IS ARCTIC SNOW DIFFERENT FROM ALPINE SNOW? DELVING INTO THE COMPLEXITIES OF SNOW COVER PROPERTIES AND SNOW INSTABILITY

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ABSTRACT: Assessing snow instability is fundamental in avalanche forecasting. In the past, snow instability was seen as a balance between weak layer shear strength and the overlying load (slab and perhaps a skier). Nowadays, we recognize that this was an oversimplification. Snow instability is best understood in terms of the complex interplay between snow stratigraphy and external loading, influencing the fundamental processes of failure initiation and crack propagation. In short, an avalanche is triggered when a locally initiated failure propagates through a buried weak layer across the slope. While the basic concepts of avalanche release are relatively well understood, there is still no unified physics-based model that can be used for practical applications. Hence, machine learning models were developed to assess snow instability. Most of our knowledge on snow stability as well as the models we use for stability assessments come from alpine snow covers, i.e. mid-latitude mountainous regions with seasonal snow covers, such as in the European Alps or in North America. This raises pertinent questions regarding the transferability of these approaches to Arctic regions. Is snow simply snow, or does Arctic snow possess its own secrets?

Arctic snowpacks present unique challenges due to distinct boundary conditions, notably the absence of solar radiation during winter months and the frozen ground. These widely different boundary conditions affect internal snowpack processes with mostly unknown repercussions on snow stability. We therefore use the snow cover model SNOWPACK to explore the transferability of a recently established machine learning model to assess snow stability from alpine to Arctic contexts. First, we assess the viability of our model approach in Arctic regions by comparing stability predictions with local avalanche observations. Subsequently, we undertake a comparative analysis of modelled stability patterns between the Alps and the Arctic, scrutinizing differences and seeking to unravel the essence of Arctic snow stability.

Keywords: Snow stability, weak layers, avalanche activity, arctic

1. INTRODUCTION

In honor of the first Arctic ISSW, we set out to examine whether Arctic snow differs from Alpine snow, particularly with respect to snow instability. This directly raises two key questions: how are Arctic and Alpine regions defined, and how is snow instability defined? Defining the geographical regions was straightforward: we defined Arctic as all areas above the Arctic Circle (66°33'N) and Alpine as mid-latitude mountainous regions with seasonal snow covers, such as in the European Alps or in North America (green and blue areas in Figure 1). The primary difference between the Arctic and Alpine regions is, of course, their climate. In the Arctic, winters are cold and long with little or no solar radiation. In contrast, Alpine winters are shorter, with generally more snowfall and significantly more sunlight. These climatic differences undoubtedly influence snow instability.

Defining snow instability is more challenging. Although many scientific papers address the concept, the term "snow stability" often carries different meanings. While most people experienced in winter backcountry travel have an intuitive understanding of snow stability, using terms like "a well-bonded stable snowpack," "a reactive and unstable snowpack," or "a rapid return to stability," providing a precise definition is difficult. Broadly speaking, snow stability is described either in terms of mechanical equilibrium within the snowpack or in probabilistic terms. In this work, we therefore defined snow instability as the likelihood that an avalanche will occur given the specific local snowpack structure and a particular trigger, which can be either artificial (e.g. a skier) or natural (e.g. snowfall).

The classical stability index exemplifies the mechanical view, expressing snow stability as the ratio between the shear strength of buried weak layers

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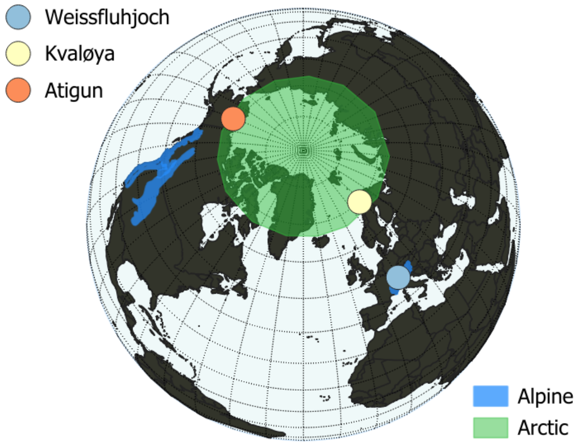

