# USING HIGH-RESOLUTION VERTICAL TEMPERATURE GRADIENTS TO FORECAST PERSISTENT WEAK LAYER FORMATION

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ABSTRACT: Vertical temperature gradients near the snow surface play a critical role in snowpack metamorphism and atmospheric energy exchange. The near-surface boundary layer strongly influences avalanche formation (Birkeland, 1998; Schweizer and Lütschg, 2001; Slaughter et al., 2009); tracking these micro-climatic shifts provides vital precursor information for avalanche forecasting. However, capturing boundary layer thermal gradients at high temporal and spatial resolutions remains challenging in operational settings.

A high-resolution field study conducted at Snoqualmie Pass, WA, USA (921 m) evaluated near-surface energy exchanges above an unbuffered, shallow snowpack. The study site is characterized by exceptionally light ambient airflow and persistently near-saturated relative humidity, creating a highly favorable micro-climate for surface hoar formation (Breyfogle, 1986). To capture these dynamics, a custom vertical thermocouple array measured air temperature profiles at 10-cm increments up to 1.5 m above the snow-air interface at 10-second intervals from December 2025 through March 2026, generating more than 15 million data points.

High-resolution profiling captured steep boundary layer temperature inversions co-occurring with relative humidity near saturation (averaging 98.5%–99.6%). A focused analysis identified distinct metamorphic drivers across two primary event windows: (1) a January 15–18 cycle where clear-sky nocturnal radiational cooling drove near-surface temperature gradients exceeding 16.0°C/m, facilitating extensive surface hoar growth; and (2) a mid-February window (Feb 10–13) where strong near-surface temperature gradients (>16.8°C/m) cultivated a secondary surface hoar layer before subsequent storm loading on February 13.

Tracking these thermodynamic precursor conditions from growth through surface evolution or storm slab burial demonstrates the operational value of monitoring near-surface boundary layer dynamics. While the January 15–18 surface hoar crystals were destroyed by rain prior to burial, the mid-February surface hoar growth (Feb 10–13) was preserved, forming the structural foundation for a reactive persistent weak layer (PWL) across the forecast zone. Multi-element vertical thermocouple arrays face practical operational deployment constraints across standard automated weather station (AWS) networks—including lower-sensor snow burial and diffuse shortwave daytime noise—results are compared with co-located infrared snow surface temperature sensors to evaluate single-sensor proxies for operational study plots.

KEYWORDS: Avalanche Forecasting, Instrumentation and Remote Sensing, Snowpack Properties, Modelling and Quantitative Forecasting

## 1. INTRODUCTION

Avalanche forecasting relies heavily on identifying structural weaknesses within the seasonal snowpack. While traditional remote weather stations track macro-scale atmospheric variables—such as air temperature, wind speed/direction and precipitation—they frequently miss the Cryosphere boundary layer immediately above the snow surface. This near-surface boundary layer, spanning the first 1.5 meters above the snowpack, is characterized by intense thermodynamic volatility. Meteorological variables in this zone directly govern energy exchange at the snow-atmosphere interface, dictating the growth of crystal structures that later evolve into weak layers.

Traditional avalanche warning frameworks utilize physical models, such as SNOWPACK, which rely on complex vertical grid resolutions and boundary-layer forcing equations to simulate thin weak layer formation from standard 2-meter meteorological inputs (Lehning et al., 2002). Such modeling methodologies approximate the micro-gradients responsible for rapid structural metamorphosis. While stations equipped with infrared

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radiometers can flag surface hoar potential by contrasting ambient air temperature with a dedicated snow surface sensor, these typical forecasting networks lack fine-scale vertical resolution. Specifically, processes such as near-surface faceting, diurnal melt-freeze cycles, and the deposition of surface hoar are dictated not by ambient air temperature, but by the steepness of the localized temperature gradient within the lowest centimeters of the atmosphere (Colbeck, 1989; Fukuzawa and Akitaya, 1993; Birkeland, 1998; Slaughter et al., 2009). The thermal gradient operates in tandem with micro-scale mass transport; optimal surface hoar propagation requires near-saturated relative humidity to supply vapor to the interface, coupled with calm-to-light boundary layer winds that prevent turbulent mixing from destroying the radiation inversion.

