The Impact of Warming Temperatures on Snowpack Structure

Clinton Alden

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Jessica Lundquist
Bart Nijssen

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Abstract

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Chair of the Supervisory Committee:
Jessica Lundquist
Department of Civil and Environmental Engineering

Warming winters will lead to a greater fraction of rain falling in traditionally snowy areas. Here we investigate the impact of these changes on snowpack stratigraphy, focusing specifically on the presence and duration of melt-freeze crusts. In this work, we use a hydrologic model with high vertical resolution (Structure for Unifying Multiple Modeling Alternatives, SUMMA) to test the sensitivity of melt-freeze crusts to warming. Model runs with up to 100 layers were initialized with observed precipitation and temperature for 2°C and 4°C uniform warming sensitivity tests. We found warming temperatures increased the frequency of crusts at colder sites, while warmer sites had fewer crusts. Melt-freeze crusts increase the complexity of avalanche forecasting and mitigation for highway, recreational forecasting, and ski area operations. These changes to the snowpack will also impact ecosystem function, with greater snow density altering large mammal movements and predator-prey interactions.

1 Introduction

Climate change and warming winters will drastically change seasonal snow in the Western United States. These changes include declines in April 1 snow water equivalent (SWE) (Mote et al., 2005, 2018), reduced days of snow cover (Scott & Kaiser, 2004), and earlier snowmelt timing (Arnell, 1999; Stewart et al., 2004; McCabe & Clark, 2005; Barnett et al., 2005; Musselman et al., 2017). However, studies connecting climate change and warming to snowpack trends have not previously analyzed the layered structure of the snowpack.

To fill an existing literature gap, our work examined the sensitivity of snowpack structure to warming air temperatures. We use observed precipitation and air temperature from the SNOw TELemetry (SNOTEL) sites to initialize the SUMMA hydrologic and snow model (Clark et al., 2015a, 2015b). The Natural Resource Conservation Service's SNOTEL network encompasses 900+ automated surface meteorology and snow study sites across the Western United States (Schaefer & Paetzold, 2000; Fleming et al., 2023). We hypothesized that increased temperatures would create a more complex stratigraphy with more ice crusts in maritime snow climates and that near-surface snow density would increase. In this work, changes in stratigraphy refer to changes to the frequency of melt-freeze crusts as defined by Fierz et al. (2009) and Greene et al. (2016). In this work, melt-freeze crusts include both ice layers and ice crusts.

Understanding the stratigraphy of a snowpack is critical for forecasters, specifically for slab avalanches (D. M. McClung, 1995). Crusts significantly impact these types of avalanches. Prior work by Colbeck and Jamieson (2001) has shown poor snow grain bonding around ice crusts to result in unstable snow and avalanches. Additionally, faceted snow grains can develop next to buried crusts and are well known to be a weak interface upon which slab avalanches can be triggered (Stethem & Perla, 1980; Colbeck, 1986). The existence of crusts in a snowpack adds complexity to avalanche forecasting and mitigation operations.

The intersection of climate change and snow stratigraphy has important implications for wildlife biology as well, and there has been increasing interest in identifying and quantifying wildlife-relevant snow properties (Boelman et al., 2019; Reinking et al., 2022). Sullender et al. (2023) established near-surface snow density as a predictor of sink depth for common predators and prey in Washington and Alaska. Ice layers in snow from rain-on-snow decrease food availability for reindeer (*Rangifer tarandus*) and other herbivores as they cannot access buried forage (Hansen et al., 2011). However, the ecological implications of finer-scale changes in snowpack and especially in snow structure remain poorly studied.

Here, we conduct a ΔT modeling experiment in this domain to test the sensitivity of snowpack structure, particularly crust frequency, to warming temperatures.

Specifically, we explore the following:

1. **How is snow stratigraphy sensitive to warming air temperatures?**
2. **In what ways does this sensitivity vary across geographic and climactic regions?**

2 Methods

2.1 Study Domain

We chose a set of SNOwpack TELEmetry (SNOTEL) sites to compare trends in snow stratigraphy across geographic space. We defined our domain from 109°W to 125°W and 42°N to 49°N to represent a range of snow climates from the Pacific Northwest to the Inland Northwest to the Rockies. Within this domain, we selected the nearest SNOTEL with at least a 25-year period of record to all ski areas. 53 SNOTEL sites with data from 2000 to 2024 satisfied this criteria. The sites range in elevation from 1204m to 2865m elevation and in mean winter (December-January-February) air temperature from $-0.7°$C to $-8.8°$C. We chose sites located near ski areas to represent where humans travel and live in the winter.

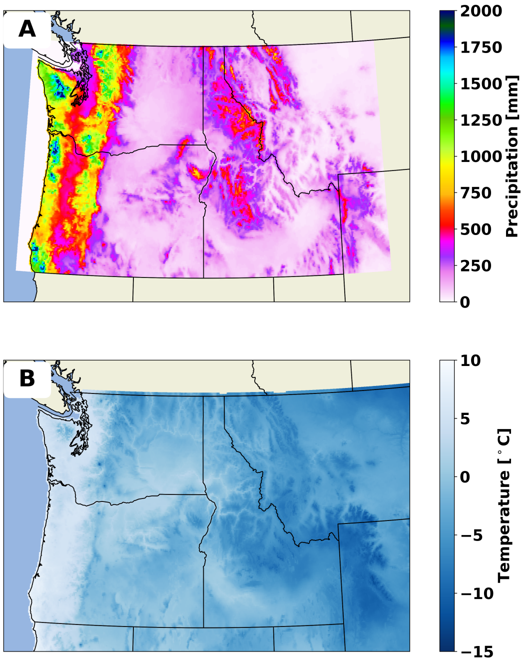


Figure 1. (a) PRISM 4km 1991-2020 mean winter (December-January-February) precipitation for our domain. (b) PRISM 4km 1991-2020 mean winter air temperature.

Figure 1 shows PRISM 4km mean winter (December-January-February) air temperature and precipitation for the 1991-2020 period. The climatology of our domain is strongly controlled by the Cascade Mountains that run North-South across Central Oregon and Washington. To the west of the Cascade crest, mean winter precipitation is high with mild winter air temperatures due to its proximity to maritime air masses and the ocean (Mass, 2021). Mean precipitation increases and mean temperatures decrease moving North towards the Washington-Canada border at 49°N, the northern boundary of our domain. East of the Cascades, mean winter precipitation and temperatures decrease.