Figure 1: (left) Overview of the Arctic (green) and Alpine (blue) regions, as well as the three sites we focused on (colored dots).

and the shear load of the overlying slab (e.g. Perla et al., 1982; Föhn, 1998; Jamieson and Johnston, 2001). This approach offered an attractive framework, as weak layer shear strength and slab density can be measured to derive a stability index. However, this index did not predict avalanches particularly well (Jamieson and Johnston, 1995). Today, we understand that snow instability must be described using fracture mechanics, which requires assessing the crack size at which the energy available for crack growth exceeds the energy needed to extend the crack (e.g. Rosendahl et al., 2018). Although fracture mechanics has provided a more accurate framework for assessing snow instability (e.g. Schweizer et al., 2016), reliable data on many relevant mechanical properties and their correlation with snow cover characteristics, such as density and grain type, are still lacking. This limits the practical application of a purely mechanical approach to snow instability assessments.

In probabilistic terms, snow instability is often equated with avalanche triggering probability. In this context, many studies investigated snowpack properties indicative of snow instability by comparing manual profiles from skier-triggered slopes with those that were skied but did not avalanche (e.g. Schweizer and Jamieson, 2003; van Herwijnen and Jamieson, 2007). Statistical methods were also developed to assess snow instability, primarily relying on machine learning techniques. Initial attempts were often limited by a lack of input data, challenges in transferability to other regions, or the incorporation of relevant snow stratigraphy (e.g. Purves et al., 2003; Schweizer and Föhn, 1996; Schirmer et al., 2009). More recently, new methods and models were developed using larger datasets including data from snow cover models (e.g. Mayer et al., 2022; Viallon-Galinier et al., 2023), with promising results in operational avalanche forecasting (Techel et al., 2022; van Herwijnen et al., 2023). Compared to mechanical models that require detailed information on the mechanical properties of snow, statistical models generally only require readily available meteorological data to assess snow instability. However, because these models are typically developed and validated with data from Alpine regions, it is uncertain whether they are equally effective in assessing snow instability in Arctic regions.

In this work, we therefore evaluate the applicability of Alpine-developed models to Arctic conditions. To do so, we used data from the snow cover model SNOWPACK (Bartelt and Lehning, 2002) from one Alpine and two Arctic sites to feed two Random Forest (RF) classifiers designed to predict skier-triggering (Mayer et al., 2022) and natural avalanche probability (Mayer et al., 2023), in line with our earlier definition of snow instability. While the primary goal is to investigate how transferable our models are, we also aim to unravel the essence of Arctic snow instability.

2. SITES AND DATA

To assess the transferability of our models to Arctic environments, we applied the models using meteorological data from three distinct sites and compared predictions with corresponding local avalanche observations. We selected three sites: (1) the Weissfluhjoch study site above Davos, Switzerland, (2) Atigun Pass in the Brooks Range of northern Alaska, USA, and (3) the Kvaløya site near Tromsø, Norway.

2.1. Weissfluhjoch

The Weissfluhjoch study plot (46.832°N, 9.806°E), a research site operated by the WSL Institute for Snow and Avalanche Research SLF, is located at an elevation of 2536 m asl, above Davos, Switzerland (Figure 2, bottom). Established in 1936, the site has maintained a continuous record of daily weather and snow measurements, avalanche observations, and bi-weekly manual snow profiles, making it the only site at this altitude worldwide with such an extensive dataset. Its accessibility and proximity to numerous avalanche-prone slopes have made Weissfluhjoch a central point for scientific observations, model development, and long-term research related to snow and avalanches.

