Rocky Mountains) snowpack regimes (Serreze et al., 1999; Sturm et al., 1995). Therefore, an avenue for further research is to examine differences in cold content development across seasonally snow covered areas, with a particular focus on disentangling the effects of precipitation and air temperature during snowfall at sites with different snowpack characteristics."

However, we agree this framing overlooks the spatially extensive cold, shallow snowpacks of the Canadian Prairies and Arctic, and we have added text to the discussion mentioning these other snowpacks (p. 15 lines 17-21). We also reframed the last paragraph of the introduction (p. 3 lines 4-5) and research question 1 (p. 3 lines 9-10) per the recommendation of Reviewer 2 to emphasize that this research is specific to our study site.

Second, is that I'm not entirely convinced by the results. As I understand it, the authors assert via Figure 3 that cold content of the snow pack is explained by cumulative precipitation. A statistically significant trend line is show for the subalpine site; however, it has an r^2 of 0.17. Cold content is effectively an instantaneous, integrated snowpack temperature expressed as energy required to bring it to zero-degree isothermal. Cold content will, by definition, become greater (more negative) as below zero-degree mass is added to the snowpack. An r^2 of 0.17 is a poor correlation and does not, at least to me, act as strong evidence for the authors conclusion. Perhaps the r^2 for the alpine site is acceptable, however given cold content will by definition increase as cold mass is added, it seems to be a circular result that does not add any new knowledge nor should be unexpected.

We agree that an $r^2$ of 0.17 is low and we note this in the original manuscript:

> "The relationship was statistically significant at the 99% level at both sites despite the low coefficient of determination in the subalpine."

We use significant portions of the text to evaluate the differences between the alpine (precipitation explains the majority of the variance in cold content development and contributes over an order of magnitude more cold content than negative energy fluxes) and subalpine (precipitation explains a small portion of the variance but still contributes nearly an order of magnitude more cold content than negative energy fluxes). We have included additional text to reiterate the differences in between the alpine and subalpine (p. 8 lines 14-19; p. 9 lines 17-21).

Additionally, we frame in the introduction how little work has been done examining how cold content develops in seasonal snowpacks and that one of the only papers to do so suggests that it was primarily through a largely negative surface energy balance. Our conclusion is not that snowfall adds cold content (which is obvious and known), it is that snowfall is the dominant pathway through which the snowpacks at our two study sites develop cold content. This finding is interesting on its own in that the alpine site should have a high potential to develop cold content through a negative energy balance due to high rates of sublimation and net longwave emission from the snowpack. Surprisingly, despite this fact, precipitation exerts a stronger control on cold content in the alpine than subalpine.

With these results, the authors then proceed to the model step, effectively trying to duplicate the observed results. Stepping back, the message I feel like the authors are trying to present are: "there is no substantial radiative cooling of the snowpack, thus the precipitation temperature (and associated cold content) is the principal control on the total snowpack temperature, and therefore cold content." I suspect this is where Figure 8 becomes important, showing a small, negative total Qnet. However, something feels off about these results. In Figure 8a, the only real difference between day and night is the shortwave radiation and a slightly dampened latent heat flux. It seems odd to me that the mean response is identical, especially for the sensible heat flux. I'm just highly skeptical of an almost entirely similar surface energy balance between night and day. I would like the authors, upon confirming these results are correct as presented, to describe in more detail what is going on here, and if this is a site-specific effect or not, as my impression is it may be.

We thank Reviewer 1 for their critical evaluation of figure 8. This caused us to go back into the simulation data and take a closer look at why the values would be so similar, and we found another interesting facet of cold content development during non-snowfall days. When subsetting the data to all hours of cold content gain without snowfall, we found that midday gains (0900 h to 1400 h) were practically negligible. Thus, the energy balance results were similar for the day and night periods because the daytime gains occurred primarily in the early morning and late afternoon hours. We added Figure S1 (histograms showing the frequency of cold content gains without snowfall at each site, binned by hour) to the supplementary material and related text to the results section (p. 10 lines 4-11).

Because daytime hours with cold content gains were so uncommon, we decided to redo figure 8 to present the daily energy balance for non-snowfall days with cold content gains. Figure 8 now shows the energy balance for the entire day and mean $Q_{net}$ by hour. Interestingly, even on days with flux-driven cold content gains, $Q_{net}$ is positive during the midday hours. As noted in the paragraph above, midday hours with negative $Q_{net}$ were rare, thus the average $Q_{net}$ for these hours was positive.

Additionally, while taking a closer look at the data we found several instances of simulated cold content spiking up and down ($0.3\ \mathrm{MJ\ m^{-2}\ h^{-1}} \leq \Delta CC \leq -0.3\ \mathrm{MJ\ m^{-2}\ h^{-1}}$) before returning to approximately its previous value. We removed these spikes from the analysis (representing less than 0.2% of the dataset) and added a note on p. 7 (lines 10-12).

Stepping back to Figure 6, I feel like this further highlights my issue with this conclusion. Full energy balance models use the balance of the energetics to simulate internal layer temperatures and energetics. Using cumulative mean air temperature feels very temperature-indexy and not really appropriate in this context – it supposes that the entirely of the snowpack energetics could potentially be explained by a mean air temperature, when in reality it's really the associated processes that would impact it.

We state our motivation for including air temperature in the introduction from the original manuscript:

> "Cold content can be estimated using at least one of three primary methods: 1) As an empirical function of air temperature (e.g., Anderson, 1976; Seligman et al., 2014; United States Army Corps of Engineers, 1956); 2) As a function of precipitation and air temperature (e.g., Cherkauer et al., 2003; Lehning et al., 2002b; Wigmosta et al., 1994) or wet bulb temperature (Anderson, 1968) during precipitation; and 3) As a residual of the snowpack energy balance (e,g., Andreadis et al., 2009; Cline, 1997; Lehning et al., 2002b; Marks and Winstral, 2001). In general, simple temperature-index models employ method 1, while both 2 and 3 are utilized in physics-based snow models. These methods suggest that cold content develops through both meteorological and energy balance processes, but few direct comparisons to observed cold content exist. This is likely due to the inherent difficulty in measuring cold content, which requires either time-intensive snow pits or co-located snow depth, density, and temperature measurements (Burns et al., 2014; Helgason and Pomeroy, 2011; Marks et al., 1992; Molotch et al., 2016). The lack of validation data introduces significant uncertainty into the dominant process by which cold content develops. Thus, it is not known whether cold content is primarily a function of air temperature (method 1), snowfall (method 2), or a negative surface energy balance (method 3)."

Given that air temperature is still used in current literature (e.g., DeWalle and Rango, 2008; Mosier et al., 2016; Seligman et al., 2014) to estimate cold content and that no research has shown the process (meteorological or energy balance) behind cold content development, we believe its inclusion appropriate.

Third, precipitation temperature and phase is unaddressed and is a critical component of this work. The simulations shown in Figure 9 c and d suppose the precipitation temperature and phase are correct. I'm assuming you used the default temperaturethreshold in Snowpack for phase? These results could be quite different if phase was wrong (i.e., rain instead of warm snow) or precipitation temperature was biased. There is substantial uncertainty associated with phase partitioning methods and snowfall temperature (e.g., Harder, et al. 2014), and these have significant implications for this work. How sensitive are these results to various phase and falling hydrometeor temperatures?

Regarding precipitation phase, we increased the standard SNOWPACK rain-snow air temperature threshold from 1.2°C to 2.5°C to better represent phase partitioning at our high-elevation continental location (a paper of ours in press at Nature Communications shows the Rocky Mountains have some of the highest rain-snow air temperature thresholds in the Northern Hemisphere; Jennings et al., In Press). To test the effect of our threshold selection, we compared the annual snow frequency using the 2.5°C threshold (alpine = 76.4%; subalpine = 61.5%) to a bivariate binary logistic regression phase prediction model (alpine = 76.7%; subalpine = 62.8%). This model predicts precipitation phase as a function of relative humidity and air temperature, and it was shown to the best precipitation phase method in a Northern Hemisphere comparison (Jennings et al., In Press). We have added this information to p. 6 (lines 10-16).

The temperature of precipitation is a likely shortcoming of SNOWPACK as the model sets precipitation temperature equal to air temperature. In independent work we have performed, we found wet bulb temperature to be a better predictor of new snow temperature, which was also noted in Harder and Pomeroy (2013). This should be included as an update in the SNOWPACK model considering wet bulb temperature could be easily estimated from the already standard forcing data. However, because SNOWPACK prescribes new snow temperature to be equal to air temperature, our estimates of the cold content added by precipitation are on the conservative side. The use of the colder wet bulb temperature (relative humidity is often below saturation, even during snowfall on Niwot Ridge) would lead to a greater amount of cold content added by precipitation. We have added this to the new modeling uncertainty discussion section (Sect. 5.2).

Fourth, despite reading through this a few times looking for it, it is unclear to me what kind of clearing this sub-alpine site is in. The site is specifically stated as a clearing, but the Snowpack canopy routine is enabled. This will significantly change the surface fluxes as well as precipitation at the snow surface; e.g., canopy interception. In my mind, this undermines the results presented herein – maybe it explains the poor result in Figure 3? – and needs to be detailed and the effects and impacts explained. Site photos would go a long way towards helping orient the reader. However as is, this is a major detail that is omitted.

This is an excellent point and we have added site photos to Figure 1. We have also changed the text from "small clearing" to "stand of lodgepole pine" to be clearer.

Fifth, A discussion on the role of Qg on cold content is needed and the assumptions behind your Qg simulation flux. These results show a treatment of the surface fluxes on cold content, but neglect discussion of soil-snowpack interactions, e.g., conditions that lead to frozen soil or refreezing of active layers.

We have added information to the manuscript discussing how $Q_G$ is simulated (covered in detail in Reviewer 1's other $Q_G$ comment on page 8 below). As to the rest of the comment, we do include $Q_G$ in our analysis of the snowpack energy balance, noting that it is typically positive even during periods of cold content gain. Frozen soil is more relevant to runoff processes and is outside the scope of this work. Refreezing of active layers leads to cold content losses (latent heat is released as the phase of water changes from liquid to solid). While this process is important to snowpack ripening and snowmelt generation, we only consider the empirical relationships between cold content and snowmelt rate/timing in this work.

Lastly, the authors assert that increased peak cold content and total spring precipitation control snowmelt onset. But this seems by-definition – doesn't this imply more mass and refreshed albedos? Isn't this just what you'd expect with increased cold content being a function of snowpack mass?

This is noted in the discussion of the original manuscript:

> "These results all suggest later seasonal snowmelt onset and faster snowmelt rates are primarily a function of persistent snowfall. While snowfall events can add significant cold content to the snowpack, they also change other fundamental properties that can delay snowmelt timing, such as increasing surface albedo (Clow et al., 2016) and adding dry pore space that must be saturated (Seligman et al., 2014)."

In summary: As I understand the results presented, the story is that the authors found limited evidence for sustained energy loss from the snowpack and that the cold content of the snowpack was mostly a result of mass inputs. However, there are many confounding factors that make it difficult to accept this at face value. Given the circular reasoning in the results (more snow -> more cold content, but that is by definition), it is difficult for the reader to accept the results. That being said, validating the model against these observations is quite interesting and diagnosing snowpack energy loss during the winter is a useful contribution. However, I think the overall message needs to be refined to more clearly articulate the site-specific nature of this study, the uncertainties in key aspects of the analysis (e.g., precipitation, canopy), and the text improved for readability.

We again thank Reviewer 1 for their critical review of this work. We have added text to the manuscript to illustrate our results are specific to our two study sites in addition to the discussion section that covered this point in the original manuscript. We have also addressed their specific comments below to improve the readability of the text and more clearly outline the project's uncertainties.

Additionally, we would like to reiterate the novelty of this work. There is relatively little previous literature assessing the meteorological and energy balance controls on cold content development. We used a combination of observed data and validated simulation output to show precipitation was the dominant source of cold content development at our two sites. This finding was particularly surprising at the cold alpine site considering its high rates of snowpack sublimation and net longwave emission.

References Harder, P., and J. W. Pomeroy (2014), Hydrological model uncertainty due to precipitation-phase partitioning methods, Hydrol. Process., 28, 4311–4327, doi:10.1002/hyp.10214.

Specific points

Throughout:
The authors introduce (para 25) increase/decrease for cold content, but proceed to use gain/loss. I think it should be consistent throughout

We have changed p. 5 (lines 4-6) to include gain/loss and increase/decrease.

Figure is used in the text but Fig. when used in brackets. Ideally should be consistent.

This usage is in accordance with The Cryosphere's style guide (https://www.the-cryosphere.net/for_authors/manuscript_preparation.html) and will be kept:

> *"The abbreviation "Fig." should be used when it appears in running text and should be followed by a number unless it comes at the beginning of a sentence, e.g.: "The results are depicted in Fig. 5. Figure 9 reveals that..."."*

Units should be separated with a cdot instead of spaces, e.g., Wâ´NEˇm^(-2)

The Cryosphere does not specify the use of c-dots. The only example units we found in the manuscript prep instructions showed the units with a space as we have in the manuscript:

> *"Units must be written exponentially (e.g. $W\ m^{-2}$)."*

Unclear what wet and dry days mean. Wet implies rain to me, but I suspect that's not what you mean. I would reword, or at least clearly define.

Yes, this is confusing. We have changed all relevant text to reflect this (snowfall/precipitation and non-snowfall/non-precipitation days instead of wet and dry days).

P1, Para 20: “cold content ... associated with reduced snowmelt” this needs to be reworded as snowmelt should be happening when CC = 0. Which melt rate is being considered?

Reworded for clarity.

P2, Para 20: “the authors” which authors?

Reworded for clarity.

P2, Para 25: “Furthermore: : :” I’m not sure I agree with this statement. CC needs to be = 0 for melt to occur, so isn’t this known? Do you have a citation?

The citations are in the following paragraphs and they indicate they provide differing perspectives on the control exerted by cold content on seasonal melt rate and timing. However, our text was not clear enough (yes, melt occurs when $Q_{net}$ is positive and CC = 0) that we were referring to winter cold content magnitude and we have edited p. 2 (line 29) for clarity.

P2, Para 30: “saturate”, word choice

Saturate is commonly used in the snow hydrology literature in reference to satisfying the irreducible liquid water content of a snowpack, but we have edited p. 3 (lines 1-2) to be more specific and be applicable to other hydrologists to whom the word saturate may indicate all pore space is filled.

P2, Para 30: “However: : :”, I’m unclear what you’re trying to say, please clarify.

Edited for clarity.

P3, Para 10, 15, 30 Need to be indented.

Changed

P3, Para 20, use “10 m/s to 13 m/s” instead of how it is written.

Changed, but units are left in exponential form to be consistent with The Cryosphere style.

P4, Para 1, “Snow” incorrect capitalized

Snow begins an independent clause, meaning it can (or should, depending on your preferred style guide) be left capitalized.

P4, Para 14, “downwelling longwave” I would put a quick note as to what method you used.

Added this information to p.4 (lines 21-22), with full methodology detailed in the appendix.

P5, Para 20, remove “proposed in Sect. 1”

Changed

P5, Para 20 “We then quantified” I found this section unclear

Rewritten for clarity.

P5, Eqn 3 Consider writing 86,400 as a variable and showing in the text the units. Either way, you need units.

Changed.

P5, Para 15 “in order to improve” Using a model doesn’t improve obs, it just compliments them. I think you should reword to make this distinction.

Yes, changed.

P5, Para 20 “number of finite elements” change to layers

Changed. Although SNOWPACK is a finite element model, that is not important here.

P5, Para 25 remove “the numerical model in”

Removed.

P5, Para 5, the canopy module stuff comes out of nowhere, especially given you say the site is in a clearing. This needs to be much clearer.

We changed the site description to note the pits are dug in a “stand” of lodgepole pine and have included a site photo in Figure 1.

P5, Para 20 “Output from snow model simulations” I don’t follow. Do you mean the comparison is more robust w/multiple outputs to validate?