2.2 Experiment Design

To create a representative range of current snow structure conditions, we ran SUMMA for the 2000-2024 period, generating the mean annual statistics for each site described in section 3.2. We performed a temperature change (ΔT) sensitivity experiment on snowpack stratigraphy for 2°C and 4°C of warming. This temperature range represents realistic late-century warming in the Pacific Northwest (Dalton et al., 2013).

2.3 Model Choice

For this work, we used the Structure for Unifying Multiple Modeling Alternatives (SUMMA) (Clark et al., 2015a, 2015b) as a variable layer model based on SNTHERM layering structure (Jordan, 1991). Decharme et al. (2016) and Cristea et al. (2022) found that snow models with more vertical layers increase skill in representing many key output variables, including density and snow temperature. Other modeling options to solve this problem include SNTHERM (Jordan, 1991), CROCUS (Brun et al., 1989), and SNOW-

PACK (Bartelt & Lehning, 2002; Lehning, Bartelt, Brown, Fierz, & Satyawali, 2002; Lehning, Bartelt, Brown, & Fierz, 2002). SUMMA allowed for the quick modification of parameterizations, including comparing modeling schemes used in separate models run within the same framework. Prior research (Currier et al., 2017; Wayand et al., 2017; Cristea et al., 2022) has used SUMMA for its flexible parameterization schemes to study various snowpack processes. SUMMA was run at hourly time steps with a high vertical resolution, allowing for the representation of small layers and interfaces that cannot be resolved with more vertically coarse modeling systems. We chose SUMMA for this work over other high-resolution models for its ease of use in tuning parameterizations, ensuring certain snow properties such as stratigraphy were properly resolved.

SUMMA sub-divided layers at each timestep (hourly) according to defined layer thickness thresholds (Clark et al., 2015b). In our model runs, the minimum layer thickness was 1cm and the maximum was 5cm. Each unique layer had various properties such as temperature, density, thickness, ice fraction, and more that we extracted for further analysis at each timestep.

2.4 Creating SUMMA Meteorological Forcings

SUMMA requires input of air temperature, precipitation, incoming longwave radiation, incoming shortwave radiation, wind speed, specific humidity, and air pressure. We used observed air temperature and precipitation at hourly timesteps from the SNOTEL network. The remaining five meteorological inputs used empirical derivations because the SNOTEL network did not contain this data. Table 1 details these data sources, and the supplemental material provides the derivations.

For the ΔT model runs, we modified the default meteorological forcings as described below. We then tested two incremental warming scenarios by uniformly increasing air temperature by 2°C and 4°C at all timesteps. We recalculated incoming longwave radiation for each set of model forcings using the modified temperatures. The other five meteorological inputs remained unchanged compared to the original model.

Table 1. Meteorological forcings from SUMMA simulations

Forcing Variable	**Temp. Eval.** *Kettle Ponds, CO*	**Density Eval.** *Snoqualmie Pass, WA*	**SNOTEL Sensitivities**
Precip. rate ($kg\, m^2\, s^{-1}$)	observed	observed	observed
Air temperature (K)	observed	observed	observed
Specific humidity ($g\, g^{-1}$)	observed	Running et al. (1987)	Running et al. (1987)
Wind speed ($m\, s^{-1}$)	observed	uniform 2 $m\ s^{-1}$	uniform 2 $m\ s^{-1}$
Air pressure (Pa)	observed	Wallace and Hobbs (2006)	Wallace and Hobbs (2006)
Shortwave rad. ($W\, m^{-2}$)	observed	Bennett et al. (2020)	Bennett et al. (2020)
Longwave rad. ($W\, m^{-2}$)	observed	Dilley and O'brien (1998)	Dilley and O'brien (1998)

2.5 Model Evaluation

Our SUMMA simulations were evaluated to test the representation of internal physical snow processes. We evaluated snowpack stratigraphy at Snoqualmie Pass, Washington using manual snow pit observations and snow temperature at Kettle Ponds near Crested Butte, Colorado using a buried thermistor array (Lundquist et al., 2024). The Washington State Department of Transportation (WSDOT) collected daily manual snow pit observations which we used to evaluate snowpack stratigraphy. Because of Snoqualmie Pass's maritime snow climate, the snowpack's typical state at this mid-elevation site was isothermal for much of the accumulation season. Therefore, it was challenging to evaluate internal snow temperature at this site with temperatures frequently near 0 °C. We instead evaluated snow temperature at Kettle Ponds, Colorado due to the high-quality data collected during Water Year 2023 during the Sublimation of Snow field campaign (Lundquist et al., 2024).

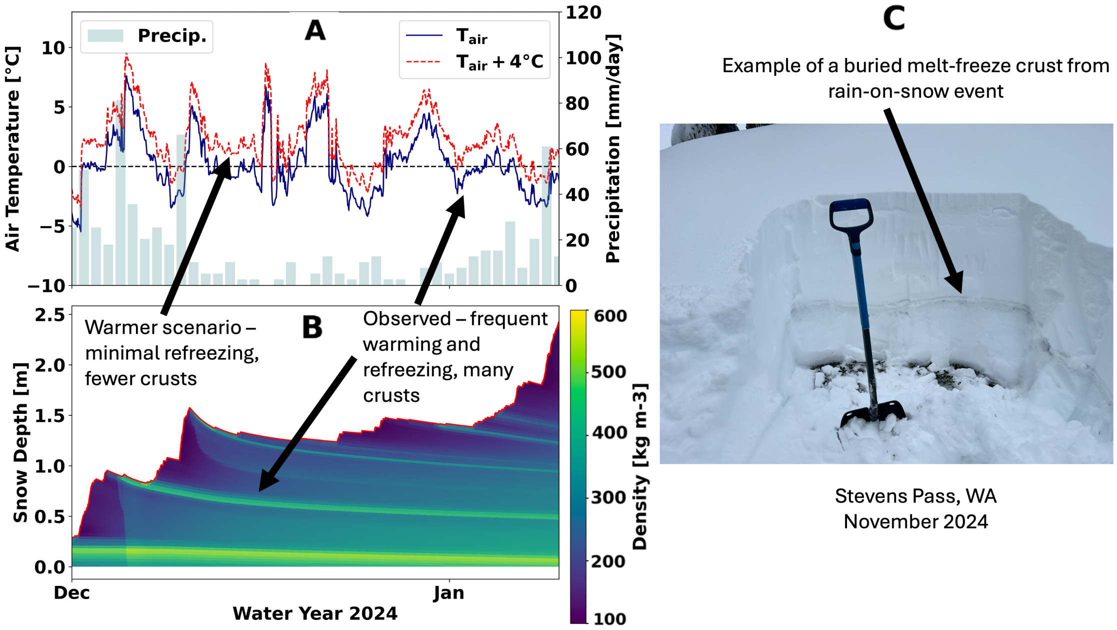
The Kettle Ponds SUMMA simulations used observations at hourly time steps for all seven input meteorological variables needed to initialize the model. The model run and temperature comparison spanned 1 December 2022 to 1 April 2023, using array of temperature sensors deployed during this field campaign every 10cm from a height of snow (HS) 40cm above the ground to an HS of 150cm. Through this work, a mean temperature error was $-1.5°C$.