Weissfluhjoch lies within an intermountain (transitional) snow climate, where the snowpack exhibits traits of both maritime and continental climates. Some winters are characterized by a deep snow cover predominantly consisting of rounded grains, while others feature a thinner snow cover mostly consisting of facets or depth hoar. The site is equipped with numerous sensors, including a full automatic weather station (AWS) that provides all necessary input data for SNOWPACK, and serves as a key location for testing and calibrating various snow-related instruments and remote sensing products (website).

2.2. Atigun Pass

Atigun Pass is a high mountain pass situated in the Brooks Range of northern Alaska (68.133°N, 149.467°W; Figure 2, top). This pass, at an elevation of approximately 1450 m asl, is a important crossing point on the Dalton Highway (Alaska Route 11), a key transportation route in the region. The surrounding mountain peaks rise to about 2300 m asl, and the road traverses the lower sections of over 40 avalanche paths. A significant avalanche in January 1993, which buried a large section of the road along with several vehicles, led to the establishment of an avalanche forecasting and control program (Bahnson, 1998). This program, managed by the Alaska Department of Transportation (DOT), includes regular avalanche monitoring and control measures to ensure the safety of travelers and the continuity of transportation.

The climate at Atigun Pass is classified as arctic continental, characterized by cold, long winters, permafrost, limited precipitation, and persistent strong winds. The snowpack typically consists of basal depth hoar, hard wind slabs, and faceted crystals. Since 1981, an automatic SNOTEL weather station at the pass (website) records meteorological data, including air temperature, snow depth, wind speed, solar radiation, and ground temperatures, which were used to run SNOWPACK.

2.3. Kvaløya

The Kvaløya site (69.680°N, 18.485°E) is located on the mountainous island of Kvaløya west of the town of Tromsø and about 60 km west of the Lyngen Alps (Figure 2, middle). The area is marked by peaks which rise approximately 1000 m asl, straight out of the fjords, creating a landscape characterized by steep ridges surrounding a deep valley. This region, with its harsh and snowy climate, is a significant location for outdoor activities such as skiing and mountaineering.

Kvaløya is situated in a maritime arctic snow climate, marked by heavy snowfall, strong winds and relatively mild temperatures compared to more continental regions. The snowpack here tends to be dense, with many wind slabs and crusts when freezing levels rise. There are regular observations in the area, providing information such as observed avalanches and manual snow profiles. As there are no AWS at the site, the Norwegian Avalanche Warning Service (website) recently set up a new model chain to perform SNOWPACK simulations forced by numerical weather prediction (NWP) data (Herla et al., 2024b).

3. METHODS

To simulate snow stratigraphy at the three sites, we utilized the physics-based model SNOWPACK (Bartelt and Lehning, 2002; Lehning et al., 2002). Modelled stratigraphy and meteorological data were then fed to two RF classifiers and predictions were evaluated against local avalanche observations.

3.1. SNOWPACK simulations

SNOWPACK, driven with meteorological input data, simulates the one-dimensional vertical snow stratigraphy over time, with snow layer thicknesses on the order of centimeters. The model characterizes distinct snow layers with microstructural properties such as sphericity, dendricity, grain and bond size, and bulk properties including density and liquid water content. Validation campaigns have shown that the modeled snow stratigraphy generally aligns well with observed data in the Alps and Canada, particularly regarding critical weak layers (e.g. Lehning