We are noting that the output of snow model simulations has greater fidelity when validated on more than just SWE, based on the work of Lapo et al. (2015). We are stating that we can make conclusions on the simulations of snowpack cold content because we have actual measurements of cold content to which we can compare the model output. We added text to p. 7 (lines 4-5) to clarify.

P6, Para 20 Any EC observations considered?

We did not consider using the EC observations on Niwot Ridge because the subalpine AmeriFlux tower measures fluxes above the canopy (21 m) and not near the snow surface. There are EC measurements in the alpine, but the records are short and the instruments are located near areas of snow scour.

P7, Eqn 4 The form for the energy balance equation given in Equation 4 is not a standard form. Generally, the change in internal energetics are given as a dU/dt and Qm is on the LHS. Qnet and Qm together are redundant in the energy balance as the energy available for melt is the net energy.

The form presented in the Equation 4 is used frequently throughout the snow hydrology literature (Cline, 1997; Marks et al., 2008; Marks and Dozier, 1992, to name just a few examples). However, we have changed the notation to the suggested form in order to avoid confusion. Additionally, we have changed $Q_{net}$ to refer to the sum of the radiative, turbulent, and ground heat fluxes in order to avoid writing out the full energy balance each time we are referring to the net surface and ground fluxes.

P7, Para 1, “time scales” -> temporal scales

Time scale is appropriate and left as-is.

P7, Para 25, as I said above, I don't buy that an r^2=0.17 demonstrates a primary control

Please see our previous note. We also clarified to say "of the two meteorological quantities evaluated here" to note we are referring to precipitation and air temperature. As mentioned previously, we devote an entire discussion section to the topic of subalpine cold content development and why precipitation exhibits a reduced effect relative to the alpine.

P8, Para 5, Probably should note these are depth averaged

Fixed.

P8, Para 10, -2.2 should have units after it P8,

Fixed.

Para 15, How is this working with the canopy module? Intercepted snow has massive sublimation losses, but that doesn't seem to be reflected here.

We are only concerned with snow surface sublimation as canopy sublimation does not directly lead to changes in snowpack internal energy.

P8, Para 20, Monotonically is either monotonic or not. There is no in-between. Reword

Correct. We removed that sentence and included a new sentence to clarify precipitation exerts a stronger control in the alpine than subalpine (p. 9, lines 17–21).

P8, Para 25, "simulations confirm" change to "support" or similar

Changed.

P9, Para 10, So how are you calculating Qg? Maybe I missed it? I think you need a reasonable treatment on the assumptions behind however you do this. Did you couple snowpack with the soil? Constant flux? Constant ground temp? Qg is important for a conduction heat flux into the snow pack, and needs to be addressed if you go after cold content. Often Qg is taken to be 0-4W/m^2, but this flux can be important for stopping a numerical model from simulating absurd cold contents.

We used version 3.3 of SNOWPACK, which assumes a ground temperature of 0°C when there is snow cover. Simulations showed $Q_G$ was typically between 0 and 4 W m$^{-2}$ when snow depth exceeded ~20 cm, which is similar to other values reported in the literature. Thus, $Q_G$ provides a small, but consistently positive to the snowpack energy balance. Cline (1997) noted ground heat flux was negligible at the alpine site using a flux plate in the soil. Snow pit data from the alpine and subalpine are consistent with this in that the warmest snowpack temperatures are observed at the bottom until ripening begins. We added this information to p. 6 (lines 20-21) in the methods and new Sect. 5.2 in the discussion.

P12, Para 10 "continued snowfall" But this is just more mass, so you'd expect snowmelt timing to be delayed P12,

Mass additions do not lead to consistent snowmelt responses because mass in and of itself is not a physical property that delays snowmelt (i.e., a given amount of warm, wet snow has a much different effect on snow energetics and runoff than the same amount of cold, dry snow due to the amount of liquid water vs. dry pore space, changes to surface albedo, and cold content). Furthermore, we note other hypotheses in the discussion of the original manuscript:

> "These results all suggest later seasonal snowmelt onset and faster snowmelt rates are primarily a function of persistent snowfall. While snowfall events can add significant cold content to the snowpack, they also change other fundamental properties that can delay snowmelt timing, such as increasing surface albedo (Clow et al., 2016) and adding dry pore space that must be saturated (Seligman et al., 2014)."

Para 20, "future work: : :" Lots of work on this already: : :.

We have rewritten to clarify that most previous work focuses on single, well-instrumented sites (such as our manuscript) or vast networks of SNOTEL-like sites with only air temperature, precipitation, and SWE observations (e.g., Trujillo and Molotch, 2014). A spatially explicit, energy balance treatment has yet to be applied to the different snow categories of the western United States despite the irreplaceable contribution of snowmelt to the hydrologic cycle and regional water resources. We have added text to this discussion section to clarify our statement (p. 14 lines 29-32).

P16, Para 30 Given Snowpack is forced hourly, this longwave estimate seems like a massive source of uncertainty, especially within the context of an energy balance model. There are many incoming longwave formulations that take into account various proxies for non-clear sky. You seem to do this for your emissivity, but it's not clear how that exactly works. With such low r^2 this needs to be detailed and expanded upon. The large error in a critically important mid-winter energy flux may have substantial implications for this work.

This is an important point and we have added a note on this limitation to the new discussion section on modeling uncertainty (Sect. 5.2). Downwelling longwave radiation is under-sampled relative to other standard forcing data (Raleigh et al., 2016) and associated errors propagate into SWE and snow temperature biases (Lapo et al., 2015). Schlögl et al. (2016) showed little sensitivity in Alpine3D SWE simulations to a selection of empirical longwave estimates and Lapo et al. (2015) indicated the largest effects of longwave uncertainty were simulated at perturbations greater than ±10 W $m^{-2}$. Thus our small mean bias likely indicates the total amount of incoming longwave radiation is correct while the low $r^2$ suggests the timing of subdaily fluctuations is not well simulated. Our multi-variable validation shows that SNOWPACK performs well relative to snow pit observations of SWE, depth-weighted snowpack temperature, and cold content.

Figures All figures – It would certainly aid readability to have them labeled as alpine/sub alpine without having to constantly refer to the caption.

Agreed. Changed on all relevant figures.

Figure 1, difficult to determine differences at high elevation.

We added contour lines to the figure along with site photos per an earlier recommendation.

Figure 2, can you change the DOY to dates for easier parsing?

Yes, changed for easier interpretation on this figure and others that previously showed DOWY.

Figure 5a,b Should have same axis extents

Axes left as-is.

Figure 8abcd would benefit from having the same y- (ab) and x- (cd) axes to aid in comparison. Also, please expand the y-axes of (ab) so-as to understand what the limits are.

Changed per this suggestion and our notes on the energy balance in pages 2 and 3 above.

Figure 9, needs legend

Changed.

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**Review of :**

**Observations and simulations of the seasonal evolution of snowpack cold content and its relation to snowmelt and the snowpack energy budget,**
**by Jennings et al.**

The authors address the issue of the drivers of cold content evolution based on the exemple of two seasonal snowpacks from a single observation catchment in the Western US. They also assess, in a much shorter part, the effect of cold-content on snow-melt timing and rates.

The paper is well written and well illustrated. The take-home message is clear and the objectives assessed in Introduction are achieved with scientific quality. I found the paper both an appreciable synthesis of existing litterature on the topic, and enlightening regarding the conclusions achieved.

We thank Reviewer 2 for their suggestions and thoughtful review of the manuscript. Our responses are in blue text throughout this document and we have made changes to the manuscript in regard to their comments.

In addition to the few suggestions made below, there is in my opinion one minor contradiction in the Result section (point 9 below), that I would recommand the authors to adress with priority as it affects the consistency of the paper. Note that this apparent contradiction may come from misunderstanding from my side, or an edit mistake from the side of the authors. Comment addressed in point 9 below.

1. Introduction-p2 Ll-6 : not the snowmelt itself is critical for the cited applications, but the timing of surface/subsurface runoff from Snowmelt, which may not be the same when surface melt occurs and refreezes (as just mentionned earlier in the manuscript). For consistence I suggest changing« snowmelt » into« runoff from snowmelt » in the current sentence.
Yes, this is a good distinction. We have changed the text to reflect this (p. 2 lines 2-3).

2. Introduction-p2 L16-18 : Aren't the « dominant processes »well-resolved by Method-3 (residual of the energy balance) at places where energy-balance models like SNOWPACK are routinely validated against data regarding most components of the energy balance ? In that case, isn't it rather a lack of investigation into the process of cold content development, than a lack of validation data, that limits knowledge of the prevailing processes ?
Given the adequate performance of advanced energy balance models (Etchevers et al., 2004; Rutter et al., 2009), it is somewhat reasonable to assume they are accurately simulating the evolution of snowpack cold content. However, recent work has shown the utility in validating snow model output on more than one state variable (Lapo et al., 2015) in order to ensure we are not "getting the right answers for the wrong reasons." In this case we stand by our assertion that having measurements of snowpack temperature and cold content are necessary for making conclusions on how cold content develops in seasonal snowpacks. I.e., previous work could have tested hypotheses using energy balance model output alone, but a lack of cold content validation data would have limited the strength of their conclusions.

   Furthermore, the dominant processes involved in cold content development likely depend on the climatology of the investigated sites. Event though it is well stated in the Discussion, specifying the perimeter of validity of your study should be done here already. Typically, I suggest transforming research question #1(p3 L6) into « What are the meteorological and energy balance controls on cold content development **at two alpine and sub-alpine sites from the Western US ? »**

Yes, we agree with this point and have changed research question 1 to reflect Reviewer 2's suggestion (p. 3 lines 9-10). This point was also noted by Reviewer 1, so we have added text wherever possible to note the results are specific to our study sites.

3. Introduction-p2 L22-26 : conduction fluxes within the snowpack, and from snowpack to the ground, can mitigate the impact of the intense negative fluxes reported here. If a gradient around 100 W/m develops within the snowpack as a result of intense surface cooling, around 20 W/m2 propagates downwards (upon hypothesis of a 0.2 W/m/K conductivity for Snow), which should somewhat prevents the snowpack from locally reaching unreaslitic temperatures ( ?)
In the cited work, the authors note that their reported values are for ΔQ, or the change in snowpack internal energy, (Marks and Dozier, 1992). Although their paper has provided many significant contributions to the state of knowledge of the snowpack energy balance, it also underlines how little we previously knew about cold content development processes. We hope our manuscript provides a small step in the right direction.

4. Introduction-p3 LÍ : uncertainties->unknowns(suggestion)
Changed.

5. Methods - p5 L28 : « vapour diffusion » in SNOWPACK is actually only calculated to compute Snow grain/bounds growth rates. There is no mass redistribution between different snow layers as a result of vapour diffusion in current versions of SNOWPACK. I therefore suggest to suppress this item from the list of existing SNOWPACK routines, as it would be otherwise misleading.
Thank you for clarifying. Given this paper is not about grain metamorphism, we have removed this part.

6. Methods- p6 L7-10 : could you specify here or in appendix the result of your calibration procedure for the parameters leaf area index, vegetation height, direct canopy throughfall, and wind speed reduction ? Note that these parameters are usually estimated from field data, and that any observation-based estimate of them would help assess the soundness of the calibrated parameter or of the canopy model.
Yes. We have added this information to the Supplemental Material (Table S2).
Additionnal, the rough size of the clearing where sub-alpine snowpits were made, should be specified (p4Ll) to justify the use the canopy module of SNOWPACK, instead of an open- area version SNOWPACK with just wind attenuation.
We have included site photos for both locations (Figure 1) in the updated manuscript and removed the "small clearing" part from the text as this caused some confusion.

7. Results-p5 L15-16 : « Peak cold content and peak SWE respectively occurred 33 d and 10 d later in the alpine than subalpine ».Add « on average » to this sentence and the next.
Changed.

8. Results-p7L25-27 : « This is likely due to the increased variability of winter precipitation, the coefficient of variation of which is 2.9 and 2.7 times greater than that of air temperature in the alpine and subalpine, respectively ». I assume that by « increased »you mean« higher» ? I would suggest that snow-atmosphere heat transfers occuring during cold air temperatures periods are less efficient in cooling the

snowpack, than the direct addition of cold Snow from fresh snowfall.

Correct, we have changed *increased* to *higher*. Additionally, we have added text to Sect. 4.1 to note that the air temperature is less effective at producing cold content than precipitation.

9. Results- p7L29-30 : « During periods of SWE accumulation, $Q_{net}$ was typically near 0 W $m^{-2}$ (Fig. 4a), indicating a large negative energy balance was not responsible for cold content development. » First, here, you infer $Q_{net}$ from the variation in CC between 2 snowpit dates, so where is the link to energy balance ? Second, based on Eq 3, $Q_{net}$ ~0 W $m^{-2}$ indicates no cold-content increase, meaning there is no visible snowfall-driven cold-content increase in the snowpit data. In my mind this contradicts the other results of the study, e.g. Fig 3 and 7 - please justify, or explain me where I am wrong. May I suggest using different names for $Q_{net}$ in Eq. 3 and $Q_{net}$ in Eq. 4 ? Like $Q_{net\text{-}pit}$ and $Q_{net\text{-}EB}$ respectively.

   This is a good point and similar to the one Reviewer 1 brought up regarding our energy balance notation. In the quoted lines we were attempting to convey that the snow pits showed no direct evidence of a large negative surface energy balance like the one reported in Marks and Dozier (1992). We computed $Q_{net}$ as a function of the change in cold content and the time between pit observations. To be more consistent, and clearer, we have changed our notation throughout the paper to have dU/dt be the change in internal energy of the snowpack ($dU/dt_{pit}$ for the snow pit data) and $Q_{net}$ to represent the sum of $SW_{net}$, $LW_{net}$, $Q_H$, $Q_{LE}$, and $Q_G$ (per the recommendation of Reviewer 1).

   In regard to your point "$Q_{net}$ ~0 W $m^{-2}$ indicates no cold-content increase, meaning there is no visible snowfall-driven cold-content increase in the snowpit data", we have clarified in lines 20-27 (p. 8) the way we presented these data. Because cold content is a relatively small value in terms of W $m^{-2}$, decreases in dU/dt will always be small, whether cold content gains come through precipitation or a negative surface energy balance. For example, if two snow pits were dug exactly one day apart, the computed dU/dt for a 0.2 MJ $m^{-2}$ increase in cold content (2 cm of new SWE at -5°C) would be just -2.4 W $m^{-2}$ (assuming all other energy balance components summed to zero). Thus, a fairly significant cold snowfall event would show up as a very small dU/dt value.

10. Results- p8 L7 : could overestimated densities be the reason for cold-content overestimation at alpine location ? (as Snow temperature tend to be overestimated ?) Maybe a line on that could be added to the Result or Discussion section

   We have added this point in the results section (p. 9 lines 3-6) and we have also added a new discussion section on the model shortcomings (Sect. 5.2).

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# Observations and simulations of the seasonal evolution of snowpack cold content and its relation to snowmelt and the snowpack energy budget

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**Abstract.** Cold content is a measure of a snowpack's energy deficit and is a linear function of snowpack mass and temperature. Positive energy fluxes into a snowpack must first satisfy the remaining energy deficit before snowmelt runoff begins, making cold content a key component of the snowpack energy budget. Nevertheless, uncertainty surrounds cold content development and its relationship to snowmelt, likely because of a lack of direct observations. This work clarifies the controls exerted by air temperature, precipitation, and negative energy fluxes on cold content development and quantifies the relationship between cold content and snowmelt timing and rate at daily to seasonal time scales. The analysis presented herein leverages a unique long-term snow pit record along with validated output from the SNOWPACK model forced with 23 water years (1991–2013) of quality controlled, infilled hourly meteorological data from an alpine and subalpine site in the Colorado Rocky Mountains. The results indicated that precipitation exerted the primary control on cold content development at our two sites with snowfall responsible for 84.4% and 73.0% of simulated daily gains in the alpine and subalpine, respectively. A negative surface energy balance—primarily driven by sublimation and longwave radiation emission from the snowpack—during days without snowfall provided a secondary pathway for cold content development, and was responsible for the remaining 15.6% and 27.0% of cold content additions. Non-zero cold content values were associated with reduced snowmelt rates and delayed snowmelt onset at daily to sub-seasonal time scales, while peak cold content magnitude had no significant relationship to seasonal snowmelt timing. These results suggest that the information provided by cold content observations and/or simulations is most relevant to snowmelt processes at shorter time scales, and may help water resource managers to better predict melt onset and rate.