Despite its operational relevance, high-resolution vertical profiling of the near-surface boundary layer has historically been constrained by instrumentation limits and the logistical challenges of mountain data collection. To address this gap, this paper analyzes continuous high-resolution temperature profiles captured at 10-cm increments across the 1.5 meters immediately above the snow surface. By examining these vertical slices, we demonstrate how micro-scale temperature gradients track complex boundary phenomena, including nocturnal radiational cooling and the precise thermodynamic precursors for surface hoar formation. Furthermore, to evaluate the practical applicability of these findings for standard automated weather stations, this study compares the high-resolution profiler output against proxy measurements from a co-located, single-sensor SI-111 infrared snow surface thermometer. Ultimately, this work aims to bridge the gap between boundary-layer physics and operational field practice, offering a framework for forecasters to utilize high-resolution boundary data to anticipate weak-layer formation before it is buried.

## 2. METHODS

### *2.1 Study Site*

The primary study plot is located at Snoqualmie Pass at an elevation of 917 meters. Operated as part of the Washington State Department of Transportation (WSDOT) Avalanche Program monitoring network, the site is characterized by a maritime climate with high-density snowfall, frequent rain-on-snow events, and rapid snowpack settlement. Topographically sheltered from prevailing ridge-line flows, the primary plot experiences exceptionally light winds and persistently high relative humidity. This unique combination of a near-saturated atmosphere and minimal wind scouring provides an ideal, highly sensitive environment for tracking delicate boundary-layer transitions and undisturbed kinetic growth.

To monitor environmental conditions, the study plot features a comprehensive automated weather station equipped with a full complement of meteorological instrumentation. The recorded metrics include standard micro-meteorological data—such as ambient air temperature and relative humidity—alongside precipitation, new snow accumulation, total height of snow (HS), barometric pressure, and infrared snow surface temperature. Additionally, the sensor suite continuously measures short-wave and long-wave radiation, as well as sub-surface soil temperatures at multiple depths. A co-located lysimeter further captures liquid water output through the snowpack. To contextualize the sheltered, surface-level observations against broader atmospheric and macro-climatic changes, the plot is also supplemented by multiple higher-elevation automated weather stations.

### *2.2 Instrumentation Architecture*

The vertical profiling instrument consists of a custom-built, 1.5-meter mast equipped with a vertical array of type-T thermocouples spaced at 10 cm intervals. To capture micro-scale forcing parameters immediately above the boundary layer, the top of the mast was outfitted with a Vaisala HMP60 relative humidity and air temperature probe. The datalogger was programmed to sample all channels at a 10-second frequency to capture rapid boundary layer fluctuations and turbulent thermal fluxes.

### *2.3 Field Logistics and Dataset Management*

The continuous dataset spans from December 27, 2025, to March 30, 2026. Because a fixed-height array would yield changing relative heights as the winter pack evolved, the mast was anchored dynamically into the snow surface. Field operators monitored local weather cycles and periodically adjusted the vertical position of the mast following significant settlement or new snow accumulation.

## 3. RESULTS

### *3.1 Overview of Monitoring Period*

Continuous automated weather station and high-resolution vertical temperature profiler datasets from the winter 2025–2026 monitoring period capture distinct surface hoar growth and persistent weak layer formation events. Macro-climatic conditions during this season were marked by a historically low snow accumulation; a snow

drought that resulted in a notably shallow snowpack across the region. This shallow stratigraphy heightened the snowpack's sensitivity to extreme surface energy exchanges, and lengthy periods between storm events prolonged the exposure to atmospheric boundary layer dynamics. To evaluate the thermodynamic and atmospheric conditions driving structural instability under these constraints, this section examines two major chronological windows: a January 15–18 surface hoar growth event, and a February 10–13 surface hoar growth and subsequent burial event.

### *3.2 January 15–18: Surface Hoar Growth Event*

The first period captured an extensive surface hoar formation cycle between January 15 and January 18. Throughout this window, relative humidity (RH) remained near saturation, with a mean RH of 96% over the night (18:00-06:00) of January 16–17, and 98% over January 17–18. Wind speeds remained exceptionally low, averaging 0.08 m/s and 0.5 m/s on the respective nights. High-resolution profiling, infrared surface data, and manual field observations revealed:

- Night 1 (Jan 15–16) - Radiational Cooling: The profiler captured a developing temperature inversion during the evening of January 15–16. Data over the nocturnal window (18:00–06:00) revealed that the snow surface temperature dropped below 0°C for 90.3% of the night. Furthermore, the near-surface thermal inversion—where the snow surface temperature was measurably colder than the ambient air 10 cm above it—was sustained for nearly 75% of the night (Figure 1).
- Night 2 (Jan 16–17) - Radiational Cooling: The profiler again captured a strong temperature inversion during the evening of January 16–17. Strong nocturnal radiational cooling drove the snow-air interface down to -6.3°C, while the air temperature 100 cm above remained significantly warmer at -4.0°C to -4.8°C. The cooling established a pronounced temperature inversion, with near-surface temperature gradients frequently exceeding 16.0°C/m (Figure 1).
- We observed significant roughness in the profiler signal on the night of the 15$^{th}$ and 16$^{th}$ that was notably absent on the night of the 17$^{th}$. This high-frequency fluctuation presents an important avenue for further research, as it could indicate the presence of micro-scale turbulent mixing, localized sensible heat flux variations interacting with the sensors, or boundary layer instabilities associated with intense radiational cooling (Figure 1).
- Night 3 (Jan 17–18) - Conversely, during the night of January 17–18, neither the vertical thermocouple array nor the infrared snow surface sensor recorded a steep localized temperature gradient. The profiler data shows the near-surface boundary layer remained largely isothermal, lacking the radiational thermal driver seen the previous night, likely due to cloud cover (Figure 1, Figure 2).
- Notably, analysis of the SI-111 sensor data indicates a strong thermal gradient early in the cycle, with the recorded snow surface temperature remaining significantly below the ambient air temperature on the first and second nights. However, during the specific window of rapid crystal growth on the third night, the air and snow surface temperatures in the SI-111 data converged, coinciding with observed cloud cover and fog. The convergence corroborates the simultaneous drop-out of the near-surface inversions in the profiler data. Ultimately, the alignment across both instruments confirms the lack of a strong thermal driver during the period of maximum kinetic growth, indicating that humidity-driven mass transport within the foggy boundary layer may have been the primary mechanism forcing deposition (Figure 2).
- Despite the absence of a thermal inversion, 2 cm surface hoar crystals were manually observed on the morning of the 18$^{th}$. This observation indicates that the rapid kinetic growth was moisture-driven rather than temperature-gradient-driven.
- Throughout the night of the 17$^{th}$-18$^{th}$, relative humidity remained quite high, averaging 95%. Because this indicates supersaturation with respect to ice at sub-freezing temperatures, the light continuous winds (averaging 0.5 m/s) effectively advected a constant supply of water vapor across the snow-air interface. This mass transport allowed water vapor to deposit rapidly and build large, delicate crystals without the need for a steep localized temperature gradient.

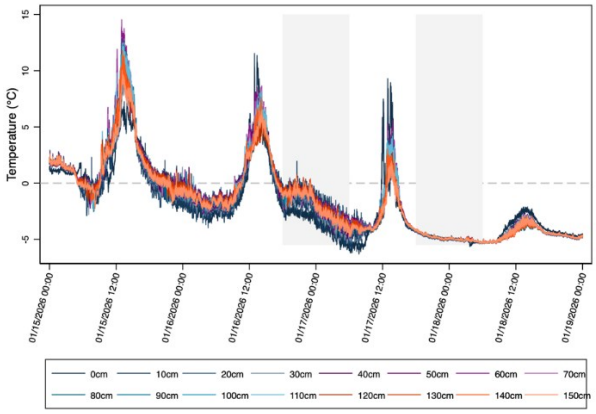



Figure 1: Thermocouple array data, Jan 15-18, 2026.

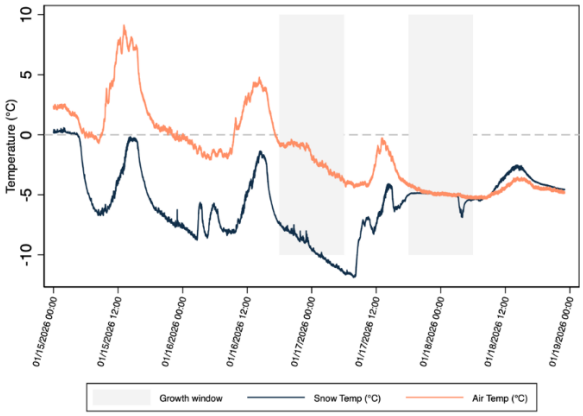



Figure 2: Air temperature and snow surface temperature, Jan 15-18, 2026.