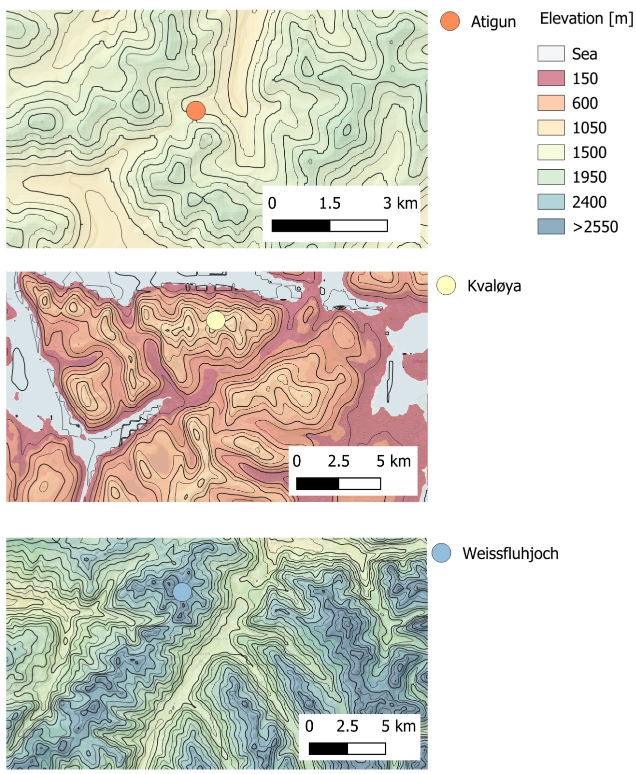

Figure 2: Topographic maps of the sites at the Atigun pass, Alaska, USA (top), Kvaløya, Norway (middle), and Weissfluhjoch, Switzerland (bottom). Colors indicate the elevations (see legend).

et al., 2001; Horton et al., 2014; Richter et al., 2019; Calonne et al., 2020).

Simulations were performed for flat terrain including snow redistribution from windward to leeward slopes (Lehning and Fierz, 2008), except for Kvaløya. For the analysis, we used simulation outputs at noon local time for each day between 15 November and 15 April for each winter season. At WFJ, the simulations were driven with meteorological data from the AWS and forced with measured snow depth. We used data from five winter seasons, from 2012-2013 to 2016-2017. At Atigun pass, the simulations were also driven with meteorological data from the AWS and forced with measured snow depth. Where lower latitude simulations can estimate incoming longwave radiation from shortwave radiation via an estimated cloudiness (Bavay and Egger, 2014), this is not possible above the polar circle due to the long absence of substantial incoming shortwave radiation. We therefore used ILWR data from ERA5 global reanalysis (website) to run the SNOWPACK simulations. The same approach was adopted for the dewpoint temperature, allowing to obtain more precise data on relative humidity (RH), which is not measured at the site. We used data from five winter seasons, from 2018-2019 to 2023-2024 (with a lack of data in the 2021-2022 winter season). At Kvaløya, the simulations were driven with input data from a numerical weather prediction model. Specifcially, we used the reanalysis product of the AROME-MetCoOp model (2.5 km resolution; Müller et al., 2017) to simulate the winter season 2023-2024 for an individual grid cell centered within the island and at an elevation of 660 m asl. For more details, see Herla et al. (2024b).

3.2. Random forest classifiers

Mayer et al. (2022) recently trained a RF classifier to assess snow instability from SNOWPACK output. This was done by manually comparing snow profiles observed in the Swiss Alps with their simulated counterparts. Observed stability test results and an estimate of the local avalanche danger level were then used to construct a binary target variable (stable vs. unstable). The snow instability classifier finally aggregates six snow stratigraphy features to determine the probability of instability for each layer in the snowpack (P_{unstable}). Although the subset of training data only consisted of about 150 profiles labeled as either unstable or stable, the model classified profiles from an independent validation data set with an accuracy of 88%. Model predictions were also in line with observed avalanche activity in the region of Davos for five winter seasons.

To assess dry-snow avalanche probability, we used a model that evaluates P_{unstable} in combination with the simulated new snow amounts (Model "combi" in Mayer et al., 2023). In this model, the daily maximum of P_{unstable} and the three-day sum of new snow are combined into a probability of natural avalanche activity $P_{\text{avalanche}}$ based on statistical models that were fit to observed avalanche activity data (Mayer et al., 2023). This dry-snow avalanche model was trained and validated using avalanche observations across the Swiss Alps.