## 1 Introduction

Cold content is a key component of the snowpack energy budget as it represents the internal energy deficit that must be overcome before snowmelt runoff can begin. It is a linear function of snowpack temperature and snow water equivalent (SWE), whereby colder snowpacks with greater SWE have increased energy deficits. Until cold content is satisfied, positive

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energy fluxes go towards raising the internal snowpack temperature to an isothermal 0°C and any surface melt that is produced may be refrozen in the colder lower layers of the snowpack. In this regard, cold content influences the timing and rate of snowmelt runoff, which is of critical importance to various ecohydrologic and cryospheric processes, including: streamflow generation (Barnhart et al., 2016; Regonda et al., 2005), water resources availability (Barnett et al., 2005; Christensen et al., 2004; Mankin et al., 2015; Stewart, 2009), water uptake by vegetation (Winchell et al., 2016), soil moisture (Harpold and Molotch, 2015), flooding (Jennings and Jones, 2015; Kampf and Lefsky, 2016), and land surface albedo (Déry and Brown, 2007), among others.

Cold content can be estimated using at least one of three primary methods: 1) As an empirical function of air temperature (e.g., Anderson, 1976; DeWalle and Rango, 2008, 2008; Seligman et al., 2014; United States Army Corps of Engineers, 1956); 2) As a function of precipitation and air temperature (e.g., Cherkauer et al., 2003; Lehning et al., 2002b; Wigmosta et al., 1994) or wet bulb temperature (Anderson, 1968) during precipitation; and 3) As a residual of the snowpack energy balance (e,g., Andreadis et al., 2009; Cline, 1997; Lehning et al., 2002b; Marks and Winstral, 2001). In general, simple temperature-index models employ method 1, while both 2 and 3 are utilized in physics-based snow models. These methods suggest that cold content develops through both meteorological and energy balance processes, but few direct comparisons to observed cold content exist. This is likely due to the inherent difficulty in measuring cold content, which requires either time-intensive snow pits or co-located snow depth, density, and temperature measurements (Burns et al., 2014; Helgason and Pomeroy, 2011; Marks et al., 1992; Molotch et al., 2016). The lack of validation data introduces significant uncertainty into the dominant process by which cold content develops. Thus, it is not known whether cold content development is primarily a function of air temperature (method 1), snowfall (method 2), or a negative surface energy balance (method 3).

Early work from California's Sierra Nevada mountains indicated cold content developed in the snowpack mainly through a negative surface energy balance. The reported monthly change in snowpack internal energy (i.e., change in cold content) ranged from -34 to -61 W m$^{-2}$ from November through April at an exposed site and -8 to -66 W m$^{-2}$ from November through February at a sheltered site (Marks and Dozier, 1992). However, such negative fluxes would result in physically unrealistic internal snowpack temperature changes. Even persistent slightly negative flux values, as reported elsewhere in the literature (Armstrong and Brun, 2008), would result in implausibly low snowpack temperatures. It can be inferred that any process producing anomalously low snowpack temperatures either misidentifies or overestimates the importance of a particular meteorological or energy balance mechanism.

Furthermore, the degree to which wintertime cold content magnitude controls snowmelt timing and rate at daily to seasonal timescales is relatively uncertain. Work from the southwestern United States suggests increased cold content may delay seasonal melt timing (Molotch et al., 2009) and the inclusion of cold content generally improves meltwater outflow predictions in point and distributed snowmelt models of varying degrees of physical complexity (Bengtsson, 1982; Jepsen et al., 2012; Livneh et al., 2010; Mosier et al., 2016; Obled and Rosse, 1977). However, two empirical studies indicated the

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energy required to satisfy cold content may be relatively small in comparison to the energy required to melt enough snow to fulfill the irreducible water content of an already isothermal snowpack (Bengtsson, 1982; Seligman et al., 2014).

Given the above unknowns, we aim to improve understanding of the processes controlling cold content development and the relationship between cold content and snowmelt timing and rate at a continental, mid-latitude alpine and subalpine site in the Colorado Rocky Mountains. Our research utilizes observations from a long-term snow pit record and simulation output from a physics-based snow model forced with a quality controlled, serially complete meteorological dataset. Analyses performed on the observations and simulation data are focused on answering the following research questions:

1. What are the meteorological and energy balance controls on cold content development at an alpine and subalpine site in the Colorado Rocky Mountains?
2. How does cold content affect snowmelt timing and rate on seasonal, sub-seasonal, and daily time scales?

## 2 Study site and snow pit and forcing data

The Niwot Ridge Long Term Ecological Research site (LTER) is located on the eastern slope of the Continental Divide in the Rocky Mountains of Colorado, USA (Fig. 1). The entirety of the LTER is situated above 3000 m with treeline occurring at approximately 3400 m (Williams et al., 1998). Dominant vegetation in the subalpine is lodgepole pine, aspen, Engelmann spruce, subalpine fir, and limber pine (Burns et al., 2014). The alpine is characterized by several tundra vegetation communities of grasses, forbs, and shrubs, whose distribution is linked to patterns of snow depth and soil moisture (Walker et al., 1993, 1994).

There are multiple meteorological stations within the boundaries of the Niwot Ridge LTER, but this work focuses on the two sites with long-term snow pit records: alpine (3528 m) and subalpine (3022 m), named Saddle and C1, respectively (Fig. 1). We employed an additional high alpine station (D1, 3739 m) in the meteorological data infilling procedure (Appendix A), but did not perform model simulations there due to a lack of snow pit validation data. From 2008 to 2012, annual precipitation in the alpine and subalpine averaged 1071 mm and 752 mm, respectively (Knowles et al., 2015) and the ratio between above- and below-treeline precipitation varies annually as a function of upper-air flow regimes (Kittel et al., 2015). The majority of annual precipitation is snow, with estimates of the proportion of snowfall ranging from 63% to 80% of total precipitation (Caine, 1996; Knowles et al., 2015). Over our study period, December, January, February mean air temperature was -10.3°C in the alpine and -6.2°C in the subalpine. Dominant wind direction is westerly, but the subalpine site also experiences easterly flow during intermittent upslope events (Blanken et al., 2009; Burns et al., 2014). Elevated wind speeds in the alpine, averaging 10 m s$^{-1}$ to 13 m s$^{-1}$ in winter, exert a primary control on patterns of snow erosion and deposition with snow depth being highly variable as a result (Erickson et al., 2005; Jepsen et al., 2012; Litaor et al., 2008). Snow depths in the alpine can range from 0 m over wind-scoured tundra to upwards of 5 m in drifts on the lee side of terrain

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features or in gullies. Additionally, blowing snow occurs frequently during winter months in the alpine due to high winds, reaching a maximum in January (Berg, 1986).

Regular snow pit measurements began in 1995 in the alpine and 2007 in the subalpine, and were taken at weekly to monthly intervals from the middle of January through the end of May in most snow seasons (Williams, 2016). A total of 292 alpine and 147 subalpine snow pit records were used in this study (Table S1). The alpine snow pit represents conditions typical of the above-treeline snowpack as it is not in an area of pronounced snow erosion or deposition. The subalpine snow pit is located in a stand of lodgepole pine, typical of vegetation conditions in the below-treeline areas. Measurement protocol follows Williams et al. (1999): Snow density is measured for each 10 cm layer using a wedge-shaped 1 L density cutter (10 cm × 10 cm × 20 cm) and snow temperature is recorded every 10 cm with dial-stem thermometers. Snow pit measurements enable per-layer and depth-weighted calculations of SWE and cold content:

$$SWE = \frac{\rho_s}{\rho_w} d_s \quad (1)$$

$$CC = c_i \rho_s d_s (T_s - T_m) \quad (2)$$

where $\rho_s$ and $\rho_w$ are the density of snow and liquid water, respectively (kg m$^{-3}$), $d_s$ is snow depth (m), $CC$ is cold content (MJ m$^{-2}$), $c_i$ is the specific heat of ice ($2.1 \times 10^{-3}$ MJ kg$^{-1}$ °C$^{-1}$), $T_s$ is the snow temperature (°C), and $T_m$ is the melting temperature of snow (0°C). Snow pit analyses focused on water years (WY, 1 October from the previous calendar year through 30 September) 2007 through 2013, the period for which overlapping snow pit data were available. The full period of record in the alpine (WY1995–WY2013) was used for model validation.

Hourly meteorological data have been collected at the LTER since 1990, but the record suffers from quality control issues and periods of missing data. Recent research has shown the quality of snow model output depends on having accurate forcing data (e.g., Förster et al., 2014; Lapo et al., 2015; Raleigh et al., 2015, 2016; Schmucki et al., 2014). Measurements were therefore subjected to an extensive quality control and infilling protocol (Appendix A) to produce a serially complete, hourly dataset with observations of air temperature, relative humidity, incoming solar radiation, wind speed, and precipitation. The dataset also includes hourly estimates of downwelling longwave radiation based on air temperature, relative humidity, and incoming solar radiation using the methods of Angström (1915), Crawford and Duchon (1999), and Dilley and O'Brien (1998) as described in Flerchinger et al. (2009).

### 3 Methodology

Observations from the Niwot Ridge LTER snow pit record and validated output data from physics-based snow model simulations were employed to answer the two research questions. We assessed the meteorological controls on cold content development using measurements of cumulative precipitation and the cumulative mean of air temperature for the full period of record at both sites. We focused the analysis on snow pit observations and simulations between 1 December and the date of peak cold content, the main period of cold content development. We then tested whether persistent large negative energy

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fluxes could be responsible for cold content development by calculating the rate of change in internal energy between pit observations and using the snow model simulations to calculate the snowpack energy budget. Model output was also used to assess the effect of cold content magnitude and timing on snowmelt rate and timing at daily to seasonal time scales. Additionally, we note that in this paper an "increase" or "gain" in cold content refers to the value increasing in magnitude and becoming more negative (i.e., the energy deficit is becoming greater). A "decrease" or "loss" of cold content occurs when the value becomes less negative and approaches 0 MJ $m^{-2}$.

### 3.1 Snow pit analysis

Mean characteristics of and differences between the alpine and subalpine snow pits were quantified using data from WY2007–WY2013, the seven years for which there were overlapping observations. To assess the control each meteorological quantity exerted on cold content, we used the cumulative mean of air temperature and cumulative precipitation as the independent variables with observed cold content acting as the dependent variable in ordinary least squares regression. The strength of the relationship was quantified using the coefficient of determination, $r^2$, while the p-value of the regression slope indicated statistical significance. Additionally, in order to evaluate whether large persistent negative energy balances were consistent with patterns of cold content development, we calculated the rate of change in internal energy between snow pit observations:

$$\frac{dU}{dt}_{pit} = \frac{\Delta CC}{(86{,}400\,\Delta t)} \tag{3}$$

where $\frac{dU}{dt}_{pit}$ is the pit-observed rate of change in internal energy (W $m^{-2}$), ΔCC is the change in cold content (J $m^{-2}$) between snow pit observations, 86,400 is the conversion factor between days and seconds (s $d^{-1}$), and Δt is the number of days between snow pit observations (d). Snow pit cold content in this context integrates the effects of incoming and outgoing fluxes, plus the cold content added by precipitation, by providing a measure of the change in the internal energy of the snowpack independent of any surface flux measurements or estimations.

### 3.2 Snow model simulations

#### 3.2.1 Model description

In order to evaluate cold content development processes at a finer temporal resolution and quantify components of the energy budget, we employed the complex, physics-based, multi-layer, one-dimensional SNOWPACK model (Bartelt and Lehning, 2002; Lehning et al., 2002a, 2002b). This model was selected because previous studies have shown complex, multi-layer models more accurately partition the snowpack energy budget and better represent internal processes (Blöschl and Kirnbauer, 1991; Boone and Etchevers, 2001; Essery et al., 2013; Etchevers et al., 2004). Additionally, SNOWPACK was utilized in previous work to simulate the snowpack energy budget at the Niwot Ridge LTER (Meromy et al., 2015) and it has been validated in the Rocky Mountains of Montana (Lundy et al., 2001). SNOWPACK is forced with air temperature,

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relative humidity, wind speed, incoming solar radiation, incoming longwave radiation, and precipitation at an hourly or higher temporal resolution. The model discretizes the snowpack into a variable number of layers that change with the addition of new snow, mass loss through snowmelt and sublimation, and densification via compaction. Each layer is composed of water in liquid, solid, and gas phases, all of which are assumed to have the same temperature. SNOWPACK is governed by four differential equations that account for the conservation of energy, mass, and momentum. Explicit routines are included for heat transfer, water transport, and phase changes. In addition, the model features quasi-physical estimations of snow microstructure and snow grain metamorphism. These properties, in turn, control the rate of heat conduction and settling within the snowpack. SNOWPACK also models the penetration of shortwave radiation and wind pumping in the upper layers of the snowpack.

We increased the standard SNOWPACK rain-snow air temperature threshold from 1.2°C to 2.5°C to better represent precipitation phase partitioning at our high-elevation continental sites. In general, the Rocky Mountains have some of the highest rain-snow air temperature thresholds in the Northern Hemisphere (Jennings et al., In Press). To test the effect of our threshold selection, we compared the mean annual snow frequency using the 2.5°C threshold (alpine = 76.4%; subalpine = 61.5%) to a bivariate binary logistic regression phase prediction model (alpine = 76.7%; subalpine = 62.8%). This model predicts precipitation phase as a function of relative humidity and air temperature, and it was shown to be the best precipitation phase method in a Northern Hemisphere comparison (Jennings et al., In Press).

The bulk Richardson number stability correction was used for computing turbulent fluxes in both the alpine and subalpine. Although Monin-Obukhov similarity theory options were available, these stability corrections generally performed worse relative to the bulk Richardson number in our preliminary simulations as well as in the work of others (Essery et al., 2013). Ground heat flux was simulated using the SNOWPACK-default constant soil temperature of 0.0°C because no long-term soil surface temperature data were available.

Additionally, the SNOWPACK canopy module was activated for the subalpine site given its location in a stand of lodgepole pine. Parameters for the canopy module were calibrated using a series of 100 Monte Carlo simulations with parameter ranges bounded by representative estimates of leaf area index, vegetation height, direct canopy throughfall, and wind speed reduction (Table S2). Modeled SWE in the subalpine proved most sensitive to the wind speed reduction parameter, likely due to the siting of the anemometer as noted in Appendix A. Using un-corrected observed wind speed as a model input led to a physically unrealistic amount of snow sublimation.

### 3.2.2 Model simulations, validation, and analysis

SNOWPACK simulations were performed in the alpine and subalpine for WY1991–WY2013 and forced with the quality controlled, infilled hourly meteorological data detailed in Appendix A. This time range included the lowest (WY2002: 178 mm) and second highest (WY1996: 523 mm) peak SWE observations in the period of record (WY1981–WY2017) at the Niwot Snowpack Telemetry (SNOTEL) station (3020 m), which is located within the Niwot Ridge LTER boundary, less than 1 km from the subalpine snow pit and meteorological tower. Thus, the analysis covered a wide range of feasible

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snowpack conditions, from pronounced snow drought to peak SWE values greater than 150% of average, according to the SNOTEL observations.