### 3.3 *February 10–13: Surface Hoar Event and Subsequent Burial*

Like the mid-January cycle, this second event was preceded by a multi-day period of pronounced diurnal temperature cycling. However, in this case the sustained daytime warming and rapid nocturnal cooling cultivated a surface hoar layer that, unlike the rain-destroyed January crystals, was buried intact by storm loading on February 13. Analysis of this cycle indicates:

- Vertical profiling captured maximum near-surface atmospheric gradients exceeding 16.8°C/m during nocturnal cooling phases (Figure 3).
- The persistence of these steep inversion gradients over multiple diurnal cycles drove continuous vapor deposition onto the snow surface, producing a surface hoar layer that was subsequently buried and preserved as a reactive persistent weak layer during subsequent storm events.
- Sustained near-saturation conditions (mean RH of 99.6%) ensured an ample supply of available water vapor to drive rapid crystal growth.
- A classic pattern for surface hoar formation—characterized by daytime warming and nighttime cooling with snow surface temperatures dropping below air temperatures—was observed. Notably, while the high-resolution profiler captured extreme, localized micro-gradients throughout every nocturnal cycle (Figure 3), the SI-111 IR sensor data also consistently confirmed the baseline inversion, recording snow surface temperatures that remained strictly below the ambient air temperature for the entire duration of the event (Figure 4).

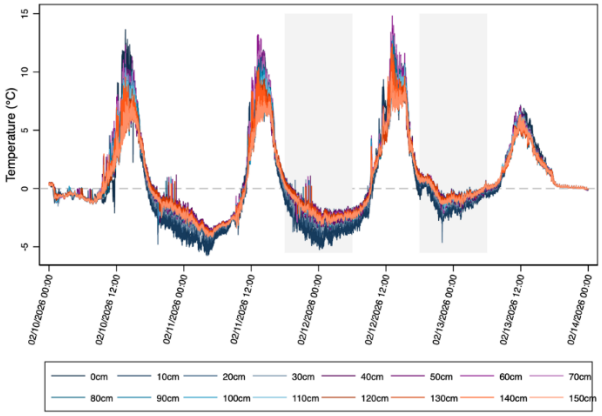



Figure 3: Thermocouple array data, Feb 10-13, 2026.

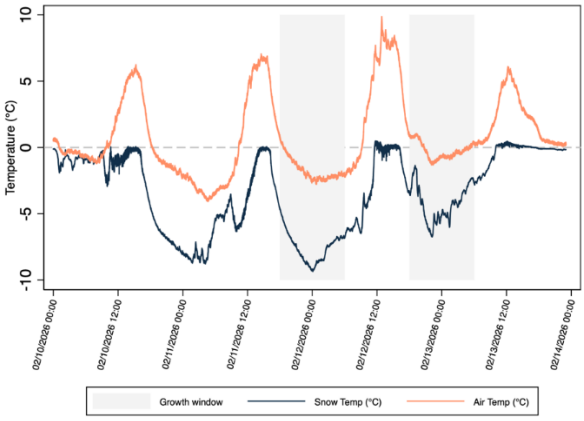



Figure 4: Air temperature and snow surface temperature, Feb 10-13, 2026.

## 4. DISCUSSION

### 4.1 *Validation of the High-Resolution Profiler*

A primary methodological objective of this study was to design, fabricate, and deploy a custom multi-element thermocouple array capable of delivering boundary layer data. The successful

deployment and operation of this system serve as a vital proof-of-concept for localized micro-meteorological monitoring.

- The custom profiling array operated continuously from December 2025 through the end of the season at the Snoqualmie Pass study plot. Despite prolonged exposure to a volatile maritime climate—characterized by exceptionally high relative humidity, dynamic settlement, and frequent rain-on-snow events (with the plot receiving nearly 650 mm of rain between December 19 and April 1)—the physical architecture and sensor housings endured without systemic failure or significant data loss.

- Operating at a 10-second temporal resolution over the four-month deployment window, the array successfully generated an uninterrupted dataset of more than 15 million discrete measurements.

- The profiler consistently and accurately resolved micro-scale thermal gradients (frequently exceeding 16.0°C/m) and diurnal temperature cycling occurring within the lowest meter of the boundary layer.

### *4.2 High Resolution Profiling vs IR snow surface sensor and standard ATRH sensor.*

A practical consideration for operational avalanche programs is whether a standard two-sensor setup—an infrared snow surface temperature sensor (SI-111) coupled with a fixed-height ambient air sensor—provides an adequate proxy for near-surface boundary layer dynamics. Comparing this data to the high-resolution profiler reveals notable differences in how these instruments record the thermal environment, while also highlighting the practical utility of the simplified setup.