2.6 Melt-freeze Crust Formation

In this paper, crusts refer specifically to melt-freeze crusts. Defined in Fierz et al. (2009) and Greene et al. (2016), they are formed by "a surface layer of wet snow that refroze after having been wetted by melt or rainfall."

Figure 2a illustrated the winter air temperatures required to create these crusts with the observed air temperature at Olallie Meadows, WA in blue from the winter of water year 2024. This site observed crusts in WSDOT manual snow pit observations on 105 days between 1 December 2023 and 31 March 2024 (86% of days). SUMMA runs with these observed temperatures showed significant crusts (thin layers of higher density snow) in Figure 2b. With $2°C$ of warming, this site would not observe sub-freezing temperatures for longer periods of time and would hypothetically have had fewer crusts.

Manual snow pits, as shown in Figure 2c, are frequently dug by avalanche forecasting operations to collect data on the relative hardness of different layers in the snowpack. Vertical hand hardness profiles were one of WSDOT's primary observations collected with snow pits. These hand hardness measurements estimated how resistant a layer is to penetration by a fist (very soft), four fingers (soft), one finger (medium), a pencil (hard), or a knife (very hard). This subjective yet repeatable metric has been widely used in the avalanche industry to identify unique layers in snow pits (Fierz et al., 2009). For this work, we classified pencil and knife-hard snow in the WSDOT snow pits as crusts.



Warmer scenario – minimal refreezing, fewer crusts

Observed – frequent warming and refreezing, many crusts

Example of a buried melt-freeze crust from rain-on-snow event

Stevens Pass, WA
November 2024

Figure 2. (a) Observed air temperature from the Olallie Meadows SNOTEL site near Snoqualmie Pass, Washington, observed air temperature $+2°C$, and observed precipitation. (b) SUMMA modeled density and depth using the observed temperature for Ollalie Meadows SNOTEL for 1 December 2023 to 10 January 2024. (c) Example of a crust from a snow pit.

2.7 Crust Identification Algorithm

We tested several algorithms to identify crusts in SUMMA output by comparing them against daily snow pit observations from WSDOT at Snoqualmie Pass. With SUMMA output, we identified crusts as layers where the rolling average density over the last 15cm of snow increases vertically by at least 150 $kg\ m^{-3}$ with height when the average temperature of all layers is less than 273.05K. The latter filter eliminated the time steps when the snowpack is isothermal in spring. Because of the constant rate compaction scheme used in SUMMA (Clark et al., 2015b), the refreezing of liquid water from either melt or rain-on-snow events was the only physical process that could create a layer with a higher density than the layer below it vertically. As used here, SUMMA was a point model with no horizontal redistribution of snow. The model did not modify snow density as a function of wind speed, and as a result, it did not simulate wind crusts.

Complex mesoscale temperature inversions are known to exist at many passes in the Washington Cascades in the winter as a result of cold air damming, including at Snoqualmie Pass (Steenburgh et al., 1997; Wayand et al., 2017). These cold air pools have created difficulty in representing precipitation type correctly. To address this issue, we ran SUMMA simulations from the nearby Olallie Meadows SNOTEL for this crust identification comparison, as the model outputs from this site were more representative of the stratigraphy at Snoqualmie Pass. We created a binary dataset with both observations and model output, denoting days with crusts and without crusts between December 1 and March 31.

2.8 Parameterization Choices

We used the manual hand hardness measurements from Snoqualmie Pass, Washington to identify the optimal parameter choices for our SUMMA version. While keeping parameterization choices physically reasonable, we optimized the values to maximize the percentage of observations we could match. These choices are described in Table 3 in the appendix. The rain-snow partitioning temperature was set at 0°C based on the conclusions of Currier et al. (2017) using the SUMMA model.

3 Results

3.1 Model Evaluation

3.1.1 Stratigraphy Evaluation

We used observed air temperature and precipitation from the meteorological station operated by the Washington State Department of Transportation (WSDOT) at Snoqualmie Pass to generate meteorological forcing for the model runs.

We highlight two dates with crusts (December 22 and February 10) and one date without crusts in the top 1m (January 23), represented in both manual and modeled snow profiles. For example, 'F3/K40/P' describes the fist-hard snow for the top 3cm, knife-hard snow from 3cm to 40cm before the surface, and pencil-hard snow from 40cm to 1m. Refer to Fierz et al. (2009) and Greene et al. (2016) for more information on this classification.

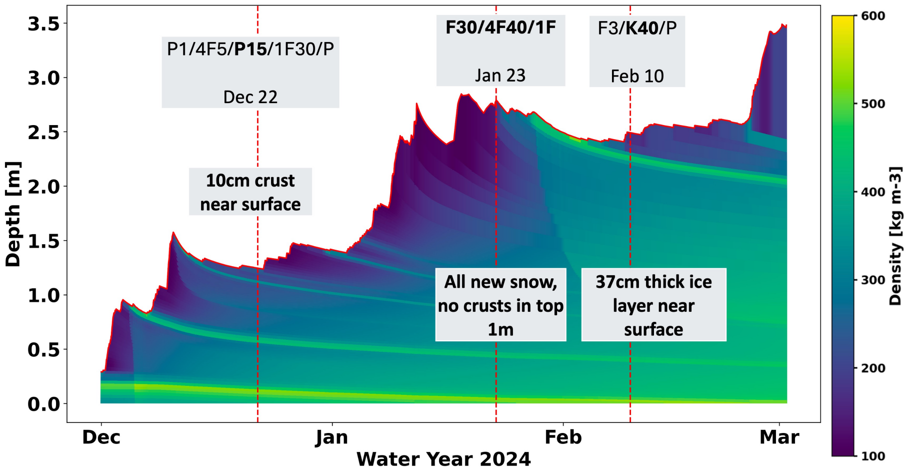


Figure 3. Modeled snow density and depth for Snoqualmie Pass, Washington for December 1, 2023 to March 1, 2024. Manual snow pit hand hardness measurements for the site from the WSDOT are annotated on December 22, January 23, and February 10. The layers are separated from each other by a backslash. Each layer's hand hardness (Fierz et al., 2009) rating is given next to a number indicating the distance from the top of the snowpack in cm.