To ensure the simulation output was suitable for in-depth analysis, we validated model SWE, snowpack temperature, and cold content values on the snow pit observations. We pursued this multi-validation approach because our work focuses on the internal energy of the snowpack and recent research has shown the output from snow model simulations (e.g., energy balance partitioning, SWE) is more reliable when several variables are used in model evaluation (Lapo et al., 2015). Modeled subalpine SWE estimates were also evaluated using observed SWE at the Niwot SNOTEL site. For each quantity of interest, we assessed model performance using the coefficient of determination and mean bias. To improve model output, we corrected precipitation measurements relative to snow pit and SNOTEL SWE observations (Appendix A) and optimized the canopy parameters for subalpine simulations (Sect. 3.2.1). Additionally, there were several times per winter when the simulated cold content spiked rapidly down ($\Delta CC$ < -0.3 MJ m$^{-2}$ h$^{-1}$), then back up. These data points, which represented less than 0.2% of the simulation hours, were filtered from the analysis.

We then used the validated output from SNOWPACK to quantify the controls on cold content development and snowmelt processes at a finer temporal resolution than the weekly to monthly snow pit observations. To evaluate the meteorological processes controlling cold content development, we used the same methods employed in the snow pit observations outlined above (Sect. 3.1). Additionally, we quantified the contributions of the simulated snowpack energy balance to cold content development:

$$\frac{dU}{dt} + Q_M = Q_{SW} + Q_{LW} + Q_H + Q_{LE} + Q_G + Q_R \qquad (4)$$

where $\frac{dU}{dt}$ is the simulated rate of change in internal snowpack energy, $Q_M$ is the energy available for melt (once cold content equals 0.0 MJ m$^{-2}$), $Q_{SW}$ is net shortwave radiation, $Q_{LW}$ is net longwave radiation, $Q_H$ is sensible heat flux, $Q_{LE}$ is latent heat flux, $Q_G$ is ground heat flux, and $Q_R$ is the heat advected by precipitation (all W m$^{-2}$). This work focuses primarily on $Q_{SW}$, $Q_{LW}$, $Q_H$, $Q_{LE}$, and $Q_G$, which we will refer to as $Q_{net}$ throughout the remainder of this paper. $Q_R$ is typically negligible because significant rain-on-snow events are rare at the Niwot Ridge LTER.

Simulation results were also used to quantify the control cold content exerts on snowmelt timing and rate at multiple time scales. At the seasonal time scale, we set snowmelt onset to correspond to the date of peak SWE and snowmelt rate to the ablation slope, which is the average daily snowmelt rate between the date of peak SWE and the date at which SWE first equals 0 mm (e.g., Barnhart et al., 2016; Trujillo and Molotch, 2014). At sub-seasonal time scales, we calculated snowmelt timing and rate in time windows from 1 d to 30 d, with a corresponding cold content value at day zero. Finally, we used the cold content at 6AM ($CC_{6AM}$) to evaluate the effect of cold content on snowmelt timing and rate at daily time scales. For the sub-seasonal and daily time scales above, we set snowmelt timing to be the first instance of simulated snowmelt runoff and snowmelt rate to be the mean rate for the time window.

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## 4 Results

### 4.1 Snow pit observations of cold content

Snow pit observations showed daily and peak annual snowpack cold content were consistently greater in the alpine than subalpine (Fig. 2). From WY2007–WY2013, mean peak cold content was 2.6 times greater in the alpine than subalpine, while mean peak SWE was 2.1 times greater in the alpine (Table 1). On average, peak cold content and peak SWE respectively occurred 33 d and 10 d later in the alpine than subalpine. The average temporal gap between peak cold content and peak SWE was also 23 d shorter in the alpine, indicating greater energy exchange between the snow and atmosphere at this site during the main time of snowpack ripening. Mean $\frac{dU}{dt}_{pit}$ for this period, as estimated using Eq. 3, was 1.2 W m$^{-2}$ and 0.4 W m$^{-2}$ in the alpine and subalpine, respectively.

From 1 December to the date of snow pit observation, increased cumulative precipitation was associated with increased cold content at both sites (Fig. 3). Cumulative precipitation explained 55% and 17% of the variance in cold content in the alpine and subalpine, respectively. The relationship was statistically significant at the 99% level at both sites despite the low coefficient of determination in the subalpine. Conversely, the cumulative mean of air temperature had no statistically significant relationship to snowpack cold content, explaining less than 1% of the variance at both sites (not shown). Although there may be snowpack energy losses during periods of cold air temperature, these results indicate that, of the two meteorological quantities evaluated here, snowfall exerts the primary control on cold content development. This is likely due to the higher variability of winter precipitation, the coefficient of variation of which is 2.9 and 2.7 times greater than that of air temperature in the alpine and subalpine, respectively. Furthermore, the difference in $r^2$ values between the two sites suggests that precipitation plays a more important role in the alpine than subalpine in terms of cold content development.

Snow pit observations were also used to calculate $\frac{dU}{dt}_{pit}$ by quantifying the change in cold content between two points in time (Eq. 3). During periods of SWE accumulation, $\frac{dU}{dt}_{pit}$ was typically near 0.0 W m$^{-2}$ (Fig. 4a), indicating a large negative energy balance was not responsible for cold content development at our two sites. The average flux in the alpine (-0.8 W m$^{-2}$) was greater in magnitude during this period than in the subalpine (-0.4 W m$^{-2}$), and both distributions were left-skewed as the energy balance was typically negative from snowfall- and/or flux-driven cold content increases. Changing the analysis to snow pit observations when melt occurred (Fig. 4b) led to a pronounced right-skew in the flux distribution with values again of a higher magnitude in the alpine. Thus, we found no evidence for highly negative internal energy changes at our sites with $\frac{dU}{dt}_{pit}$ values only being large in magnitude during snowmelt.

### 4.2 Model SWE, snowpack temperature, and cold content validation

SNOWPACK simulations reproduced observed snow pit SWE patterns at both sites, with a higher coefficient of determination and lower bias in the subalpine than alpine (Fig. 5a,b; Table 2). Subalpine simulations were also in line with



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daily SWE observations from the Niwot SNOTEL (Table 2). Simulated depth-weighted snowpack temperature had a slight warm bias of 1.1°C in the alpine and 0.6°C in the subalpine (Fig. 5c,d, Table 2), while cold content was overpredicted in the alpine and underpredicted in the subalpine (Fig. 5e,f, Table 2). In this regard, simulated cold content errors integrated the SWE and snowpack temperature biases. Overprediction in the alpine was a result of the positive SWE bias having a greater effect on simulated cold content than the warm temperature bias. Conversely, underprediction of snowpack cold content in the subalpine was primarily due to the warm temperature bias.

Modeled annual peak SWE and peak cold content were also similar to the previously reported pit values for WY2007 through WY2013 (Table 2). Additionally, simulated LTER subalpine peak cold content values were within the range of those reported in a simulation of a subalpine snowpack (-2.2 MJ m$^{-2}$ to -1.7 MJ m$^{-2}$) at the nearby Fraser Experimental Forest during NASA's Cold Land Processes Experiment (Marks et al., 2008). Direct observations of snow surface sublimation were not available for comparison, but modeled sublimation rates were in line with other values reported in the literature for alpine and subalpine areas in the Colorado Rocky Mountains (Berg, 1986; Hood et al., 1999; Knowles et al., 2012; Molotch et al., 2007; Sexstone et al., 2016). On average, simulated snow-surface sublimation represented 28.8% (383 mm) and 11.4% (53 mm) of snow-season precipitation in the alpine and subalpine, respectively.

### 4.3 Meteorological and energy balance controls on cold content development: Simulation results

#### 4.3.1 Primary control: Snowfall

Similar to the snow pit observations, simulated cold content was strongly related to cumulative precipitation in the alpine, indicating cold content developed primarily through the addition of new snowfall (Fig. 6a). The subalpine snowpack, however, frequently approached an isothermal state in the winter with cold content fluctuating between gains during snowfall and losses during dry periods (Fig. 6b). Due to this effect, cumulative precipitation in the subalpine explained less of the variance in cold content than in the alpine. Additionally, the cumulative mean of air temperature explained little of the variance in simulated cold content at both sites (Fig. 6c,d). In general, decreases in air temperature did not produce large increases in cold content, meaning periods of below-average air temperature did not significantly contribute to cold content development. These simulations support the results of the snow pit observations, namely that of the two main meteorological quantities, precipitation exerts the primary control on cold content development.

Discretizing snow season days into those with and those without precipitation further clarifies the relationship between cold content development and snowfall. Figure 7 shows the monthly differences between days with and without precipitation in the alpine and subalpine in terms of cold content gains and losses. Precipitation days were commonly associated with cold content gains, particularly in December, January, and February when precipitation was coincident with low air temperatures. Days without precipitation, conversely, were associated with decreases in snowpack cold content, indicating a positive surface energy balance warmed the snowpack between snowfall events. Magnitudes were typically

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greater in the alpine where colder temperatures and increased precipitation led to greater cold content gains on snowfall days, while higher wind speeds facilitated increased rates of energy transfer and cold content losses on days without precipitation.

#### 4.3.2 Secondary control: Negative surface energy balance

Although non-snowfall days were typically associated with cold content losses, flux-driven gains did sometimes occur on days without precipitation. On these days, $Q_{net}$ was slightly negative, averaging -2.9 W m$^{-2}$ in the alpine and -2.4 W m$^{-2}$ in the subalpine, with $Q_{LE}$ and $Q_{LW}$ the primary negative energy balance terms at both sites (Fig. 8a,b). $Q_H$, $Q_G$, and $Q_{SW}$ were typically positive, adding energy to the snowpack even during periods of increasing cold content. The majority of flux-driven cold content additions took place at night (1800 h through 0600 h), while daytime hours were commonly associated with cold content losses (Fig. 8c). Cold content gains between 0900 h and 1400 h accounted for less than 5% of total gains at both sites (Fig. S1). In total, nighttime cold content additions outnumbered daytime additions by a 2.7:1 ratio in the alpine and 3.7:1 in the subalpine.

#### 4.3.3 Comparing the relative importance of cold content development processes

Overall, snowfall contributed more cold content to the snowpacks at each site than negative energy fluxes, while air temperature showed little relationship to cold content development. The number of snowfall days with cold content increases exceeded the number of non-snowfall days with increases in the alpine by a 4.2:1 ratio, with snowfall days responsible for 438% more cold content additions than non-snowfall days. On an average annual basis in the alpine, snowfall days contributed -12.5 MJ m$^{-2}$ to cold content development and non-snowfall days -2.3 MJ m$^{-2}$. As previously noted, the effect of precipitation was smaller in the subalpine in terms of both the variance explained by cumulative precipitation and the ratio of snowfall-to-non-snowfall cold content gains. Snowfall days in the subalpine were responsible for 166% more cold content gains than non-snowfall days, generating -4.1 MJ m$^{-2}$ and -1.5 MJ m$^{-2}$ of cold content development on an annual basis, respectively.

Although cumulative mean air temperature had little effect on seasonal cold content development, air temperature did influence the amount of cold content added to the snowpack per snowfall day. Figure 9 shows the daily change in cold content in the alpine and subalpine relative to daily total precipitation (a,b), and cold content from precipitation (c,d) on days with snowfall. Here the cold content from precipitation was calculated as in Eq. 2 but $T_S$ was replaced with air temperature and $d_S$ was replaced by the depth of precipitation. At both sites, the cold content from precipitation explained more of the variance in daily change in cold content than daily total precipitation alone, showing air temperature provides a secondary control on cold content development during snowfall events. Confirming previous results, the control exerted by precipitation on cold content development was stronger in the alpine than subalpine.

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### 4.4 The effect of cold content on snowmelt rate and timing

On seasonal time scales, increased annual peak cold content magnitude had a delaying, but statistically non-significant effect on snowmelt onset, according to both observations and simulations (not shown). However, using the 23 y of snowpack simulations, we found the date of peak cold content and spring precipitation—defined here as the total precipitation between the date of peak cold content and peak SWE—accurately predicted melt onset. A multiple linear regression (MLR) using the date of peak cold content and spring precipitation as the predictor variables explained 84.7% and 61.4% of the variance in snowmelt onset in the alpine and subalpine, respectively (Fig. 10). At both sites, later peak cold content and increased spring precipitation delayed melt onset. In the alpine, the MLR predicted a 1 d delay in snowmelt timing per 1.6 d later in peak cold content timing or 8.8 mm extra spring precipitation. These values shifted to 2.3 d and 5.9 mm, respectively, in the subalpine. Furthermore, we found cold content exerted no statistically significant control on the seasonal snowmelt rate. Rather, statistically significant increases in the ablation slope were associated with later peak SWE timing and increased peak SWE magnitude.

While peak cold content magnitude exerted little control on seasonal snowmelt timing and rate, the simulations indicated increased cold content had a damping effect on snowmelt timing and rate at sub-seasonal time scales from 1 d to 30 d. Greater initial cold content values were associated with decreased snowmelt rates (Fig. 11a,b) and longer delays between day zero and the day of first snowmelt (Fig. 11c,d). All relationships were significant at the 99% level, except for the effect of cold content on snowmelt timing for the 1 d time window in the subalpine. Simulated melt rates in the alpine only exceeded 40 mm d$^{-1}$ when initial cold content was between -0.1 MJ m$^{-2}$ and 0 MJ m$^{-2}$. The same initial cold content range was responsible for all simulated melt rates greater than 15 mm d$^{-1}$ in the subalpine. Examining only the 30 d window for snowmelt timing revealed further patterns at the two sites. Initial cold content explained 47.3% of the variance in time to first melt in the alpine and 37.6% in the subalpine using ordinary least squares regression. An initial cold content increase of 1.0 MJ m$^{-2}$ led to a 3.7 d delay in snowmelt in the alpine and 12.1 d in the subalpine.

To examine the control of cold content on daily snowmelt rate and timing, we used $CC_{6am}$ to represent the energy state of the snowpack at time t = 0 for each day. Figure 12a,b shows melt rates did not increase until $CC_{6AM}$ neared 0 MJ m$^{-2}$ in the alpine and subalpine. Both the number of melt days and the daily melt rate were greater when $CC_{6AM}$ = 0 MJ m$^{-2}$. The proportion of daily melt occurring on days when $CC_{6AM}$ = 0 MJ m$^{-2}$ ranged from 75.0% in the alpine to 79.5% in the subalpine. Mean melt rates were also greater when there was no energy deficit to satisfy in the alpine (21.1 vs. 14.3 mm d$^{-1}$) and subalpine (9.7 vs. 6.2 mm d$^{-1}$). Additionally, non-zero $CC_{6AM}$ values were associated with delayed snowmelt onset (Fig. 12c,d). The mean time between 6AM and simulated snowmelt onset was 2.3 h in the alpine and 2.8 h in the subalpine when $CC_{6AM}$ = 0 MJ m$^{-2}$. These values shifted to 5.7 h and 6.7 h, respectively, when $CC_{6AM} \neq 0$ MJ m$^{-2}$. Thus the presence of cold content produced a 3.4 h delay in alpine snowmelt onset and 3.9 h in the subalpine. These data indicate that even small energy deficits had a damping effect on daily snowmelt rate and timing.

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## 5 Discussion

### 5.1 Representation of cold content development processes in snow models

In Sect. 1 we noted the three main methods by which cold content is represented in snow models. Temperature index models typically compute cold content as an empirical function of air temperature (method 1), while physical models estimate cold content as a function of precipitation and the air temperature during precipitation (method 2) and/or as a residual of the snowpack energy balance (method 3). A model comparison is outside of the scope of this work, but the results presented above suggest method 2 was the primary pathway through which cold content developed at our continental, mid-latitude alpine and subalpine sites. We found air temperature had little influence on cold content development except when included as a variable in computing the cold content of new snowfall. Prior work from the subalpine site of the Niwot Ridge LTER showed a weak relationship between cold air temperatures and snowpack cooling and that periods of snowpack cooling were generally coincident with clear skies and longwave emission from the snowpack (Burns et al., 2014). Thus, method 1 would likely misrepresent cold content development processes and incorrectly estimate cold content magnitude at our sites due to the irreplaceable role of snowfall in cold content development.