- Analysis indicates that the SI-111 snow surface temperature remains consistently below the air temperature during cooling events. While the profiler captures distinct, highly localized micro-inversions that the standard setup misses, the continuous thermal delta recorded by the SI-111 may be sufficient for daily operational forecasting. The simpler instrument reliably flags the fundamental prerequisite—a snow surface significantly colder than the ambient air—without the mechanical complexity of a vertical array. Additionally, the SI-111 recorded a lower average snow surface temperature of -2.82°C, compared to the profiler's 0cm average of -0.91°C, ensuring these cooling trends are prominently visible to forecasters.

- An interesting observation across all datasets is that the most substantial surface hoar crystals developed on the day exhibiting the lowest temperature differences and gradients. While such an observation initially appears to challenge traditional radiational cooling models, the data highlights the significance of an alternative mass-transport mechanism: humidity-driven hoar.

- Rather than viewing these events in isolation, it is highly probable that the preceding days—which featured highly favorable thermal conditions and steep gradients—played a critical role in priming the snow surface. Such cumulative cooling may have established a conducive environment where subsequent high-humidity advection could drive significant kinetic growth, even as the localized thermal gradient weakened.

### *4.3 Are the instruments a good predictor of surface hoar formation?*

Neither the high-resolution profiler nor the standard SI-111 proxy operates as a perfect, standalone predictor of surface hoar formation. However, analyzing both datasets together reveals the nuanced relationship between localized temperature gradients and humidity-driven mass transport.

- The field deployment was designed around the baseline theory that surface hoar forms under low wind and high relative humidity when specific thermal conditions are met at night: the sky remains clear, promoting radiational cooling; the surface temperature is 0°C or below; and the surface temperature is measurably lower than the ambient air temperature, thus meeting or exceeding the saturation point.

- Surface hoar was confirmed to have grown during two specific events (January 15–18 and February 10–13). However, observational data from both

the profiler and the SI-111 reveals that the expected temperature inversion—where the surface is significantly colder than the air—converged or weakened during the exact window of maximum kinetic growth on the night of January 17 into the 18th. The observed convergence suggests that moisture advection can overpower the need for a strong localized thermal driver, relying instead on humidity to force deposition.

- Analysis demonstrates that the SI-111 consistently recorded the snow surface temperature remaining well below the air temperature throughout the broader event windows. While the single-sensor proxy smooths out the highly localized micro-inversions captured by the profiler, the simpler instrument reliably flags the fundamental prerequisite of surface cooling. Ultimately, both instruments effectively measure the necessary preliminary cooling phases, but relying solely on thermal data leaves a predictive gap. The data from these events demonstrates that once the snow surface is adequately primed, high relative humidity and advection can become the dominant drivers of kinetic growth, sustaining rapid deposition even as the initial temperature inversions converge.

### *4.4 Moisture-Driven Surface Hoar*

Standard avalanche education and operational forecasting models emphasize clear skies and calm winds as the primary prerequisites for surface hoar formation. This heuristic relies on nocturnal radiational cooling to drive snow surface temperatures well below ambient air temperatures, establishing the steep vapor pressure gradients necessary to draw moisture out of the atmosphere. However, the January 17–18 event demonstrates an exception to this model, highlighting a different mechanism for kinetic growth.

- Manual observations confirmed 2 cm of surface hoar growth occurred during the night of January 17–18 under obscured, foggy conditions.
- During the specific window of rapid crystal growth on the night of January 17 into the 18th, neither the high-resolution profiler nor the SI-111 sensor recorded a strong near-surface temperature inversion. Instead of the severe gradient typically associated with radiational cooling, both datasets indicated that the snow surface and ambient air temperatures converged. The observed convergence highlights a departure from the classic thermal model, reinforcing the conclusion that high relative humidity and moisture advection were the primary mechanisms forcing vapor deposition during that specific period.
- During this period, kinetic growth was moisture-driven rather than temperature driven. Light winds (averaging 0.5 m/s) advected supersaturated air (averaging 95% RH) across the snow-air interface, forcing rapid surface hoar deposition. This mass transport mechanism is supported by laboratory research (Ozeki et al., 2018), which demonstrated that utilizing a wind tunnel to force high water vapor advection is a highly efficient driver for large surface hoar growth, entirely independent of clear sky radiational cooling, more like a riming event.