Table 2. Crust Detection Model vs Manual Observations - Snoqualmie Pass, Washington - Water Year 2024

	No Observed Crust	**Observed Crust**
No Modeled Crust	7 (6%) True Negative	14 (11%) False Negative
Modeled Crust	10 (8%) False Positive	91 (75%) True Positive

Using the crust identification algorithm discussed in section 2.6, our model correctly matched observations 81 percent of days.

3.2 Stratigraphy Changes

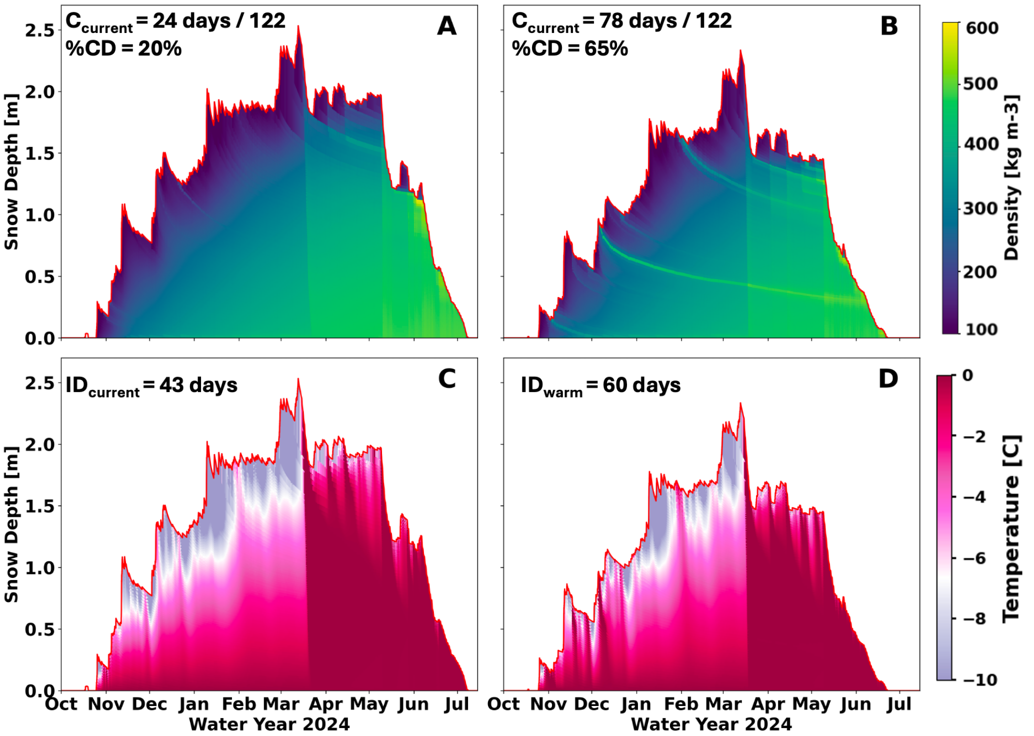


Figure 4. (a) Water year 2024 SUMMA modeled snow depth and density for Harts Pass with observed meteorology. (b) Modeled snow depth and density for Harts Pass with 2°C of warming. (c) Modeled snow depth and temperatures for Harts Pass observed meteorology. (d) Modeled snow depth and temperatures for Harts Pass with 2°C of warming.

The first of two criteria used here to quantify stratigraphy changes was the change in the number of winter days with a crust present (ΔCD) between current climate and warmed model runs. This quantity is defined in Equation 1. C (crust) represents the average number of days with a crust present between December 1 and March 31 for each site.

$$\Delta CD = C_{warm} - C_{current} \tag{1}$$

The second criterion was the percent of the snow-covered season with an isothermal snowpack as defined in Equation 2 where ID (isothermal days) represents days where the average snowpack temperature was equal to 0°C and SCD represents the average snow-covered days for each site. An isothermal snowpack has an average snow temperature equal to 0°C.

$$\%I = \frac{ID}{SCD} \tag{2}$$

In general, in the current climate, warmer sites had fewer unique melt-freeze crusts (i.e., Western Oregon), while cooler locations had more crusts (i.e., Interior Idaho).

We compared the number of ice layers in both the current climate and warming scenarios and observed trends that varied between the sites. As seen in Figure 5, warmer sites closer to the Pacific Ocean had fewer crusts in the +2°C model run. The opposite was true for sites cooler sites and those further inland, where most sites in Idaho, Wyoming, and Montana had more crusts with warming.

The number of winter days with a crust (ΔCD, see Equation 1 above) was negatively correlated with the mean winter air temperature at any given site. Sites with colder mean December-January-February (DJF) air temperatures saw an increase in crusts with warming, while those with warmer mean winter air temperatures saw fewer crusts with warming.

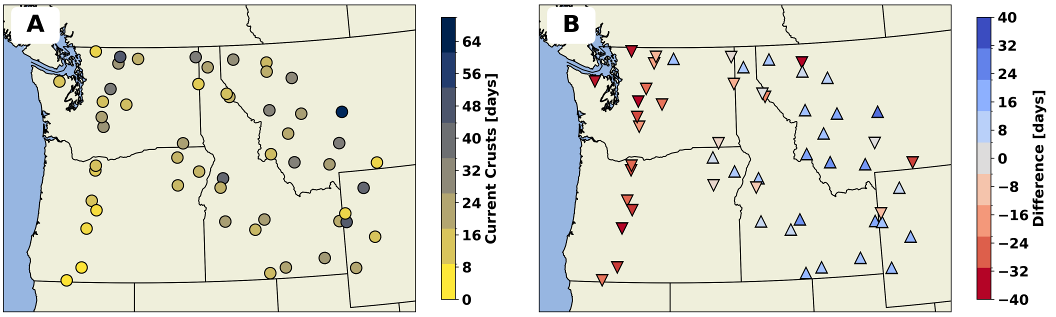


Figure 5. (a) The number of days in the observed climate with a crust present, CD. (b) The change in the number of days with a crust with 2°C of simulated warming, ΔCD.