Based on first principles, method 3 is important in that cold content is an integration of both mass (i.e., snowfall) and energy balance processes. Due to high sublimation rates and a dry, cold climate, the alpine site should have a high potential to gain cold content through $Q_{LE}$ and $Q_{LW}$. However, our results showed that daily energy balance cold content gains were small in comparison to those from snowfall. We also found no evidence in either the simulations or observations of consistent, large negative energy balances producing cold content. Rather, the energy balance was typically near zero before peak SWE and only became significantly positive once melt commenced. Days with a negative surface energy balance were generally associated with nighttime cooling from $Q_{LE}$ and $Q_{LW}$, with $Q_{net}$ small in magnitude, averaging > -3.0 W m$^{-2}$. Marks and Winstral (2001) similarly noted the simulated energy balance in a semi-arid mountain basin was generally near 0 W m$^{-2}$ until the melt season. Overall, these findings imply snowpack cold content development at our study locations is primarily a function of method 2 and that large flux-driven increases in cold content are unlikely, even in areas where the energy balance plays a larger relative role (e.g., the subalpine site studied here).

### 5.2 Differences between cold content development controls in the alpine and subalpine

Recent years have seen an increase in the number of papers leveraging physics-based models to quantify snowpack processes. To complement such work, researchers have also evaluated sources of snow model errors and biases (Clark et al., 2017; Essery et al., 2013; Lapo et al., 2015; Raleigh et al., 2015, 2016; Rutter et al., 2009). The preceding literature concludes physics-based snow models must: 1) Have accurate, quality controlled forcing data; 2) Be validated on at least one snowpack state variable, but preferably more; and 3) Have physics that accurately reflect snowpack processes. This study has followed these practices through: 1) A rigorous, hierarchical quality control and infilling forcing data protocol; 2) SWE, cold content, and snowpack temperature validation data from multiple years of snow pit observations; and 3) Use of the

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widely validated, physics-based SNOWPACK model. Despite our adherence to such protocols, there are still significant sources of uncertainty inherent to model-based snow studies.

Snow model intercomparison work has consistently shown there is no one best model and that model performance varies between and within sites and water years (e.g., Boone and Etchevers, 2001; Essery et al., 2013; Etchevers et al., 2004; Rutter et al., 2009; Slater et al., 2001). This body of research acknowledges that all models imperfectly represent snow cover evolution and the snowpack energy balance. One example shortcoming of SNOWPACK relevant to the work presented herein is that the temperature of new snow is set to be equal to air temperature despite the fact that hydrometeor temperature is more accurately estimated as a function of the psychrometric energy balance (e.g., Harder and Pomeroy, 2013). Using the psychrometric approach gives snowfall a temperature near the wet bulb temperature, which is lower than air temperature when relative humidity is under 100% (Harder and Pomeroy, 2013). Thus, the temperature of new snow is likely to be overestimated by SNOWPACK, while cold content additions are underestimated. This means our computation of the total cold content contributed by precipitation is likely on the conservative side as using the wet bulb temperature would lead to increased cold content gains during snowfall.

Another source of uncertainty in our work is the use of an empirical method to estimate incoming longwave radiation as a function of air temperature, relative humidity, and incoming shortwave radiation (Appendix A). Recent research has shown errors in incoming longwave radiation propagate into SWE, snow surface temperature, and energy balance biases (Lapo et al., 2015; Raleigh et al., 2016). We aimed to reduce the error in our incoming longwave radiation estimates by using the recommended clear sky and cloud correction protocols for Niwot Ridge (Flerchinger et al., 2009). At both the alpine and subalpine site, the mean biases were within the instrument range of error when compared to shorter-term observations, indicating the total estimated amount of incoming longwave radiation was acceptable. However, the low $r^2$ of the hourly estimates suggests the sub-daily fluctuations of incoming longwave radiation were not well simulated. Despite these issues, model performance was high in terms of simulated SWE, depth-weighted snowpack temperature, and cold content (Sect. 4.2). This may due to compensatory errors in the model (Etchevers et al., 2004; Kirchner, 2006) or because SNOWPACK is relatively insensitive to the choice of incoming longwave radiation estimate (Schlögl et al., 2016).

Additionally, we had no long-term ground surface temperature data to force the model, so we used the SNOWPACK default value of 0°C. This produced mean $Q_G$ values of 2.0 W m$^{-2}$ and 0.8 W m$^{-2}$ during periods of SWE > 1 cm in the alpine and subalpine, respectively. Previous work from Niwot using a heat flux plate indicated $Q_G$ in the alpine to be negligible (Cline, 1997), while other researchers showed the upper layer of alpine soil could approach temperatures significantly below freezing during periods of shallow snow cover (Brooks and Williams, 1999). Therefore, the SNOWPACK-simulated alpine $Q_G$ is likely an overestimate. In the subalpine, the soil temperature at 5 cm below the surface is typically between -1°C and 0°C during the winter (Burns et al., 2014), meaning the use of the default 0°C ground surface temperature is reasonably in agreement with shorter term observations.

### 5.3 Differences between cold content development controls in the alpine and subalpine

Despite only a 506 m elevation difference between the two sites, the role of a negative energy balance in developing cold content in the subalpine was approximately double that of the alpine. Simulations of snowpack temperature indicated the increased sensitivity was likely due to the shallower subalpine snow depth. Diurnal snowpack temperature range generally decreases with depth (e.g., Burns et al., 2014; DeWalle and Rango, 2008; Sturm et al., 1995) and our simulations showed daily fluctuations to be largest in the snowpack's upper layers, converging towards 1.0°C as depth exceeded 500 mm (Fig. 13). This is the same depth at which the insulating effects of snow on soil temperature become marginal (Slater et al., 2017). Likely this is because the penetration of incoming shortwave radiation and sensible heat transfer through windpumping are limited to the top portion of the snowpack (Albert and McGilvary, 1992; Colbeck, 1989a, 1989b; Lehning et al., 2002b), while the low thermal conductivity of snow modulates energy transfer below the active upper layers (Sturm et al., 1997). In this case, proportionally more of the shallower subalpine snowpack was interacting with surface energy exchange, making it more sensitive to positive and negative fluxes. Furthermore, subalpine cold content was consistently lower in magnitude, meaning it took less energy input to drive cold content to zero and relative fluctuations were larger. Therefore, shallower snowpacks with reduced cold content, like those in the subalpine, are more susceptible to relatively rapid changes in internal energy from surface energy fluxes.

### 5.4 Other controls on seasonal snowmelt timing and rate

Previous research has suggested uncertainty in the degree to which cold content controls snowmelt timing at daily to seasonal time scales. In our research, we found no statistically significant relationship between peak cold content magnitude and seasonal snowmelt onset using data from both observations and simulations. Rather, the majority of the variance in seasonal snowmelt onset was explained by the timing of annual peak cold content and total spring precipitation. Later peak cold content generally occurred due to cold spring storms depositing significant snowfall. If such events were then followed by continued snowfall, then snowmelt timing was delayed. Meanwhile, seasonal snowmelt rate, or the ablation slope, was primarily controlled by peak SWE magnitude and timing, with greater, later peak SWE corresponding to more rapid snowmelt.

These results all suggest later seasonal snowmelt onset and faster snowmelt rates are primarily a function of persistent snowfall. While snowfall events can add significant cold content to the snowpack, they also change other fundamental properties that can delay snowmelt timing, such as increasing surface albedo (Clow et al., 2016) and adding dry pore space that must be saturated (Seligman et al., 2014). Other research shows seasonal snowmelt onset is also related to air temperature (Kapnick and Hall, 2012) and snow surface impurities (Painter et al., 2010; Skiles et al., 2012). Although much work has been done evaluating the empirical controls exerted by snowpack and climatic properties on snowmelt rate and timing across large spatial extents (e.g., Trujillo and Molotch, 2014), relatively little research has been done at such scales on the physical processes (e.g., cold content and the snowpack energy balance). Given the importance of seasonal snowmelt

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timing to water resources management and various hydrologic processes, future synthesis work should evaluate the effect of various physical processes on snowmelt rate and timing across snow-dominated regions globally, leveraging both field observations and physics-based snow model simulations.

### 5.5 Cold content development processes in other seasonal snow classes and climates

Despite the research presented here, there are still unanswered questions regarding cold content development as well as its effect on snowmelt rate and timing. Firstly, we have only presented results from two sites within a single snow-dominated research catchment. Seasonal snow cover in the western United States spans a large elevational gradient and includes both maritime (e.g., the Cascades and Sierra Nevada) and continental (e.g., the Rocky Mountains) snowpack regimes (Armstrong and Armstrong, 1987; Serreze et al., 1999). Globally, seasonal snow cover includes an even greater number of classes, including the cold, thin snowpacks of the Arctic and the Canadian Prairies (Sturm et al., 1995). Therefore, an avenue for future research is to examine differences in cold content development across seasonally snow covered areas, with a particular focus on disentangling the effects of precipitation and air temperature during snowfall at sites with different snowpack characteristics. For example, snowpacks in California's Sierra Nevada are typically deep, but air temperature is generally near freezing, even during winter storm events. Considering the cold content of precipitation is a linear function of air temperature and precipitation depth (Eq. 2), a given unit of snowfall in the Sierra Nevada should contribute less snowpack cold content than that same unit in the colder Rocky Mountains. Therefore, the control that precipitation exerts on cold content development is likely different between the two locations. Additionally, it is uncertain how our results translate to cold, shallow tundra and taiga snowpacks. In this study, we observed marked differences in cold content development processes between the alpine and subalpine, with the energy balance exerting greater control in the shallower subalpine snowpack. It may be that the energy balance is of even greater importance in tundra and taiga snowpacks, but further work is needed.

Secondly, a large amount of recent literature has shown unequivocally that, due to climate warming, patterns of snow accumulation and melt are changing across the globe with resultant effects on myriad hydrologic processes (Barnhart et al., 2016; Berghuijs et al., 2014; Knowles et al., 2006; Mote et al., 2005; Musselman et al., 2017; Pederson et al., 2011; Stewart, 2009). It is uncertain what role, if any, cold content plays in the climate-driven changes on snow processes. In our investigations we found pit-observed SWE was a strong predictor of cold content (alpine $r^2 = 0.84$; subalpine $r^2 = 0.50$), with subalpine cold content lower per unit SWE due to warmer depth-weighted snowpack temperatures. Both sites also exhibited a significant positive linear relationship between the cumulative mean of air temperature and snowpack temperature. Therefore, a unit of SWE in a warmer location or climate should correspond to reduced cold content due to increased snowpack temperature. Our work showed that decreased cold content magnitudes corresponded to faster snowmelt rates and earlier snowmelt timing at time scales less than 1 month. Therefore, reductions in snowpack cold content due to climate warming have implications for meltwater timing and availability, which could impact water resources management.

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## 6 Conclusions

We have presented an analysis of snowpack cold content using data from a long-term snow pit record and 23 y of physics-based snow model simulations at an alpine and subalpine site within the Niwot Ridge LTER. The research questions were designed to fill important missing gaps in the snow hydrology literature, namely the meteorological and energy balance processes behind cold content development and how cold content controls snowmelt rate and timing. Observations and simulations showed new snowfall was the primary pathway for cold content development at our sites, being responsible for 84.4% and 73.0% of modeled daily cold content gains in the alpine and subalpine, respectively. Snowfall days with cold content gains outnumbered non-snowfall days with gains by a 4.2:1 ratio in the alpine and 2.6:1 in the subalpine. A negative energy balance—averaging > -3.0 W m$^{-2}$ in the alpine and subalpine—was responsible for the remainder of cold content gains, primarily due to the cooling effect of sublimation and net longwave emissions. At subdaily time scales, dry-period cold content increases occurred preferentially at night at both sites. We found no evidence in either the snow pit record or the simulation data for large negative energy fluxes generating significant snowpack cold content. Additionally, air temperature showed little to no relationship to cold content development at either of the sites we studied.

Seasonal snowmelt timing was not significantly correlated with peak cold content magnitude, but rather the timing of peak cold content and total spring precipitation controlled snowmelt onset. Later peak cold content and increased spring precipitation delayed snowmelt in both the alpine and subalpine, explaining 84.7% and 61.4% of the variance in peak SWE timing. Cold content magnitude did affect sub-seasonal snowmelt in that non-zero initial cold content values corresponded to delayed snowmelt timing and slower snowmelt rates. At daily time scales, the majority of melt events and the fastest melt rates occurred only when $CC_{6AM}$ = 0.0 MJ m$^{-2}$. Any existing energy deficit at 6AM damped daily snowmelt rates.

The Niwot Ridge LTER provided the ideal study location for the research presented in this paper. The site's unique long-term snow pit and hourly meteorological records facilitated in-depth analyses into snowpack processes using both observations and physics-based snow model simulations. Lacking either data source would have limited the scope of this paper and added further uncertainty. Therefore, we hope this work underlines the utility of long-term *in situ* snowpack and meteorological measurements as they allow for robust analyses on the observations themselves and also enable model validation on multiple snowpack properties (e.g., mass, depth-weighted temperature, and cold content), which improves the quality of simulated output.

## Data availability

The quality controlled, infilled meteorological dataset presented in this work is hosted on the Niwot Ridge LTER website (http://niwot.colorado.edu/data/data/infilled-climate-data-for-c1-saddle-d1-1990-2013-hourly). Please use this paper as the data citation and contact KSJ with questions (Keith.Jennings@colorado.edu). Snow pit (http://niwot.colorado.edu/index.php/data/data/snow-cover-profile-data-for-niwot-ridge-and-green-lakes-valley-1993-ongoi) and precipitation data (http://niwot.colorado.edu/index.php/data/data/precipitation-data-for-c1-chart-recorder-1952-ongoing

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and http://niwot.colorado.edu/index.php/data/data/precipitation-data-for-saddle-chart-recorder-1981-ongoing) can also be accessed through the Niwot Ridge LTER. Niwot SNOTEL data can be found at http://www.wcc.nrcs.usda.gov/nwcc/site?sitenum=663. Niwot Ridge AmeriFlux data were provided by PI Peter Blanken and site manager Sean Burns and can be accessed at http://urquell.colorado.edu/data_ameriflux/.

# Appendix A

## A.1 Meteorological data quality control and infilling

The quality control routine for all observation types except precipitation followed the three-step procedure outlined in Meek and Hatfield (1994) where observations were flagged for removal if: 1) they fell outside of a prescribed minimum-maximum range for that day of year; 2) their hourly rate of change exceeded a given threshold; 3) the same value was recorded in four consecutive time steps, indicating a stuck sensor. A full description of the protocol for each variable falls outside the scope of this paper, but can be viewed in Meek and Hatfield (1994). The only changes made to their schema were applied to better represent climate processes on Niwot Ridge, particularly the high variability in hourly air temperature and wind speed common at dry, high-elevation, mountainous, continental locations. These modifications allowed more valid observations to pass the quality control checks than the original Meek and Hatfield (1994) protocol.

Following the quality control procedure, missing observations were imputed using a hierarchical routine based on the work of Liston and Elder (2006), Kittel (2009), and Henn et al. (2012), where gaps of 72 h and shorter were infilled using temporal techniques and longer gaps were infilled using a multi-station regression. Data gaps of 1 h were filled using a linear interpolation between the observations directly preceding and following the missing value. Gaps between 2 h and 24 h were filled using an average of the value recorded 24 h prior and 24 h after the missing observation. Gaps between 25 h and 72 h were filled using a forecasted and back-casted autoregressive integrated moving average (ARIMA) model with imputed values linearly weighted by their temporal distance from the beginning/end of gap. Data gaps longer than 72 h, plus shorter gaps that could not be filled using the temporal protocol due to missing data, were infilled with a one- or two-station regression. We pursued this approach because each station collected the same required forcing data for SNOWPACK and the three stations were located within 7 km of one another (Fig. 1). If the two remaining stations were reporting valid observations, then the two-station regression was used. Otherwise, the one-station regression was employed. Regression equations were generated for each variable per month and 3 h time block where a day is divided into eight 3 h periods (e.g., 00:00–03:00, 03:00–06:00, etc.). Although such an approach neglects the spatial variability inherent to meteorologic processes in complex terrain, the values generated by the regressions reproduce changes in conditions due to frontal passages and storm events. For periods when no stations were reporting, data were infilled using the mean value for the given station, variable, month, and 3 h time block.

