EARLY DETECTION OF SNOWPACK WETTING USING SENTINEL-1 DATA: LINKING SEASONAL SNOWPACK DYNAMICS AND GLACIER MELT UNDER CLOUD-COVERED CONDITIONS ON THE BRØGGER PENINSULA, SVALBARD (2022–2025)

Jean-Michel Friedt[1]*, Eric Bernard[2]

[1] *Université Marie et Louis Pasteur, CNRS, Institut FEMTO-ST (UMR 6174), Besançon, France*
[2] *Université Marie et Louis Pasteur, CNRS, Théma (UMR 6049), Besançon, France*

ABSTRACT: Seasonal snow cover plays a fundamental role in controlling the timing, spatial distribution and intensity of glacier melt in the High Arctic. In Svalbard, winter warming, rain-on-snow events and earlier spring melt modify snowpack structure and promote transitions between dry snow, wet snow, refreezing and runoff. Observing these transitions at the glacier scale remains challenging because optical satellite observations are frequently affected by cloud cover and limited illumination. Synthetic Aperture Radar (SAR), and particularly Sentinel-1 C-band observations, provides an alternative because radar acquisitions are independent of cloud cover and solar illumination and are sensitive to changes in the dielectric properties of snow associated with liquid water. This study investigates the spatial and temporal dynamics of snowpack wetting across small glaciers of the Brøgger Peninsula, western Spitsbergen, using Sentinel-1 time series acquired between 2022 and 2025. Rather than attempting a direct inversion of snow water content, we use a relative, hypsometrically normalized approach designed to characterize the timing and vertical extent of snowpack transitions. Backscatter profiles are extracted along longitudinal glacier flowlines and transformed into a normalized elevation coordinate. Deviations from a winter reference state are used to identify statistically significant reductions in backscatter associated with the transition from cold, relatively dry snow towards wetter conditions. The resulting time–altitude information is summarized using a normalized hypsometric index, allowing comparison among glaciers with different elevation ranges. The Sentinel-1 observations are interpreted jointly with meteorological observations from Ny-Ålesund, including air temperature, precipitation and snow-cover information. Ground-based automated photography from the Austre Lovén glacier basin provides an independent local reference for interpreting major snowline and surface-state transitions. Across the 19 analysed glaciers, the radar time series reveal a coherent regional seasonal signal but also substantial differences in the timing, duration and vertical development of wet-snow conditions. The mean annual duration of detected wet-snow conditions is approximately 78 days over the 2022–2025 period. The onset of widespread wetting generally occurs after sustained positive-temperature forcing, while warm and wet periods associated with rain-on-snow conditions produce pronounced increases in the vertical extent of the radar-derived wet-snow signal. The results demonstrate the potential of Sentinel-1 time series for regionalizing observations of snowpack state across Arctic glaciers while emphasizing that radar backscatter remains an indirect proxy of snow wetness. The proposed framework therefore provides a spatially distributed diagnostic tool rather than a direct measurement of liquid-water content or glacier melt.

KEYWORDS: Sentinel-1; SAR; wet snow; snowpack; glacier melt; Svalbard

1. INTRODUCTION

Seasonal snow cover is a key component of the Arctic cryosphere. On glaciers, the snowpack regulates surface energy exchange, controls the timing of ice exposure and influences the partitioning and timing of meltwater production. In Svalbard, increasing winter temperatures and rain-on-snow events promote melt–freeze cycles, the development of ice layers and changes in snow density and liquid-water content.

Monitoring these processes at the glacier scale remains difficult. Optical satellite observations provide valuable information on snow cover, but cloud cover is frequent in maritime Arctic environments and illumination conditions are seasonally restrictive. SAR observations overcome these limitations and are sensitive to changes in the electromagnetic properties of snow. In particular, the presence of liquid water strongly modifies the effective dielectric properties of snow and commonly produces a reduction in C-band radar backscatter.

However, radar backscatter is not uniquely controlled by liquid water: snow stratigraphy, grain size, ice layers, surface roughness, incidence angle and the underlying surface also contribute to the signal. We therefore do not attempt to retrieve absolute snow-water content. Instead, we investigate whether relative and temporally repeatable changes in Sentinel-1 backscatter can identify and compare seasonal snowpack wetting across small Arctic glaciers.

We address three questions: (1) How does the spatial distribution of radar-derived wet-snow conditions evolve along the elevation gradient? (2) To what extent are these dynamics related to regional meteorological forcing? and (3) Can the resulting temporal signatures identify contrasting glacier response regimes?

2. STUDY AREA AND DATASETS

The Brøgger Peninsula is located on the western coast of Spitsbergen, Svalbard. The area contains numerous small cirque and valley glaciers over an elevation range from sea level to approximately 1000 m a.s.l. Their contrasting topographic settings and proximity to Ny-Ålesund provide an appropriate natural laboratory for investigating spatial variability in Arctic snow and glacier processes. Nineteen glaciers were retained for the regional analysis.

Sentinel-1A C-band SAR observations acquired in Interferometric Wide Swath mode with VV and VH polarization between 2022 and 2025 were processed using ESA SNAP. Processing included precise orbit information, radiometric calibration, debursting and Range–Doppler terrain correction. The resulting data were resampled to 20 m pixel spacing, and a three-image moving median filter was applied to reduce temporal speckle.