3.3 Quantifying a Warmer Snowpack

As seen in Figure 6, all sites had a higher percentage of the snow season with an isothermal snowpack for both air temperature warming scenarios when compared to the current climate model runs. We found a strong relationship between mean DJF air temperature in the current climate and percent change in isothermal temperatures for both warming scenarios. The relationship was stronger for the 4°C warming scenario, indicating a higher sensitivity of snowpack temperature to warmer temperatures than the 2°C warming scenario.

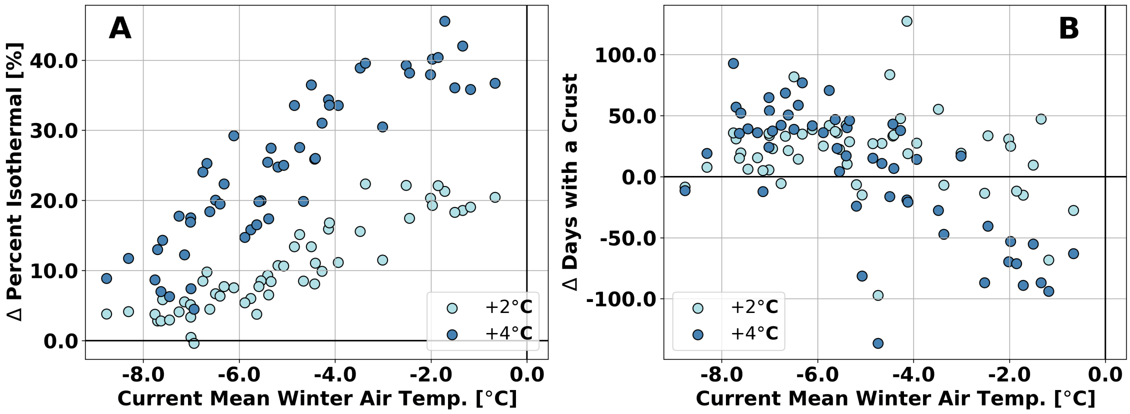


Figure 6. (a) Percent change in days with an isothermal snowpack ($\Delta\%I$) and mean winter air temperature (DJF) for the 2°C and 4°C warming scenarios compared to present. (b) Change in number of days with a crust ΔCD against mean winter air temperature (DJF).

4 Discussion

4.1 Stratigraphy Changes

The relationship between the trend in ice layers with warming and mean winter air temperature can be explained by the process by which these crusts are formed. Ice layer formation requires liquid water from either melt or rain-on-snow (RoS) events to be present in an otherwise predominantly dry snowpack consisting of non-ice snow grains. With warming, more rain will fall, on average, than in the current climate (Ikeda et al., 2021). In warmer regions, the average snowpack in a warmed climate will not possess this dry snow component and thus will not have the distinct ice layers in question. If a site is too warm, rain may either fall directly on the ground without snow or fall on a homogenous snowpack that lacks lower-density dry snow. However, in cooler regions, a future warmed climate will still possess dry snow and thus will have more crusts with more frequent RoS events in a warmed climate (ie Harts Pass, WA, see figure 4).

The results discussed in Section 3.2 demonstrate that crust formation requires rain falling on cold snow. A snowpack with an isothermal temperature profile at 0°C lacks the cold content required to exchange latent heat energy with incoming rain to refreeze. Figure 6 shows that sites with warmer mean winter air temperatures in the current climate are more sensitive to warming's impact on snow temperature gradients than colder sites. These warm sites are predominantly in the maritime snow climates of the Cascade Mountains of Western Oregon and Western Washington. If air temperatures were to warm, these sites would see even fewer snow-covered days, fewer mid-winter freezing temperatures, and therefore, fewer crusts.

4.2 Wildlife Implications

Changing snow stratigraphy and the frequency of ice crusts within seasonal snow also have implications for wildlife. Most large herbivores forage in the winter by digging through the snowpack to reach buried grasses, lichen, and other food sources (Fancy & White, 1985; Peters et al., 2019). Previous research has identified the number of days of the winter with ice present in a snowpack as having a significant negative impact on reindeer (*Rangifer tarandus*) population growth rates (Hansen et al., 2011). More ice crusts may increase winter mortality rates of herbivores for which winter food availability is already a significant bottleneck (Prugh et al., 2024). Conversely, increased winter mortality may benefit scavengers such as Arctic foxes (*Vulpes lagopus*) and boost carnivore populations (Hansen et al., 2013; Borg & Schirokauer, 2022).

Changes in stratigraphy may also impact animal movement ecology. While ice crusts can lock up forage for herbivores, increased snow density may improve the movement abilities of some animals. Carnivores, such as wolves, gain an even more pronounced locomotion advantage in denser snow (Sullender et al., 2023), which may be linked with observations of increased predation rates in snowier winters (Mech et al., 2001).

Given the spatial patterns of our results, the changes to wildlife populations will vary depending on the region. Warmer regions with fewer crusts may enhance forage accessibility and, therefore, benefit herbivore populations. In colder areas, on the other hand, more frequent rain-on-snow events will render forage inaccessible for herbivores. Regardless, the shrinking snow season that we observe across all regions provides a reduced window of opportunity for predators to exploit movement advantages, although greater ice layers and increased density may boost hunting effectiveness within these limited times.

4.3 Avalanche Implications

The model simulations show an increase in ice crusts as a result of more frequent winter rain-on-snow events in colder climates. The transition to a higher fraction of wintertime precipitation falling as rain as a consequence of climate change has already begun in the Western United States, particularly in the Pacific Northwest (Knowles et al., 2006; Ikeda et al., 2021).

Changes to ice layer stratigraphy impact avalanche type, size, frequency, and mitigation practices. With more thick ice layers persisting throughout the winter in the snowpack, meltwater can pool on these interfaces, increasing the likelihood of large (scale D2) to very large (D3+) wet slab avalanches (D. McClung & Schaerer, 2006). The dynamics of wet slab avalanches are more complex than the typical storm slab and wet loose avalanche problems faced by avalanche mitigation professionals. The presence of ice crusts can also prolong avalanche instability during the spring as meltwater reactivates avalanche activity on a previously dormant ice layer. In some instances, wet slab avalanches can be nearly impossible to trigger with explosives and require days, if not weeks, for the snowpack to regain strength. For avalanche practitioners, this can complicate mitigation work and delay the opening of seasonal roads and ski terrain. Additionally, crusts provide a smooth and fast bed surface for avalanches to run on. With this bed surface, avalanches can run further and faster down their path.