Quality controlled, gap-filled relative humidity, air temperature, and incoming solar radiation measurements were used to generate two estimates of incoming longwave radiation at an hourly time step. The equations presented in Angström

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(1915) and Dilley and O'Brien (1998) were used to estimate clear sky atmospheric emissivity based on vapor pressure, which was calculated from relative humidity. Flerchinger et al. (2009) noted these two methods performed best at the subalpine site on Niwot Ridge relative to observations from the co-located AmeriFlux tower. Emissivity was then corrected for estimated cloud cover based on the ratio of observed solar radiation to maximum clear sky solar radiation using the approach of Crawford and Duchon (1999). Finally, incoming longwave radiation was calculated using the Stefan-Boltzmann equation:

$$LW \downarrow = \epsilon \sigma T_a^4 \quad \text{(A1)}$$

where $LW \downarrow$ is incoming longwave radiation (W m$^{-2}$), $\epsilon$ is the estimated atmospheric emissivity (dimensionless, 0 to 1), $\sigma$ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8}$ W m$^{-2}$ K$^{-4}$), and $T_a$ is air temperature (K).

Measuring solid precipitation is inherently difficult, particularly at higher wind speeds (Rasmussen et al., 2012; Yang et al., 1999) and snowpack simulations are reliant on accurate precipitation input to produce reliable output (Raleigh et al., 2015; Schmucki et al., 2014). Thus, any snow modeling project has the compounded problem of requiring accurate precipitation forcings and sensitivity to said forcings. For this study, two primary precipitation data sources were utilized along with site-specific gage corrections as described below.

Alpine precipitation data came from the quality controlled LTER dataset (http://niwot.colorado.edu/index.php/data/data/precipitation-data-for-saddle-chart-recorder-1981-ongoing). While snowfall undercatch is commonly documented in the literature, Williams et al. (1998) showed blowing snow events lead to significant overcatch at the LTER alpine precipitation gage from October through May. To correct the overcatch we created monthly precipitation reduction factors by comparing cumulative precipitation from the date of each snow pit observation to the following snow pit observation to the change in SWE between those observation dates when the change in pit SWE was positive. We found overcatch was greatest in months where Berg (1986) reported the highest frequency of blowing snow events (January, March —average reduction = 0.59) and lowest in months with fewer blowing snow events (December, February, April—average reduction = 0.86).

Subalpine precipitation data came from the quality controlled, gap-filled Kittel et al. (2015) dataset with further corrections applied for snow undercatch relative to the Niwot SNOTEL snow pillow during snowfall events, which averaged 2.1 mm per snowfall day. Air temperature during precipitation events showed the strongest control on undercatch with decreasing air temperature corresponding to increased negative precipitation biases. Notably, wind speed was not correlated with undercatch at the subalpine gage, likely due to the siting of the anemometer. This instrument is located 5 m above ground level in a roadside clearing and is generally unrepresentative of the wind speed magnitude in the dense subalpine forest where the snow pit, LTER precipitation gage, and Niwot SNOTEL station are located. Compared to the subalpine snow pit, accumulated precipitation in the gage was on average 88.3 mm or 32.3% lower than observed maximum SWE.

Daily precipitation observations from both datasets were temporally disaggregated to the hourly time step of SNOWPACK by dividing the daily total by 24 and equally distributing the values to each hour of the day. Hourly precipitation observations were not available, and therefore a more advanced disaggregation method was not pursued.

### A.2 Meteorological data infilling validation

Missing observations and measurements failing the quality control checks were more common in the alpine than subalpine (Table A1). The variable with the greatest number of missing values was solar radiation in the alpine due to a long instrument outage period in the 2000s. The multi-station regression was the most utilized infilling technique (temporal infilling accounted for, at most, 3.0% of the missing data) and cross-validation statistics are presented in Table A1. Generally, infilling performance was greater in the alpine due to the close proximity of the high alpine meteorological station. Of the forcing variables, air temperature exhibited the highest infilling performance and wind speed the lowest.

Estimates of incoming longwave radiation exhibited low biases relative to shorter-term observations taken near the alpine and subalpine meteorological stations. In the alpine, measurements of incoming longwave radiation were taken at the Subnivean Laboratory from 1996 through 2008 and intermittently in more recent years. Here, the Dilley and O'Brien (1998) equation produced the best results relative to the observed data with a mean bias of 4.9 W $m^{-2}$. In the subalpine, the mean bias relative to Ameriflux observations (1999-07-12 through 2013-12-31) was 10.4 W $m^{-2}$ with the Angström (1915) estimate providing the best match. The positive biases in the alpine and subalpine represented 2.0% and 4.1%, respectively, of the average hourly observed incoming longwave radiation, values which were within the manufacturer-reported precision range of ±10% for the Kipp and Zonen CG2 net pyrgeometer at the Subnivean Laboratory and the CNR1 net radiometer at the AmeriFlux tower. The coefficient of determination for hourly and daily incoming longwave values were 0.51 and 0.72, respectively, in the alpine and 0.44 and 0.60 in the subalpine.

### Author contributions

KSJ, TGK, and NPM designed the study. KSJ performed the analyses and wrote the manuscript. TGK and NPM provided feedback and edited the manuscript.

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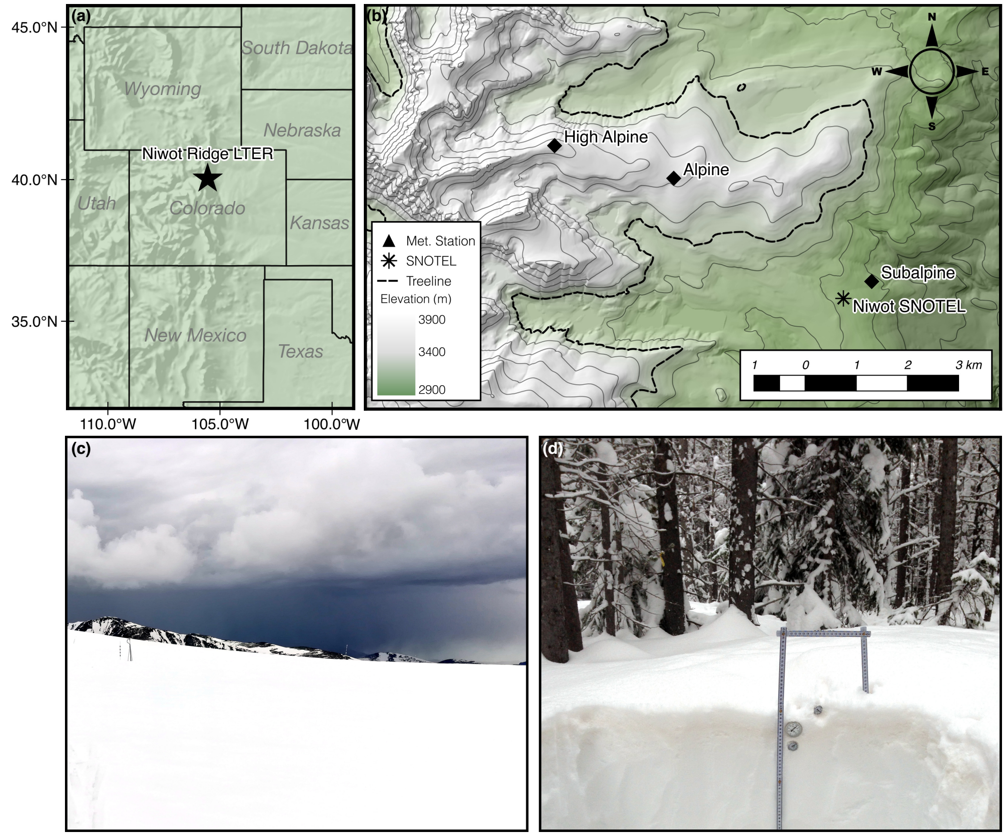


**Figure 1: The location of the Niwot Ridge LTER within the western United States (a) and a topographical map showing the meteorological stations and snow pit sites. The dashed line in the LTER inset (b) represents approximate treeline (3400 m) and the thin, solid lines are 100 m contours. The snow study focused on the alpine (c) and subalpine sites (d), the two locations which have co-located snow pit observations and meteorological stations. The high alpine site was used as an additional station in the meteorological data infilling protocol and the Niwot SNOTEL was used for model validation.**

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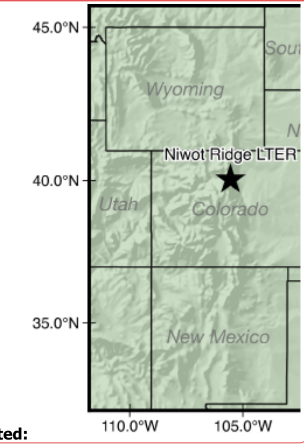


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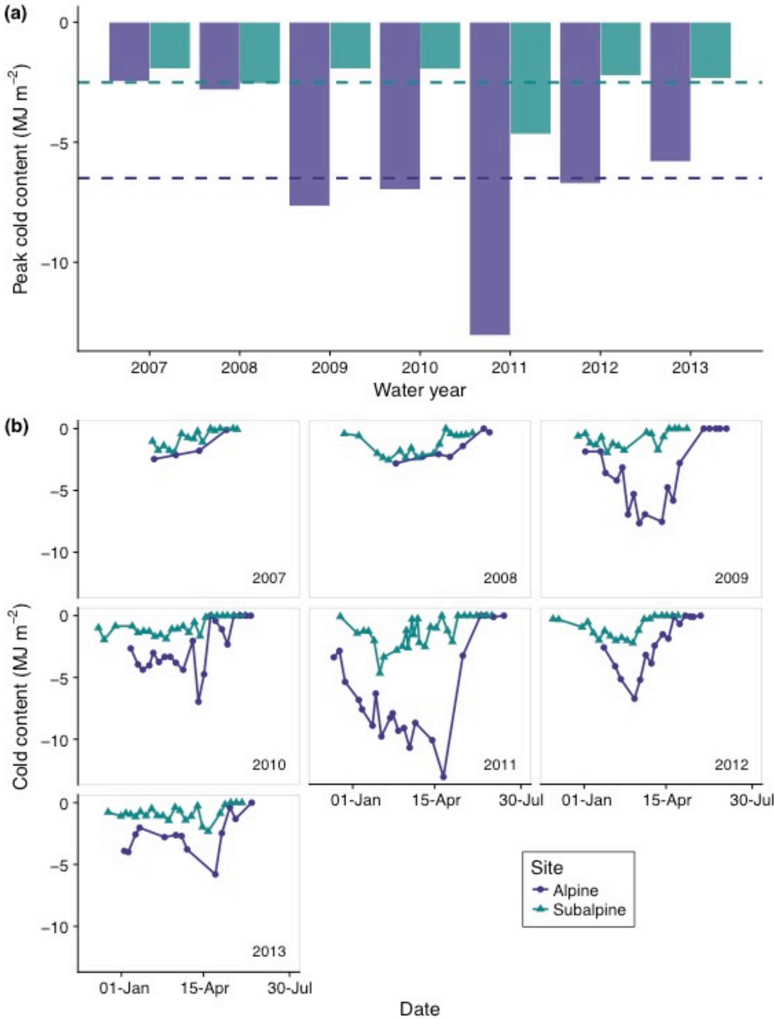


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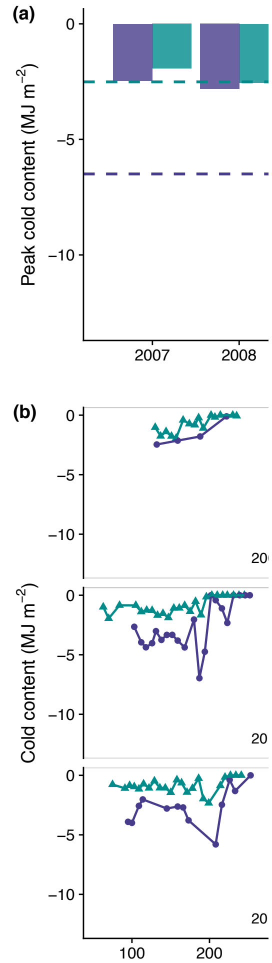


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Figure 2. Peak annual cold content (a) and individual snow pit observations of cold content (b) for the alpine and subalpine from WY2007–WY2013. The dashed horizontal lines in (a) represent the mean peak annual cold content values for the two sites.

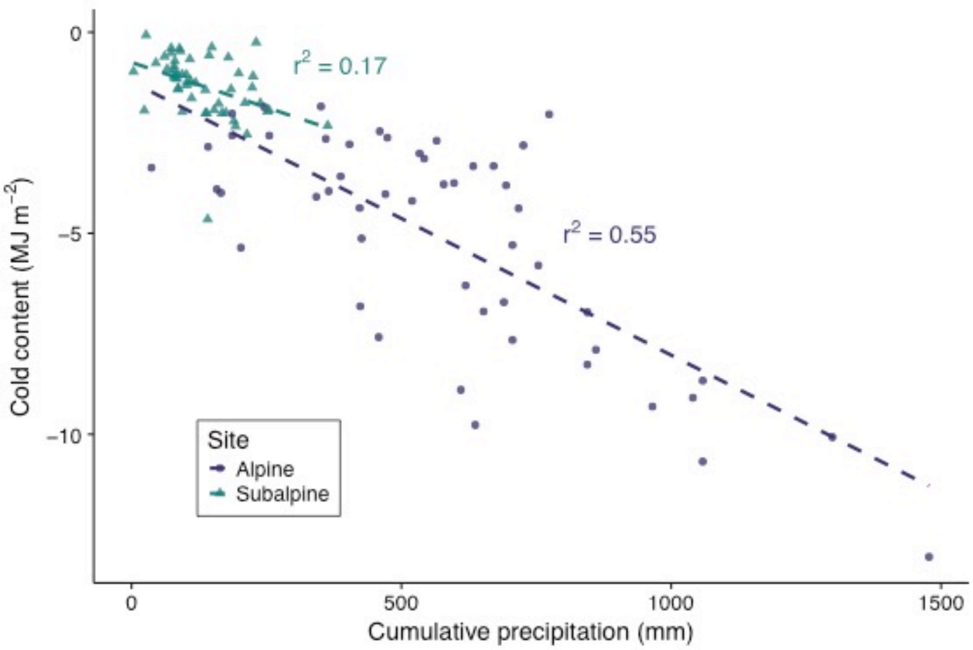


**Figure 3. Cold content plotted against cumulative precipitation from 1 December to the date of snow pit observation for the alpine and subalpine for the snow season up to and including the date of peak cold content from WY2007–WY2013. The dashed lines of best fit were calculated using ordinary least squares linear regression.**

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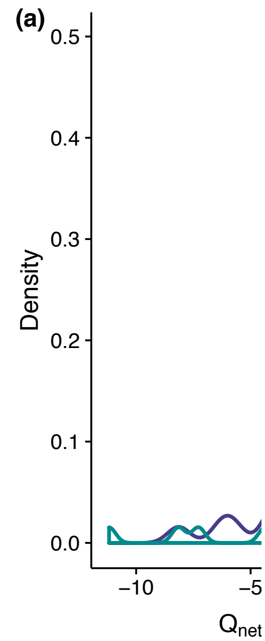