3.3. Model validation

To validate model predictions, we compared the probabilities P_{unstable} and $P_{\text{avalanche}}$ with observed avalanche data. This required a robust definition of an "avalanche day" that accounts for uncertainties in observed avalanches due to visibility conditions. Both RF models were trained using a stringent definition of the target variable to minimize noise from erroneous observations. For instance, in the dry-snow avalanche model, a binary target variable was used: an avalanche day ($AvD = 1$) was assigned only if avalanche activity across multiple spatial scales (250 km², 1000 km², 5000 km²) exceeded specific thresholds. A non-avalanche day ($AvD = 0$) was defined when no avalanches were reported anywhere in the Swiss Alps on that day (Mayer et al., 2023). As the spatial avalanche observations at the Arctic sites were insufficient, we adapted this approach by imposing temporal constraints on the number of observed avalanches (N_a) per day. Specifically, a day d_i was classified as:

$$AvD(d_i) = \begin{cases} 1 & \text{if } N_a(d_i) > 0 \text{ and} \\ & \sum_{j=i-2}^{j=i+2} N_a(d_j) > \text{med}(N_a) \\ 0 & \text{if } \sum_{j=i-2}^{j=i+2} N_a(d_j) = 0 \\ \text{NaN} & \text{otherwise} \end{cases} \quad (1)$$

where $\text{med}(N_a)$ is the median number of observed avalanches on days with avalanches, and NaN represents "not a number." Essentially, an avalanche day was defined as a day where at least one avalanche was observed, and the total number of avalanches from two days before to two days after that day exceeded $\text{med}(N_a)$.

This AvD definition ensured that isolated avalanche observations were excluded and that only sustained periods of activity or inactivity were considered. This allowed us to statistically compare differences between predictor variables (Table 1) on avalanche days and non-avalanche days using the non-parametric Mann-Whitney U-test. Lastly, we calculated a continuous avalanche day probability P_{AvD} for a predictor variable x, defined as:

$$P_{\text{AvD}}(X) = \frac{N(x \geq X \text{ and } AvD = 1)}{N(x \geq X)} \quad (2)$$

Variable	Description
HN24	24 hour height of new snow
$HN24_{drift}$	HN24 + 24 hour wind drifted snow
HN72	72 hour height of new snow
$HN72_{drift}$	HN72 + 72 hour wind drifted snow
$P_{unstable}$	Maximum daily probability of instability
$P_{avalanche}$	Probability of natural avalanche day

Table 1: Predictor variables and their descriptions

where N represents the number of days. For example, $P_{AvD}(HN = 10\text{ cm})$ indicates how often days with HN ≥ 10 cm were avalanche days.

4. RESULTS AND DISCUSSION

Our primary objective was to determine how snow instability in the Arctic differs from that in the Alps. We therefore first compared key meteorological variables, qualitatively compared snowpack stratigraphy, and finally, evaluated the accuracy of our model predictions against local avalanche observations.

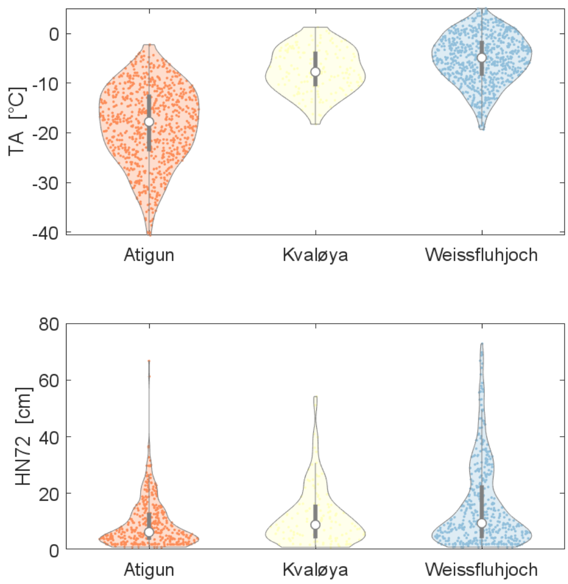

Figure 3: Violin plot showing the distribution of air temperature (TA; top) and 72 hour height of new snow (HN72; bottom) at the three sites. The width of each violin represents the density of the data, with wider sections indicating a higher frequency of observations. The white dot within each violin marks the median, and the black bar represents the interquartile range. The outer lines extend to the range of the data, excluding outliers.