Stratigraphy changes, such as the increase in ice crusts as observed within our warmed simulations, create vertical discontinuities in the pore space and conductivity between snow grains in different layers. These discontinuities, in turn, create a non-linear temperature profile in snow that is not yet isothermal. Above and below the interfaces between these crusts and other layers, sharp temperature gradients can exist, higher than the $1°C/10\text{cm}$ threshold needed for kinetic metamorphism, or faceting (D. McClung & Schaerer, 2006). Facets are a critical weak layer that can trigger and propagate avalanches, requiring careful consideration for forecasting and mitigation.

As snowpack stratigraphy evolves, avalanche forecasting operations must adapt to a new paradigm. Reliance on past experience alone may no longer suffice to guide future decision-making. Heuristics and institutional knowledge about snowpack behavior within an operational boundary become inadequate when faced with the types of changes described in this work. If snow stratigraphy shifts in a specific region, corresponding adjustments to avalanche forecasting and mitigation strategies may be necessary.

5 Conclusion

A warming climate has significant impacts on seasonal snow cover. In this study, we modeled the sensitivity of snowpack structure to climate warming across 53 SNOTEL sites in the Pacific Northwest. Using observed precipitation and temperature data from 2000 to 2024, we simulated snowpack statistics for each site under current conditions and with uniform temperature increases of $2°C$ and $4°C$. The results showed that cooler, inland sites experienced more crust formation, while warmer sites in Oregon and Washington exhibited fewer crusts under the modeled warming scenarios. Furthermore, all sites demonstrated an increased percentage of the snow season with an isothermal snowpack at both warming thresholds.

Crusts introduce new challenges for avalanche forecasting operations. Weak, faceted snow grains can form near buried crusts, potentially altering the type and frequency of avalanches in a region. These findings also have implications for wildlife biology, as crusts affect animals' ability to access buried forage and navigate the winter landscape.

6 Appendix

Table 3. SUMMA Model Key Parameterization Values

Model Parameter Name	Model Parameter Description	Value
tempCritRain T_{crit} ($°C$)	Rain/snow partitioning temperature	$0°C$
newSnowDenMin	Min Density of New Snow	50 $kg\ m^{-3}$
densScalGrowth	Compaction Rate	0.1
fixedThermalCond_snow	Thermal Conductivity of Snow	0.35
Fcapil	Capillary Pressure	0.04

Table 4. SUMMA Model Key Model Decisions

Model Decision Name	Model Decision Description	Choice
snowLayers	Snow Layering Scheme	jrdn1991
snowDenNew	New Snow Density Scale	hedAndPom
compaction	Compaction Scheme	consettl
astability	Atmospheric Stability	mahrtexp

7 Supplemental

7.1 Model Forcing Derivations

Due to previously recognized errors with the temperature observations in the SNOTEL network, adjustments to temperature observations were made using the correction discussed in Currier et al. (2017). This error is a result of an erroneous conversion from voltage to degrees Celsius, resulting in a warm bias at colder temperatures. The temperature correction is as follows:

$$T_{corr} = 1.03 \times T_{SNTL} - 0.90 \tag{3}$$

where T_{corr} is corrected temperature in $°C$ and T_{SNTL} is raw observed temperature in $°C$. This correction methodology from Currier et al. (2017) used a least squares regression of temperature observations from secondary instrumentation co-located at SNOTEL sites in Western Washington.

Observations of wind speed, air pressure, specific humidity, incoming shortwave radiation, and incoming longwave radiation are not consistently collected at SNOTEL sites. Therefore, various empirical methods and approximations were employed to fill the meteorological forcing dataset used by SUMMA.

Air pressure was derived using the hypsometric equation with the typical scale height of the atmosphere and standard sea level pressure to determine an average air pressure for the elevation of the site, given by:

$$p_{typical} = p_0 \times e^{-z/H} \tag{4}$$

where $p_{typical}$ is the typical/average air pressure for a given elevation, $p_0 = 101325Pa$ is the standard sea level air pressure, z is the elevation of the site above sea level in meters, and $H = 8000m$ is the scale height of the atmosphere for mid-latitudes. Once typical air pressure is calculated, specific humidity and virtual temperature are calculated for each hourly time step using $p_{typical}$. Air pressure can then be recomputed using the hypsometric equation with virtual temperature for each time step as seen below where $g = 9.8\frac{m}{s^2}$, $R_d = 287\frac{J}{kgK}$, and T_v represents the virtual temperature.

$$p = p_0 e^{\frac{-zg}{R_d T_v}} \tag{5}$$

Specific humidity is filled by assuming a running minimum temperature to approximate the dew point using the method described in Running et al. (1987). For each hourly time step, the lowest temperature in the antecedent or subsequent 12 hours (24-hour window) is assumed to be the dew point. From dew point and air temperatures, relative humidity and thus specific humidity can be calculated using the following empirical relationship for each timestep (Lawrence, 2005):

$$RH = 100 - 5 \times T_a - T_d \tag{6}$$

where T_a and T_d represent air and dewpoint temperatures in $^\circ C$ respectively.

Wind speed was assumed to be $2m/s$ at all time steps, consistent with other studies using uniform wind speed in the absence of quality in situ observations (Cristea et al., 2014).

Incoming shortwave radiation was generated using the MetSim methodology developed by Bennett et al. (2020) using latitude, time of day, and time of year to generate theoretical maximum solar insolation values for each time step. A cloud correction was then applied using air temperature and precipitation to approximate cloud albedo.

Incoming longwave radiation was calculated using the empirical relationship from Dilley and O'brien (1998), defined as

$$LW = 59.38 + 113.7(\frac{T_a}{273.16})^6 + 96.96\sqrt{\frac{465 \cdot e_0}{2.5 \cdot T_a}} \tag{7}$$

where T_a is air temperature in K and e_0 is vapor pressure in kPa. Currier et al. (2017) explored the different empirical longwave radiation schemes described in Flerchinger et al. (2009) against observations at Snoqualmie Pass, Washington. They found the Dilley and O'Brien method to be the most accurate, which we used to generate forcing radiative fluxes for our model simulations.