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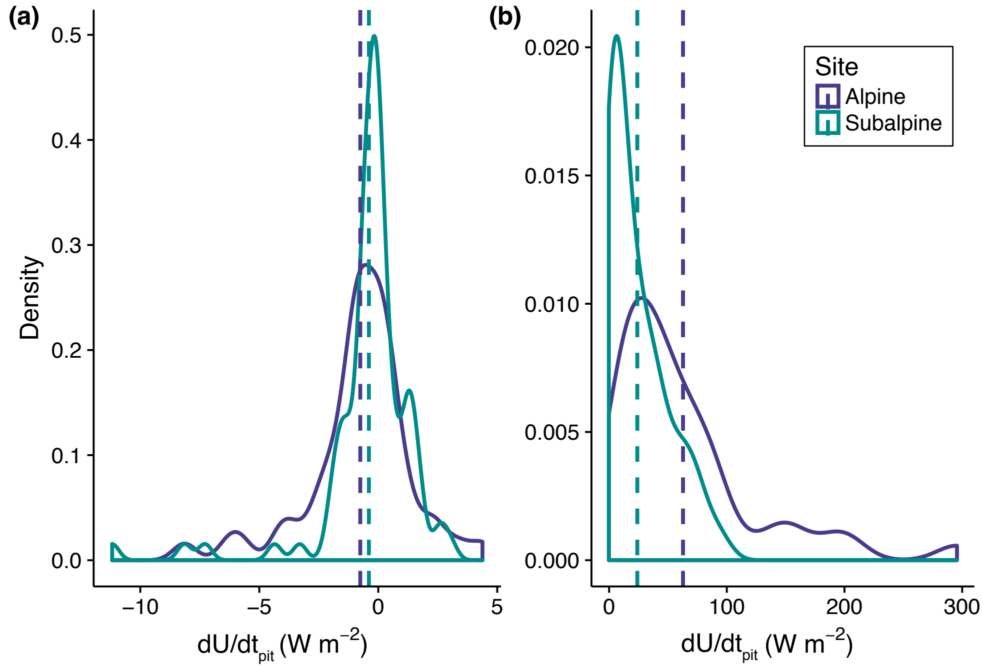


**Figure 4. Kernel density estimates of $\frac{dU}{dt}_{pit}$ distributions as calculated from snow pit observations for periods with SWE gain (a) and loss (b) in the alpine and subalpine for WY2007–WY2013. The dashed vertical lines represent the mean $\frac{dU}{dt}_{pit}$ for the alpine (a = -0.8 W m$^{-2}$; b = 62.8 W m$^{-2}$) and subalpine (a = -0.4 W m$^{-2}$; b = 23.9 W m$^{-2}$).**

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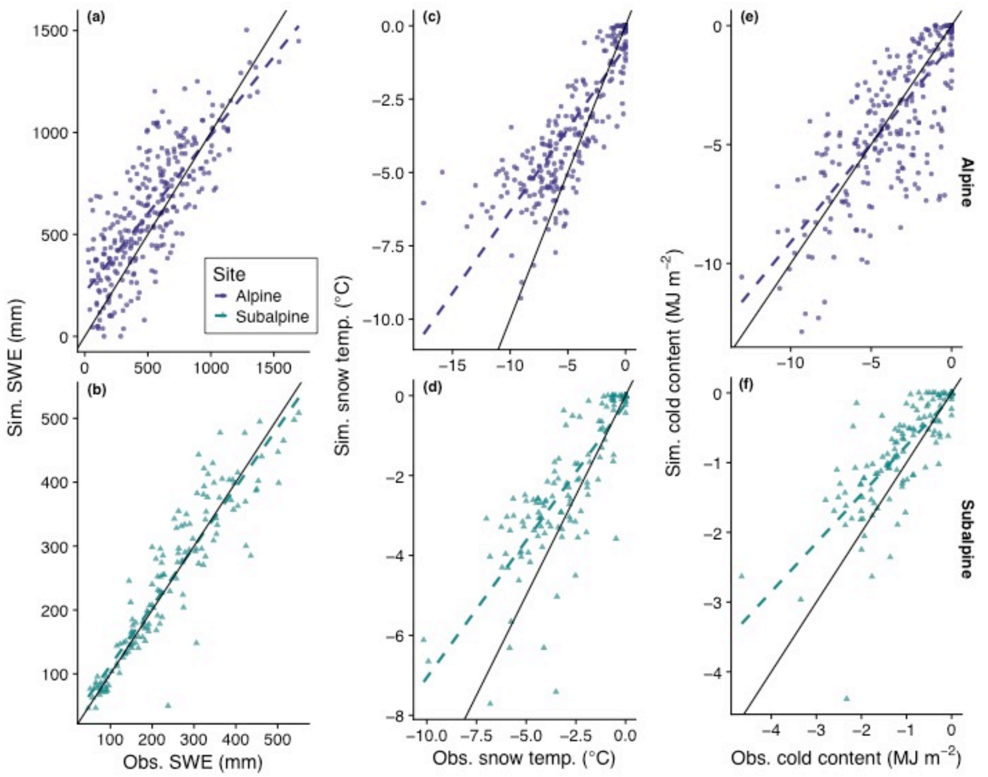


**Figure 5. Plots of simulated versus snow-pit observed SWE (a,b), snowpack temperature (c,d), and cold content (e,f) in the alpine (top, WY1995–WY2013) and subalpine (bottom, WY2007–WY2013). The solid black line is the 1:1 line and the dashed lines are the lines of best fit as determined by ordinary least squares linear regression. Simulation error metrics are presented in Table 1.**

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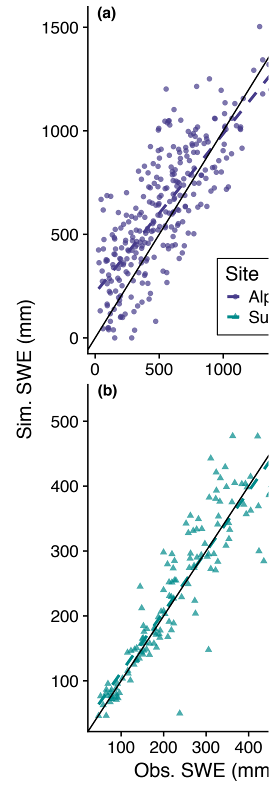


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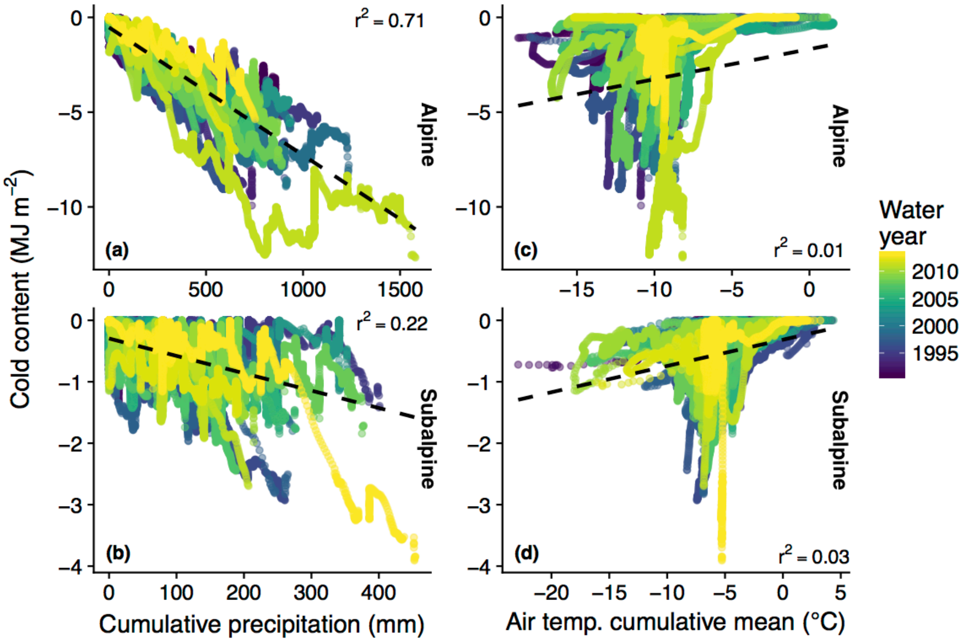


**Figure 6. Simulated cold content plotted against cumulative precipitation in the alpine (a) and subalpine (b), and the cumulative mean of air temperature in the alpine (c) and subalpine (d). Shading denotes the corresponding water year.**



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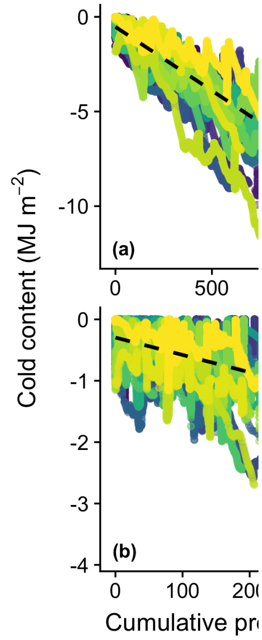

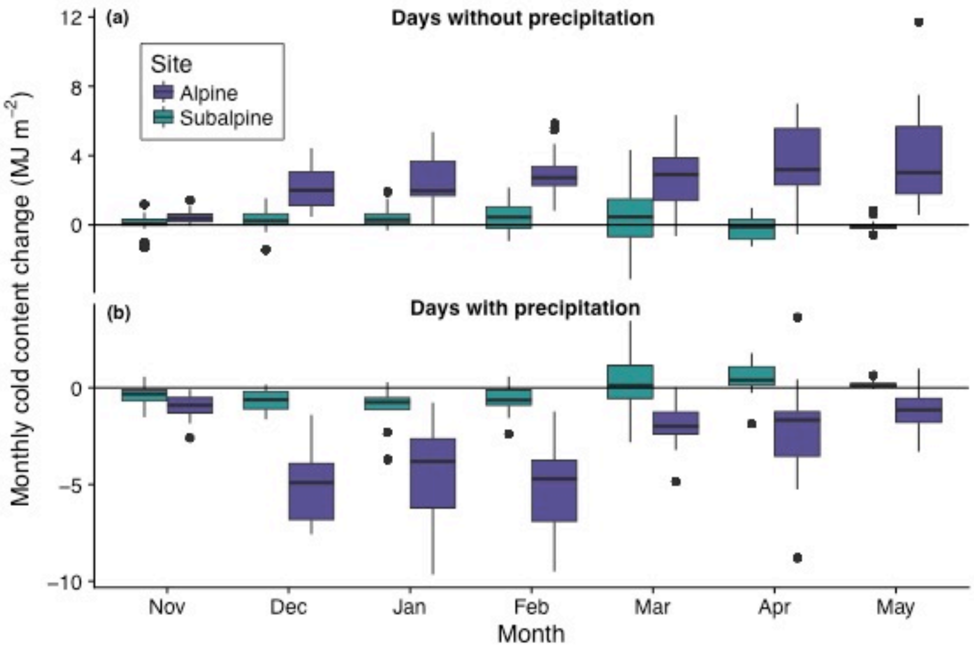


**Figure 7. Simulated cold content gain and loss per month in the alpine and subalpine for days without precipitation (a) and days with precipitation (b). Values above the zero line correspond to a loss of cold content (i.e., cold content approaches zero), while values below correspond to a gain of cold content.**



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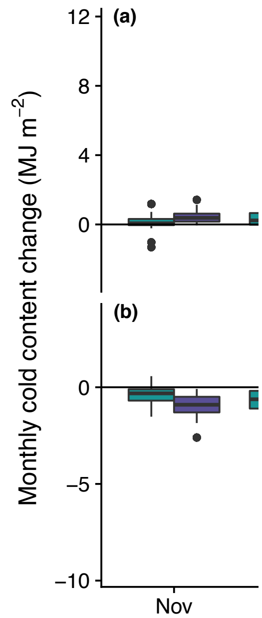


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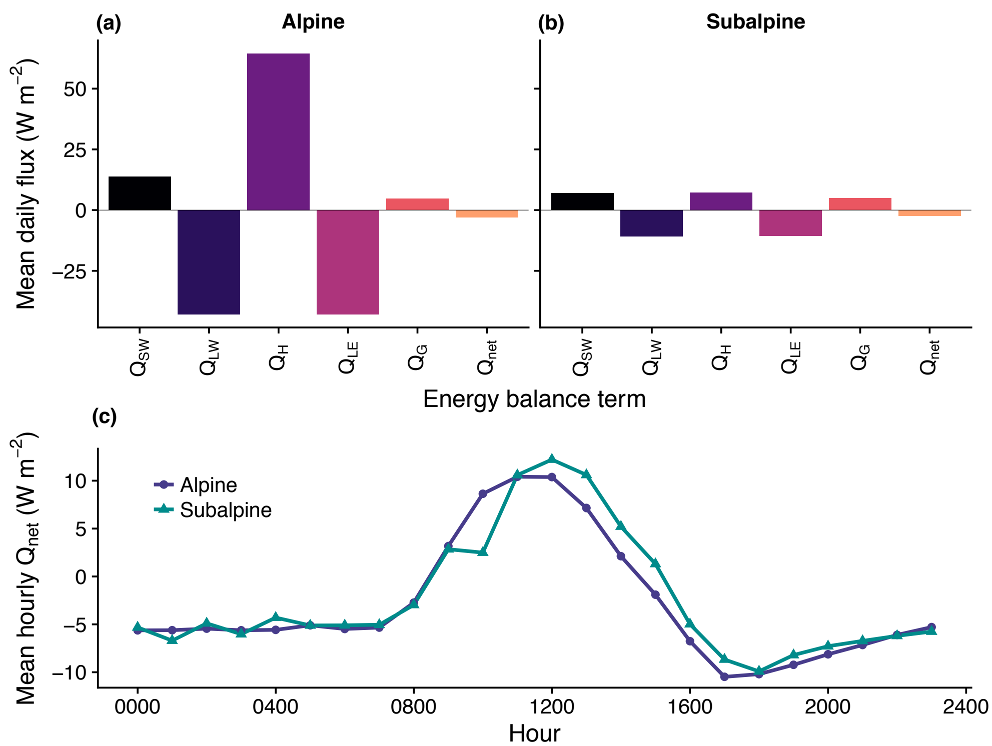


Figure 8. Simulated snowpack energy balance in the alpine (a) and subalpine (b), plus mean hourly $Q_{net}$ (c) for days of cold content gain without precipitation.