### *4.5 System Limitations and Data Quality Considerations*

While vertical thermocouple arrays yield valuable boundary layer resolution, several operational and environmental limitations must be accounted for in data interpretation and automated processing workflows:

- Snow Burial of Lower Sensors: As the snowpack accumulates, the lower thermocouples are sequentially buried, transitioning them from measuring atmospheric boundary layer temperatures to measuring conductive heat transfer within the snowpack. To maintain a consistent measurement geometry relative to the active snow-air interface and avoid relying on post-processing algorithms, the profiler array was manually repositioned vertically following major accumulation events.
- Solar Radiation and Daytime Noise: Although the array was shielded from direct solar radiation, diffuse daytime shortwave radiation and ambient solar loading introduced thermal noise across exposed thermocouples during midday hours. To prevent false-positive inversion detections caused by radiative heating of sensor housings, data analysis for this study was confined to nighttime hours (18:00 to 06:00). Restricting the analytical framework to the nocturnal window ensured that the measured radiational cooling signals remained

reliable, and free from shortwave interference.

- Drought Season Representativeness: Because the 2025–2026 monitoring season occurred during an extreme low-snow year, observed inversion magnitudes and surface energy exchanges may reflect upper-bound sensitivities. Future multi-season deployments across average and above-average snowpacks will be necessary to establish baseline operational thresholds across varying snowpack depths.

## 5. CONCLUSION

Our study successfully designed, deployed, and validated a custom high-resolution vertical thermocouple array capable of capturing complex near-surface thermal regimes. Over a continuous four-month deployment in a volatile environment, the instrument proved to be robust, reliably generating a continuous dataset of more than 15 million measurements. The array effectively resolved fine-scale boundary-layer temperature gradients. While our analysis indicates that above-surface thermal profiling alone is not a standalone predictor for widespread weak crystal nucleation, the profiler's precise ability to capture severe, localized inversions—which are consistently missed by standard fixed-height ATRH sensors—demonstrates its value as an observational tool. Moving forward, the high-resolution array provides a proven, highly capable platform for further boundary-layer research. Future applications combining precise above-surface atmospheric tracking with high-resolution sub-surface temperature measurements will offer the comprehensive thermodynamic framework necessary to accurately trace complex metamorphic transitions.

Key insights from this deployment include:

- Micro-Gradient Resolution & Array Maintenance: The vertical thermocouple array reliably documented near-surface temperature differentials, proving physically resilient over a continuous four-month deployment. Operationally, the physical repositioning of the array following storm cycles proved essential for isolating atmospheric boundary-layer heat transfer from internal snowpack conduction, ensuring accurate interface gradient calculations.
- Predictive Constraints & Cumulative Priming: While the array successfully captured localized thermal gradients, the data demonstrates that thermal profiling alone cannot deterministically predict weak layer formation. The observation of massive kinetic crystal growth during periods of thermal convergence on the night of January 17-18th confirms that mass transport can overpower radiational cooling. Observations from the dataset indicate that consistent prediction requires accounting for mass-transport mechanisms, as cumulative surface priming and high relative humidity ultimately drove the most substantial crystal growth even when localized thermal gradients weakened.
- Operational Sufficiency of Standard Proxies: Ultimately, comparing both datasets clarifies the practical value of standard automated weather stations. An infrared snow surface radiometer (SI-111) coupled with a fixed-height ambient air temperature sensor—consistently demonstrates that the snow surface temperature remains well below the ambient air temperature during early cooling phases. While standard proxy setups smooth out the highly concentrated micro-inversions captured by the profiler, the simpler configuration reliably flags the fundamental prerequisite of surface cooling. The persistent thermal delta serves as a necessary baseline condition for operational forecasting, even though standard thermal proxies do not fully capture the advection-driven mechanisms responsible for the most rapid periods of micro-structural evolution.

Future Work: Targeted deployments of the multi-sensor vertical profiler should be utilized during brief inter-storm clearing windows—short periods between storm cycles where rapid radiative cooling and intense surface temperature gradients can drive rapid, localized faceting prior to subsequent storm burial. Furthermore, deliberately allowing snowfall to bury the lower sensors could provide significant utility for evaluating near-surface faceting. Tracking the sub-surface thermal gradients captured by these newly buried nodes will clarify the profiler's value as a high-resolution diagnostic tool for analyzing the formation of weak grain types.

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