References

Arnell, N. W. (1999, April). The effect of climate change on hydrological regimes in Europe: A continental perspective. *Global Environmental Change*, *9*(1), 5–23. doi: 10.1016/S0959-3780(98)00015-6

Barnett, T. P., Adam, J. C., & Lettenmaier, D. P. (2005, November). Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, *438*(7066), 303–309. doi: 10.1038/nature04141

Bartelt, P., & Lehning, M. (2002, November). A physical SNOWPACK model for the Swiss avalanche warning: Part I: Numerical model. *Cold Regions Science and Technology*, *35*(3), 123–145. doi: 10.1016/S0165-232X(02)00074-5

Bennett, A. R., Hamman, J. J., & Nijssen, B. (2020, March). MetSim: A Python package for estimation and disaggregation of meteorological data. *Journal of Open Source Software*, *5*(47), 2042. doi: 10.21105/joss.02042

Boelman, N. T., Liston, G. E., Gurarie, E., Meddens, A. J. H., Mahoney, P. J., Kirchner, P. B., … Vierling, L. A. (2019, January). Integrating snow science and wildlife ecology in Arctic-boreal North America. *Environmental Research Letters*, *14*(1), 010401. doi: 10.1088/1748-9326/aaeec1

Borg, B. L., & Schirokauer, D. W. (2022, March). The Role of Weather and Long-Term Prey Dynamics as Drivers of Wolf Population Dynamics in a Multi-Prey System. *Frontiers in Ecology and Evolution*, *10*. doi: 10.3389/fevo.2022.791161

Brun, E., Martin, E., Simon, V., Gendre, C., & Coleou, C. (1989, January). An Energy and Mass Model of Snow Cover Suitable for Operational Avalanche Forecasting. *Journal of Glaciology*, *35*(121), 333–342. doi: 10.3189/S0022143000009254

Clark, M. P., Nijssen, B., Lundquist, J. D., Kavetski, D., Rupp, D. E., Woods,

R. A., … Rasmussen, R. M. (2015a). A unified approach for process-based hydrologic modeling: 1. Modeling concept. *Water Resources Research*, *51*(4), 2498–2514. doi: 10.1002/2015WR017198

Clark, M. P., Nijssen, B., Lundquist, J. D., Kavetski, D., Rupp, D. E., Woods, R. A., … Marks, D. G. (2015b). A unified approach for process-based hydrologic modeling: 2. Model implementation and case studies. *Water Resources Research*, *51*(4), 2515–2542. doi: 10.1002/2015WR017200

Colbeck, S. C. (1986). *A review of the metamorphism and classification of seasonal snow cover.* https://scholar.google.com/scholar_lookup?title=A%20review%20of%20the%20metamorphism%

Colbeck, S. C., & Jamieson, J. B. (2001, December). The formation of faceted layers above crusts. *Cold Regions Science and Technology*, *33*(2), 247–252. doi: 10.1016/S0165-232X(01)00045-3

Cristea, N. C., Bennett, A., Nijssen, B., & Lundquist, J. D. (2022). When and Where Are Multiple Snow Layers Important for Simulations of Snow Accumulation and Melt? *Water Resources Research*, *58*(10), e2020WR028993. doi: 10.1029/2020WR028993

Cristea, N. C., Lundquist, J. D., Loheide II, S. P., Lowry, C. S., & Moore, C. E. (2014). Modelling how vegetation cover affects climate change impacts on streamflow timing and magnitude in the snowmelt-dominated upper Tuolumne Basin, Sierra Nevada. *Hydrological Processes*, *28*(12), 3896–3918. doi: 10.1002/hyp.9909

Currier, W. R., Thorson, T., & Lundquist, J. D. (2017, October). Independent Evaluation of Frozen Precipitation from WRF and PRISM in the Olympic Mountains.
doi: 10.1175/JHM-D-17-0026.1

Dalton, M., Mote, P. W., & Snover, A. (2013). *Northwest Climate Assessment Report* (Tech. Rep.).

Decharme, B., Brun, E., Boone, A., Delire, C., Le Moigne, P., & Morin, S. (2016, April). Impacts of snow and organic soils parameterization on northern Eurasian soil temperature profiles simulated by the ISBA land surface model. *The Cryosphere*, *10*(2), 853–877. doi: 10.5194/tc-10-853-2016

Dilley, A. C., & O'brien, D. M. (1998). Estimating downward clear sky long-wave irradiance at the surface from screen temperature and precipitable water. *Quarterly Journal of the Royal Meteorological Society*, *124*(549), 1391–1401. doi: 10.1002/qj.49712454903

Fancy, S. G., & White, R. G. (1985). Energy Expenditures by Caribou while Cratering in Snow. *The Journal of Wildlife Management*, *49*(4), 987–993. doi: 10.2307/3801384

Fierz, C., Armstrong, R., & Durand, Y. (2009). *The International classification for seasonal snow on the ground.*
https://unesdoc.unesco.org/in/documentViewer.xhtml?v=2.1.196&id=p::usmarcdef_0000186462&file=/in/re
b1cf-4ace-b000-f50bf236e3c3%3F_%3D186462eng.pdf&locale=en&multi=true&ark=/ark:/48223/pf000018646

Fleming, S. W., Zukiewicz, L., Strobel, M. L., Hofman, H., & Goodbody, A. G. (2023). SNOtel, the Soil Climate Analysis Network, and water supply forecasting at the Natural Resources Conservation Service: Past, present, and future. *JAWRA Journal of the American Water Resources Association*, *59*(4), 585–599. doi: 10.1111/1752-1688.13104

Flerchinger, G. N., Xaio, W., Marks, D., Sauer, T. J., & Yu, Q. (2009). Comparison of algorithms for incoming atmospheric long-wave radiation. *Water Resources Research*, *45*(3). doi: 10.1029/2008WR007394

Greene, E., Birkeland, K., Elder, K., Staples, M., & Staples. (2016). Snow, Weather, and Avalanches: Observational Guidelines for Avalanche Programs in the United States.