4.1. Comparison of weather data

Substantial differences were observed in the meteorological variables across the three snow climates. Air temperatures at Atigun were notably lower than at the other two sites (Figure 3, top), similar to the trends observed in snow surface temperatures (not shown). Snowfall at Atigun was also lower compared to the other locations, both for HN24 (not shown) and HN72 (Figure 3, bottom). Consequently, the seasonal maximum snow depth at Atigun was generally around 100 cm, while at Kvaløya and Weissfluhjoch, it typically exceeded 200 cm (not shown). In terms of wind speed, Weissfluhjoch experienced the lowest levels, while Kvaløya had the highest (not shown). These variations in meteorological conditions contributed to the distinct snowpack structures observed at each site, which we explore in the following section.

4.2. Snow stratigraphy

We illustrate differences in snowpack stratigraphy across three example winters (Figure 4). At Atigun, the thin snowpack predominantly consisted of depth hoar (dark blue; Figure 4, top). This aligns with expectations and local observation Bahnson (1998), given the combination of cold temperatures and low precipitation, imposing large temperature gradients in the snowpack. However, local experts noted that new snow layers in our simulations tend to persist longer than observed (green in Figure 4). Typi-

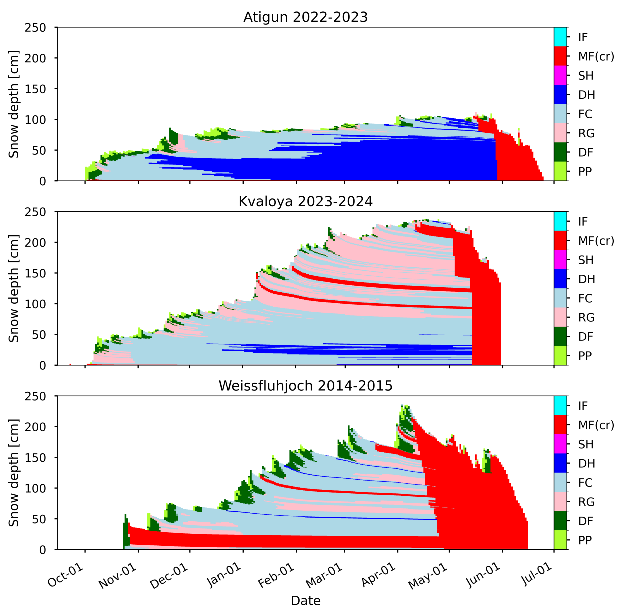

Figure 4: SNOWPACK simulations from Atigun (top), Kvaløya (middle) and Weissfluhjoch (bottom). Colors indicate the different grain types (see legends) following the classification of Fierz et al. (2009)

cally, this fresh snow is quickly redistributed by wind, forming hard wind slabs (small rounded grains) that gradually transform into indurated (hard) depth hoar, a process SNOWPACK does not reproduce. The very rapid snowmelt in June is often associated with slush-flow avalanches (Bahnson, 1998).

At the Kvaløya site, frequent light snowfalls led to a gradual increase in snow depth (Figure 4, middle). Up until early January, the snowpack mainly consisted of faceted crystals and some basal depth hoar. Afterwards, the upper layers evolved into rounded grains with occasional crusts formed by rain events. Feedback from local experts, along with an ad-hoc comparison with manual snow profiles from the region, suggests that our simulations produced a snowpack that was generally too soft and too deep. This discrepancy is partly due to the use of NWP data as input to SNOWPACK, which have been shown to overestimate precipitation (Bellaire et al., 2016; Horton and Haegeli, 2022). Additionally, SNOWPACK does not simulate the hard wind slabs that are commonly observed in this region. As in Atigun, the melt-out phase was rapid, though it occurred slightly earlier.