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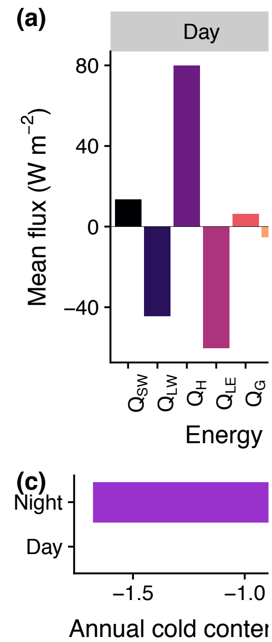


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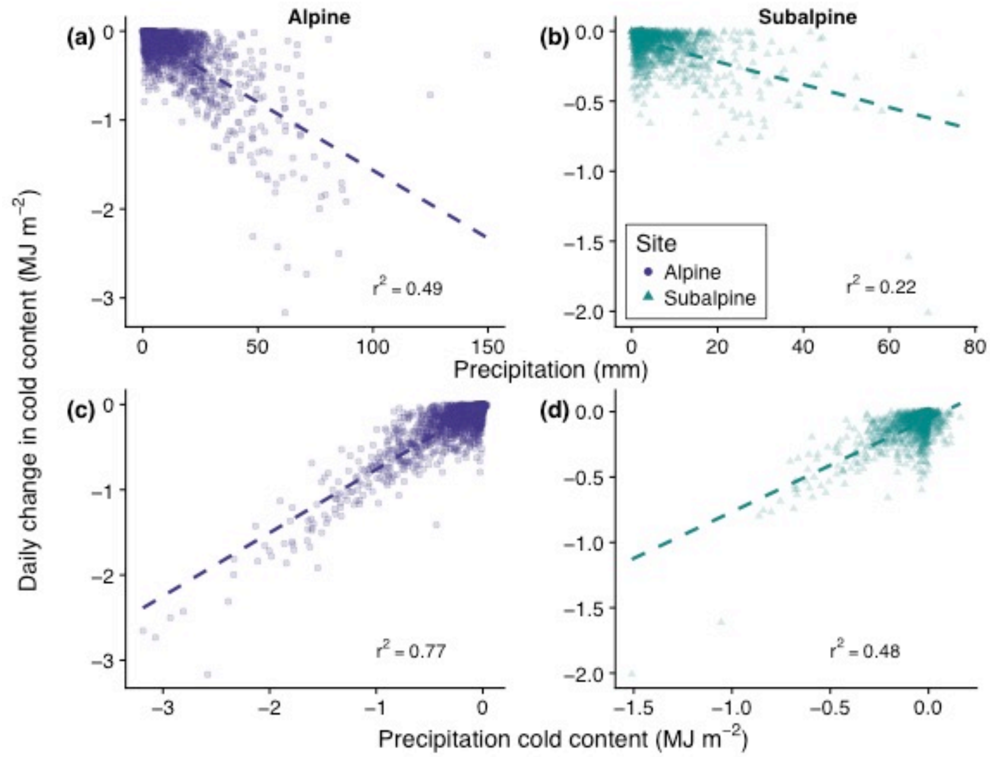


**Figure 9. Simulated daily change in cold content plotted against daily precipitation in the alpine (a) and subalpine (b), and cold content from precipitation in the alpine (c) and subalpine (d).**

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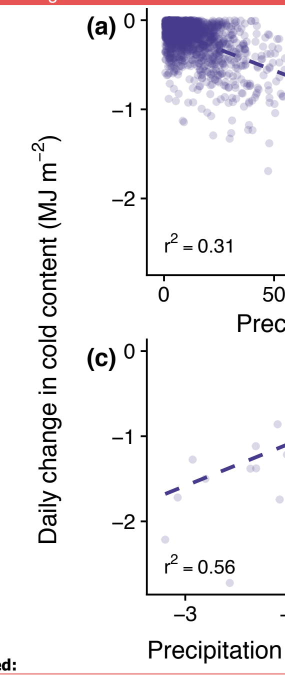

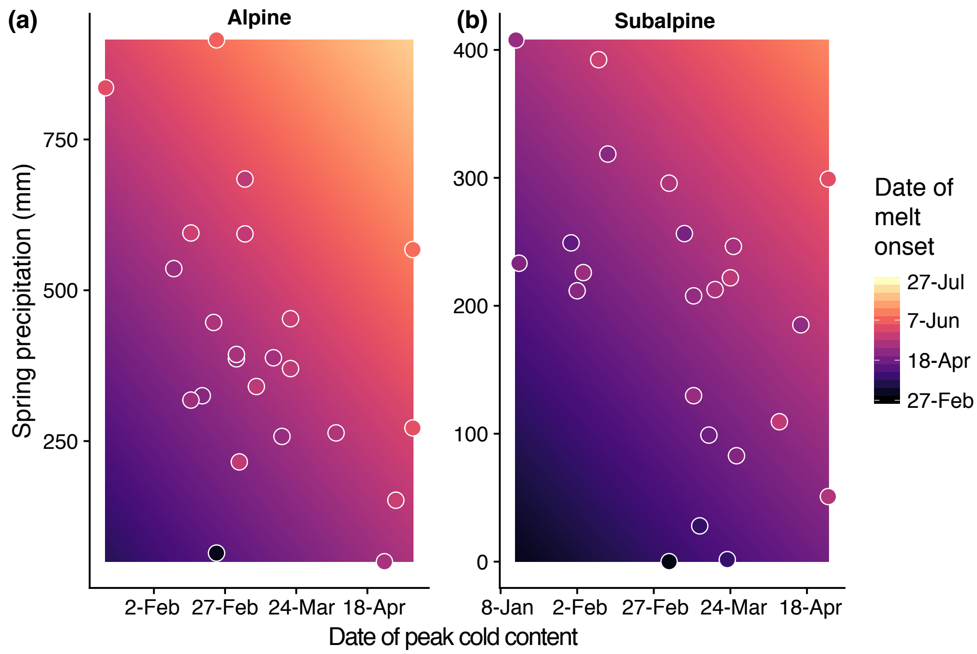


**Figure 10. Annual melt onset as predicted by peak cold content timing and spring precipitation in the alpine (a) and subalpine (b). The background gradient in each plot displays the predicted melt onset date as calculated by a multiple linear regression, while the shading within each point represents the actual melt onset simulated in a given water year at its peak cold content date and spring precipitation value.**

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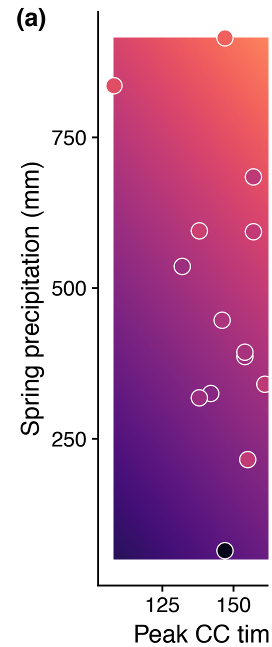


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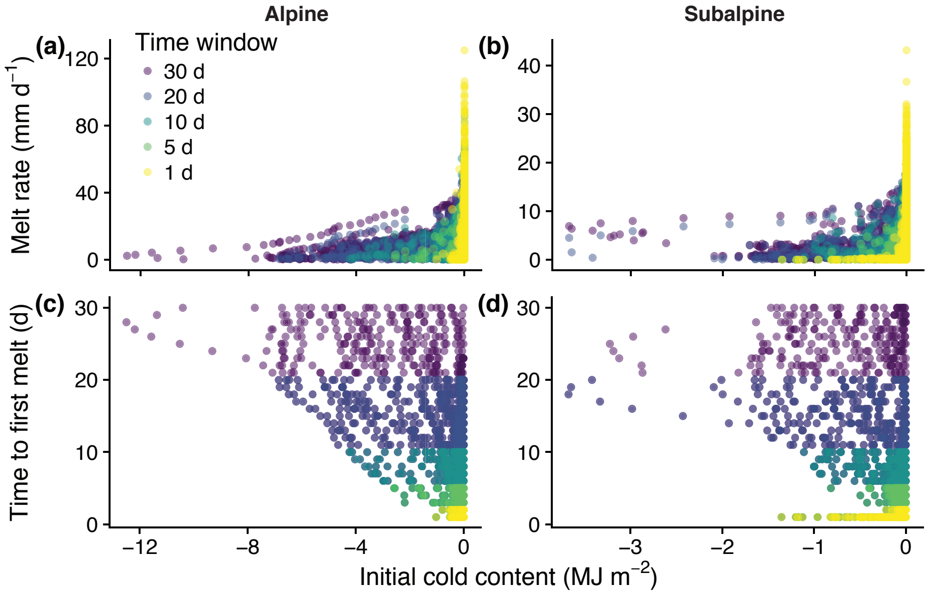


**Figure 11. Simulated sub-seasonal snowmelt rate plotted against initial cold content in the alpine (a) and subalpine (b), and time to first melt plotted against initial cold content in the alpine (c) and subalpine (d) for time windows from 1 d to 30 d.**

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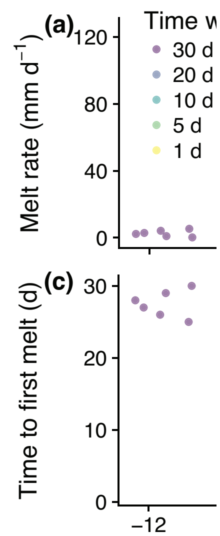


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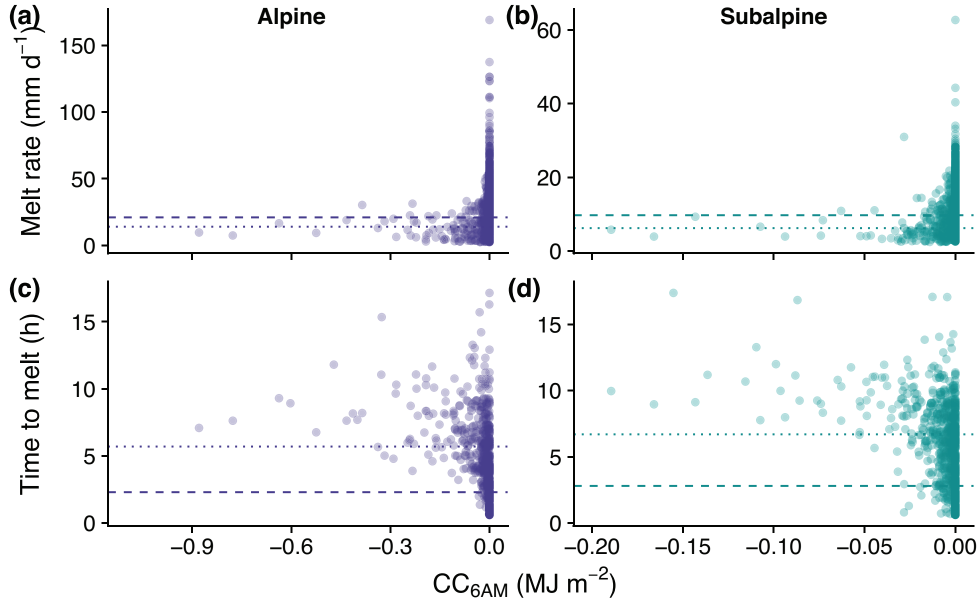
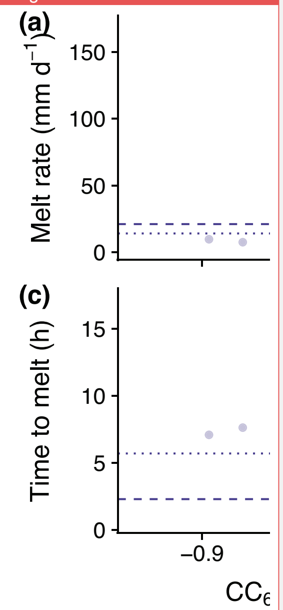



**Figure 12. Simulated daily melt rates in the alpine (a) and subalpine (b) and time to snowmelt in the alpine (c) and subalpine (d) as a function of CC$_{6AM}$. The dashed line in each figure represents the mean melt rate (a,b) and time to melt (c,d) for days when CC$_{6AM}$ = 0 MJ m$^{-2}$ and the dotted line represents those quantities for days when CC$_{6AM}$ < 0 MJ m$^{-2}$.**



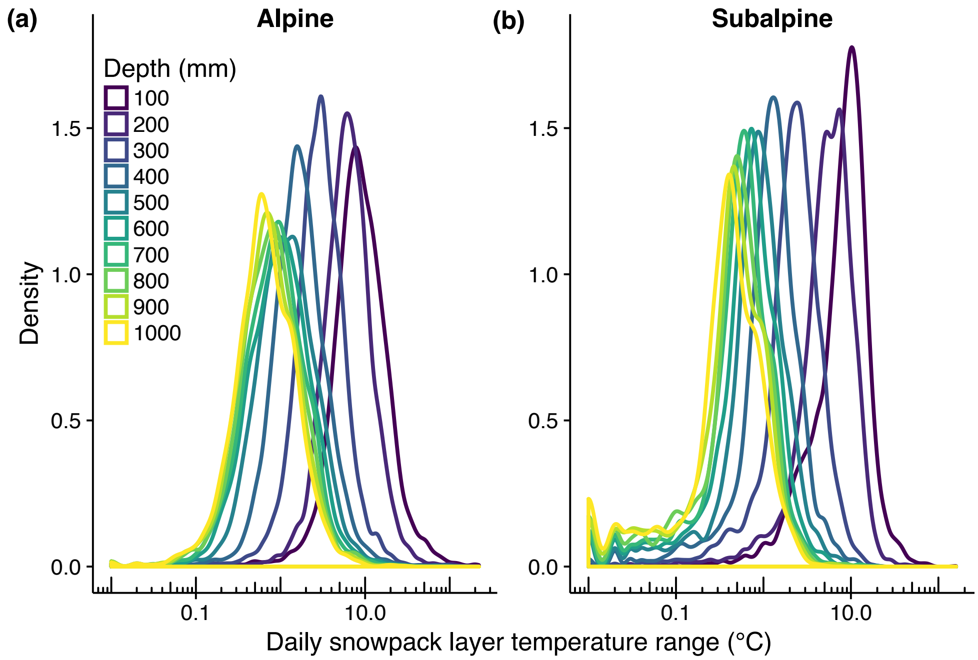



**Figure 13. Kernel density estimates of simulated daily snowpack layer temperature ranges in the alpine (a) and subalpine (b). Line shading represents the bottom depth of the layer with layers near the top of the snowpack in purple and blue and lower layers in green and yellow.**

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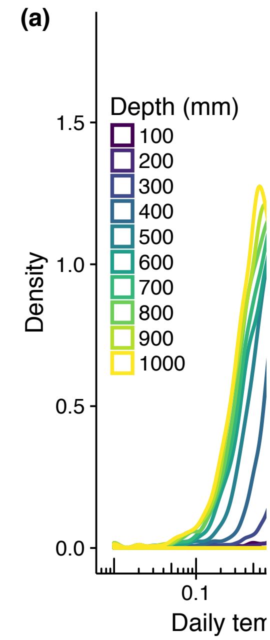


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**Table 1. Mean quantities for the alpine and subalpine snow pits from WY2007–WY2013**

| Site | Peak CC ($MJ\ m^{-2}$) | Peak SWE (mm) | Date of Peak CC | Date of Peak SWE |
|---|---|---|---|---|
| Alpine | -6.5 | 843 | 19-March | 6-May |
| Subalpine | -2.5 | 395 | 14-February | 26-April |

**Table 2. Statistics for SNOWPACK simulations relative to daily and annual observations from the snow pits in the alpine and subalpine, and Niwot SNOTEL in the subalpine. There is no SNOTEL station in the alpine and SNOTEL does not observe cold content and snowpack temperature. Comparisons are for the water years listed in the second column.**

| | | Daily | | | | | | Annual | |
|---|---|---|---|---|---|---|---|---|---|
| **Site** | **WY Range** | **SWE $r^2$** | **SWE Mean Bias (mm)** | **$T_s$ $r^2$** | **$T_s$ Mean Bias (°C)** | **CC $r^2$** | **CC Mean Bias (MJ $m^{-2}$)** | **Max SWE Mean Bias (mm)** | **Max CC Mean Bias (MJ $m^{-2}$)** |
| Alpine | 1996-2013 | 0.63 | 95.8 | 0.74 | 1.1 | 0.63 | -0.3 | 99 .0 | -0.7 |
| Subalpine (Snow Pit) | 2007-2013 | 0.85 | 3.4 | 0.72 | 0.6 | 0.63 | 0.2 | 15.0 | 0.6 |
| Subalpine (SNOTEL) | 1991-2013 | 0.89 | -5.4 | NA | NA | NA | NA | 44.1 | NA |

**Table A1. Cross-validation statistics for the multi-station regression infilling procedure for air temperature ($T_a$, °C), total incoming solar radiation ($SW_{in}$, MJ $m^{-2}$), wind speed (VW, m $s^{-1}$), and dew point temperature ($T_d$, °C). Note: Relative humidity values were converted to $T_d$ for computing the multi-station regression.**

| Site | Variable | Missing Obs. (%) | Mean Bias | RMSE | $r^2$ |
|---|---|---|---|---|---|
| Alpine | $T_a$ | 8.2 | $2.8 \times 10^{-3}$ | 1.6 | 0.97 |
| | $SW_{in}$ | 25.3 | $-4.4 \times 10^{-2}$ | 0.4 | 0.83 |
| | VW | 6.0 | -0.5 | 3.2 | 0.69 |
| | $T_d$ | 6.9 | -1.3 | 3.7 | 0.84 |
| Subalpine | $T_a$ | 3.8 | $-6.4 \times 10^{-2}$ | 3.5 | 0.86 |
| | $SW_{in}$ | 2.9 | $-4.8 \times 10^{-2}$ | 0.6 | 0.67 |
| | VW | 3.6 | -0.3 | 2.1 | 0.30 |
| | $T_d$ | 3.6 | -2.9 | 4.7 | 0.81 |