Hansen, B. B., Aanes, R., Herfindal, I., Kohler, J., & Sæther, B.-E. (2011). Climate, icing, and wild arctic reindeer: Past relationships and future prospects. *Ecology*, *92*(10), 1917–1923. doi: 10.1890/11-0095.1

Hansen, B. B., Grøtan, V., Aanes, R., Sæther, B.-E., Stien, A., Fuglei, E., … Pedersen, Å. Ø. (2013, January). Climate Events Synchronize the Dynamics of a Resident Vertebrate Community in the High Arctic. *Science*, *339*(6117), 313–315. doi: 10.1126/science.1226766

Ikeda, K., Rasmussen, R., Liu, C., Newman, A., Chen, F., Barlage, M., … Musselman, K. (2021, October). Snowfall and snowpack in the Western U.S. as captured by convection permitting climate simulations: Current climate and pseudo global warming future climate. *Climate Dynamics*, *57*(7), 2191–2215. doi: 10.1007/s00382-021-05805-w

Jordan, R. E. (1991, October). A One-dimensional temperature model for a snow cover : Technical documentation for SNTHERM.89.

Knowles, N., Dettinger, M. D., & Cayan, D. R. (2006, September). Trends in Snowfall versus Rainfall in the Western United States.
doi: 10.1175/JCLI3850.1

Lehning, M., Bartelt, P., Brown, B., & Fierz, C. (2002, November). A physical SNOWPACK model for the Swiss avalanche warning: Part III: Meteorological forcing, thin layer formation and evaluation. *Cold Regions Science and Technology*, *35*(3), 169–184. doi: 10.1016/S0165-232X(02)00072-1

Lehning, M., Bartelt, P., Brown, B., Fierz, C., & Satyawali, P. (2002, November). A physical SNOWPACK model for the Swiss avalanche warning: Part II. Snow microstructure. *Cold Regions Science and Technology*, *35*(3), 147–167. doi: 10.1016/S0165-232X(02)00073-3

Lundquist, J. D., Vano, J., Gutmann, E., Hogan, D., Schwat, E., Haugeneder, M., … Carver, L. (2024, June). Sublimation of Snow.
doi: 10.1175/BAMS-D-23-0191.1

Mass, C. (2021). *The Weather of the Pacific Northwest.* University of Washington Press.

McCabe, G. J., & Clark, M. P. (2005, August). Trends and Variability in Snowmelt Runoff in the Western United States.
doi: 10.1175/JHM428.1

McClung, D., & Schaerer, P. A. (2006). *The Avalanche Handbook.* The Mountaineers Books.

McClung, D. M. (1995, March). Use of Expert Knowledge in Avalanche Forecasting . *Defence Science Journal*, *45*(2), 117.

Mech, L. D., Smith, D. W., Murphy, K. M., & MacNulty, D. R. (2001). Winter Severity and Wolf Predation on a Formerly Wolf-Free Elk Herd. *The Journal of Wildlife Management*, *65*(4), 998–1003. doi: 10.2307/3803048

Mote, P. W., Hamlet, A. F., Clark, M. P., & Lettenmaier, D. P. (2005, January). DECLINING MOUNTAIN SNOWPACK IN WESTERN NORTH AMERICA*.
doi: 10.1175/BAMS-86-1-39

Mote, P. W., Li, S., Lettenmaier, D. P., Xiao, M., & Engel, R. (2018, March). Dramatic declines in snowpack in the western US. *npj Climate and Atmospheric Science*, *1*(1), 1–6. doi: 10.1038/s41612-018-0012-1

Musselman, K. N., Clark, M. P., Liu, C., Ikeda, K., & Rasmussen, R. (2017, March). Slower snowmelt in a warmer world. *Nature Climate Change*, *7*(3), 214–219. doi: 10.1038/nclimate3225

Peters, W., Hebblewhite, M., Mysterud, A., Eacker, D., Hewison, A. J. M., Linnell, J. D. C., … Cagnacci, F. (2019). Large herbivore migration plasticity along environmental gradients in Europe: Life-history traits modulate forage effects. *Oikos*, *128*(3), 416–429. doi: 10.1111/oik.05588

Prugh, L. R., Lundquist, J. D., Sullender, B. K., Cunningham, C. X., Dechow, J., Borg, B. L., … Durand, M. T. (2024, November). Landscape heterogeneity buffers the impact of an extreme weather event on wildlife. *Communications Biology*, *7*(1), 1–11. doi: 10.1038/s42003-024-07195-1

Reinking, A. K., Højlund Pedersen, S., Elder, K., Boelman, N. T., Glass, T. W., Oates, B. A., … Liston, G. E. (2022). Collaborative wildlife–snow science: Integrating wildlife and snow expertise to improve research and management. *Ecosphere*, *13*(6), e4094. doi: 10.1002/ecs2.4094

Running, S. W., Nemani, R. R., & Hungerford, R. D. (1987, June). Extrapolation of synoptic meteorological data in mountainous terrain and its use for simulating forest evapotranspiration and photosynthesis. *Canadian Journal of Forest Research*, *17*(6), 472–483. doi: 10.1139/x87-081

Schaefer, G., & Paetzold, R. (2000). *SNOTEL (SNOwpack TELemetry) and SCAN (soil climate analysis network). Automated weather stations for applications in agriculture and water resources management: Current use and future perspectives.* USDA-NRCS.

Scott, D., & Kaiser, D. (2004, January). Variability and trends in united states snowfall over the last half century.

Steenburgh, W. J., Mass, C. F., & Ferguson, S. A. (1997, June). The Influence of Terrain-Induced Circulations on Wintertime Temperature and Snow Level in the Washington Cascades.

Stethem, C., & Perla, R. (1980, January). Snow-Slab Studies at Whistler Mountain, British Columbia, Canada. *Journal of Glaciology*, *26*(94), 85–91. doi: 10.3189/S0022143000010613

Stewart, I. T., Cayan, D. R., & Dettinger, M. D. (2004, January). Changes in Snowmelt Runoff Timing in Western North America under a ‘Business as Usual’ Climate Change Scenario. *Climatic Change*, *62*(1), 217–232. doi: 10.1023/B:CLIM.0000013702.22656.e8

Sullender, B. K., Cunningham, C. X., Lundquist, J. D., & Prugh, L. R. (2023). Defining the danger zone: Critical snow properties for predator–prey interactions.
doi: 10.1111/oik.09925

Wallace, J. M., & Hobbs, P. V. (2006). *Atmospheric Science: An Introductory Survey.* Elsevier.

Wayand, N. E., Clark, M. P., & Lundquist, J. D. (2017). Diagnosing snow accumulation errors in a rain-snow transitional environment with snow board observations. *Hydrological Processes*, *31*(2), 349–363. doi: 10.1002/hyp.11002