The snowpack at Weissfluhjoch exhibited two distinct phases (Figure 4, bottom). The first was characterized by a dry snowpack that persisted until early April, resembling the conditions at Kvaløya. In the second half of the season, the snowpack was mostly isothermal. Nevertheless, snow depth remained substantial until the melt-out phase began in May. Based on our personal observations and several studies (e.g. Lehning et al., 2001; Richter et al., 2019; Calonne et al., 2020), simulated snow stratigraphy at this site closely aligns with manual snow profiles taken at the same location.

4.3. Avalanche activity and model predictions

The overall observed avalanche activity was substantially different between the three sites. There were significantly more avalanche days at Weissfluhjoch than at Atigun. On average, over the five winters we analyzed, the ratio of avalanche days to non-avalanche days at Weissfluhjoch was about 40%, while it was only 8% at Atigun. At Kvaløya, with only one winter of data, this ratio was 25%.

The output from our classifiers also varied significantly across the three sites (Figure 5). Since the snowpack at Atigun predominantly consisted of layers of depth hoar, the $P_{unstable}$ distribution was narrow and concentrated at values at or above the threshold of 0.78 used to define an unstable snowpack (dashed line in Figure 5, bottom). In contrast, the distributions at Kvaløya and Weissfluhjoch were much broader. For $P_{avalanche}$, this pattern was reversed, with distributions for Kvaløya and Weissfluhjoch concentrated at lower values than those at

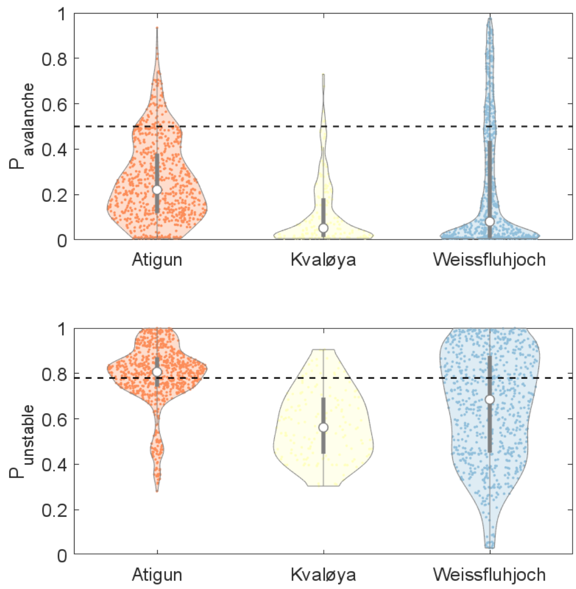

Figure 5: (left) Violin plot showing the distribution of $P_{avalanche}$ (top) and $P_{unstable}$ (bottom) at the three sites. The black dashed lines show the threshold values used to separate stable from unstable layer, or avalanche from non-avalanche days. See Figure 3 for the detailed description of the violin plots.

Atigun (Figure 5, top). Nevertheless, most $P_{avalanche}$ values were below the threshold of 0.5 for all sites.

Comparing model output to observed avalanches highlighted important differences between the three snow climates. At Weissfluhjoch, where the models were developed and validated, the predictor variables were all significantly different on avalanche days compared to non-avalanche days (Table 2 and Figure 6). At Kvaløya, however, only HN72 and $P_{avalanche}$ effectively discriminated between avalanche and non-avalanche days. Nevertheless, $P_{avalanche}$ values on avalanche days were still mostly below 0.5. This could in part be a re-

Variable	Atigun	Kvaløya	Weissfluhjoch
HN24	✓	×	✓
$HN24_{drift}$	✓		✓
HN72	×	✓	✓
$HN72_{drift}$	✓		✓
$P_{unstable}$	×	×	✓
$P_{avalanche}$	×	✓	✓

Table 2: U-test results for the comparison of avalanche days and non-avalanches days. Predictor variables that were significantly different are marked with ✓, while those that were not are marked with ×. Predictor variables that failed in the model output are left blank.

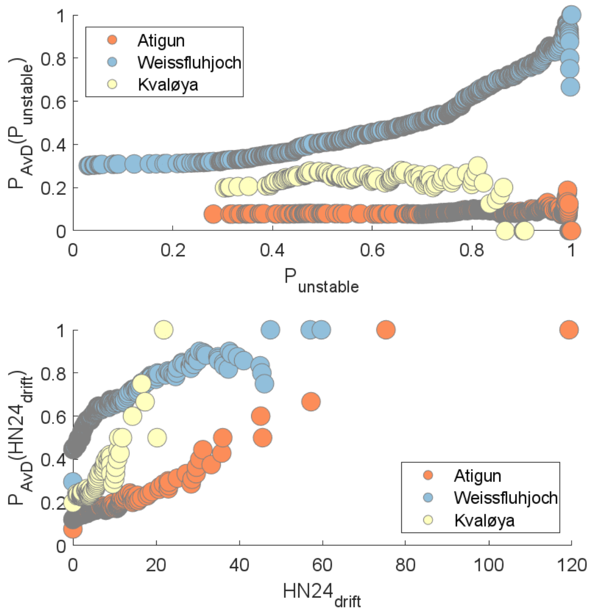

Figure 6: Probability of an avalanche day P_{AvD} (eq. 2) for the predictor variable $P_{unstable}$ (top) and $HN24_{drift}$ (bottom) at the three sites (colors).

sult of using NWP input data, as SNOWPACK can then encounter challenges in accurately reproducing critical weak layers (Herla et al., 2024a). Finally, at Atigun, the classifiers did not predict avalanche days well, with only HN24, $HN24_{drift}$, and $HN72_{drift}$ emerging as predictive variables. This suggests that the classifiers we developed cannot be readily applied in a continental Arctic setting ($P_{unstable}$ in Figure 6, top). This is partly because SNOWPACK does not capture all relevant snow cover processes, such as the formation of hard depth hoar, while for example wind compaction is not sufficiently strong in the simulations, as field observations suggest. Additionally, our classifiers may not be applicable in these regions, where the predictive nature of HN24, $HN24_{drift}$ (Figure 6, bottom), and $HN72_{drift}$ suggests that avalanches are primarily driven by wind-drifted snow and are influenced by processes occurring on the order of 24 hours, whereas in Alpine regions time scales are typically on the order of several days to a week (van Herwijnen et al., 2018).

5. CONCLUSIONS

Our goal was to assess whether Arctic snow differs from Alpine snow, particularly with respect to snow instability, using the SNOWPACK model alongside classification models at three distinct sites. While snow forms through similar processes in both climates, our results showed that the conditions under which it accumulates and persists are markedly different. Specifically, at Atigun Pass, where the snowpack is thin, predominantly consists of depth hoar and is heavily influenced by strong winds, our models showed limited transferability. This suggests that while Alpine-derived models can be applied to Arctic conditions, their accuracy is hindered by the unique characteristics of Arctic snowpacks. However, it remains unclear whether the rather poor transferability is due to uncertainties in input data, the absence of relevant snow processes modeled in SNOWPACK, or the need to recalibrate or retrain our classifiers. This insight is critical not only for Arctic regions but also broadly highlights challenges in transferring models to new sites with different snow climates.

Looking ahead, there are several avenues for improvement. Incorporating advanced processes within SNOWPACK, such as the POLAR mode for enhanced wind compaction simulation (Groot Zwaaftink et al., 2013; Wever et al., 2023), could better capture the specificities of Arctic snowpacks. Additionally, improving the quality and precision of meteorological input data, particularly at remote Arctic sites, is crucial. High-quality meteorological measurements, more comprehensive snow profiles to validate SNOWPACK outputs, and robust avalanche observations are essential for refining existing models and developing new probabilistic models tailored to diverse regions. Expanding the training datasets to include multiple regions and snowpack types could also improve the robustness of machine learning models, ensuring better performance across various climates and topographies.

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