2	Pedersenbreen	7	Mørebreen W	12	Vestre Lovénbreen	17	No name
3	Austre Lovénbreen	8	Kjaerfjellbreen	13	Mørebreen E	18	Botnbreen
4	Midtre Lovénbreen	9	Steenbreen	14	Trongskarbreen	19	No name
5	Austre Brøggerbreen	10	Edithbreen	15	Trongskarbreen	20	No name
6	Vestre Brøggerbreen	11	No name	16	No name		

Fig. 1 – Study area description & localization of the studied glaciers.

Hourly observations from the Ny-Ålesund meteorological station were used to characterize air temperature, precipitation and snow-cover conditions. Daily means and positive degree-days (PDD) were derived, and rain-on-snow periods were identified from the combination of precipitation, temperatures around or above 0 °C and snow cover.

Automated cameras in the Austre Lovén glacier basin provide high-frequency ground observations. These images were used as an independent local reference for major snowline and surface-state transitions. Because the camera network is restricted to Austre Lovén, this comparison constitutes local qualitative validation rather than a direct validation for all 19 glaciers.

3. HYPSOMETRIC DETECTION OF SNOWPACK WETTING

For each glacier, a longitudinal transect was defined approximately along the principal flow direction, extending from the upper glacier towards the terminus. The terrain-corrected radar backscatter was represented as a function of elevation and acquisition time, $\gamma^{0}(z,t)$. A winter reference profile was derived from January–March observations, and a backscatter anomaly was calculated as:

$$\Delta\gamma^{0}(z,t) = \gamma^{0}(z,t) - \gamma^{0}\mathrm{winter}(z) \quad (1)$$

A statistically defined threshold based on winter variability was used to identify significant negative anomalies:

$$T(z) = \mu\mathrm{winter}(z) - 2.5\sigma\mathrm{winter}(z) \quad (2)$$

Pixels with anomalies below this threshold were classified as showing a radar response consistent with wetting. The detected spatial distribution was then expressed in a normalized hypsometric coordinate. The normalized index $H^{*}(t)$ describes the relative vertical position and extent of the detected wet-snow distribution:

$$H^{*}(t) = [H50(t) - H\mathrm{min}] / [H\mathrm{max} - H\mathrm{min}] \quad (3)$$

Here H50 is the elevation associated with the median position of the detected wet-snow distribution along the transect. The normalization allows glaciers with different absolute elevation ranges to be compared. $H^{*}(t)$ is therefore interpreted as a descriptor of relative vertical development of wet-snow conditions, not as a direct measurement of liquid-water content or melt elevation.

4. RESULTS

The Sentinel-1 time series reveal a coherent seasonal evolution across the analysed glaciers. During the cold season, radar backscatter remains relatively close to the glacier-specific winter reference state. During spring and summer, negative backscatter anomalies develop and progressively extend along the elevation gradient.

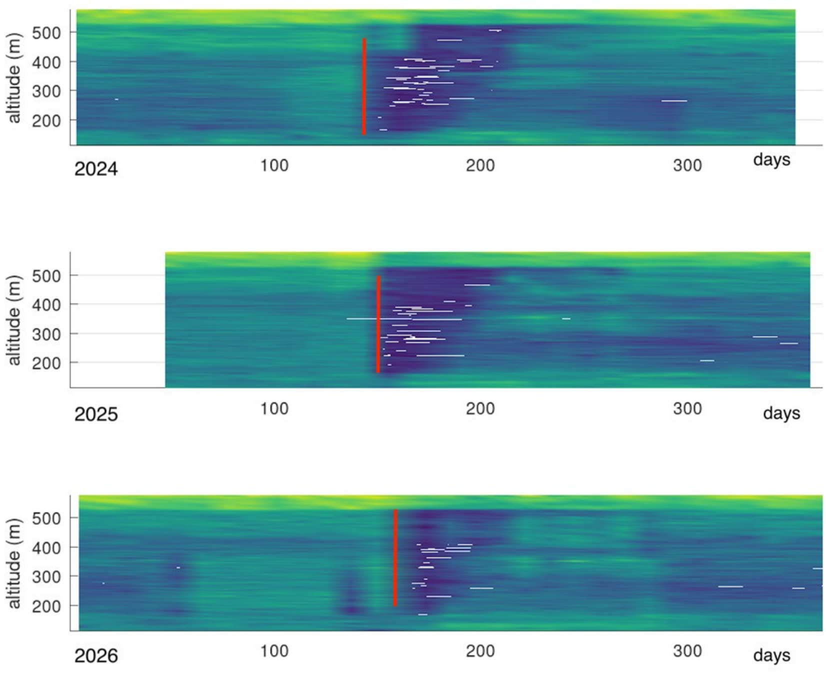

Fig. 2 – Example of results for the 3 last years. A blue pattern indicates when and how the snowpack melts during the year. The red lines highlights the start of the snowpack's humidification.

Across the 19 glaciers, the mean duration of detected wet-snow conditions is approximately 78 ± 6 days over 2022–2025. The onset generally follows sustained positive-temperature forcing at Ny-Ålesund. Warm and wet periods, including conditions interpreted as rain-on-snow, are associated with pronounced increases in the vertical extent of the radar-derived wet-snow signal.

The response is not purely monotonic. Renewed snowfall or short cold periods can temporarily interrupt the seasonal transition. At the end of the season, radar recovery may lag the disappearance of continuous snow cover at the low-elevation meteorological station, consistent with the elevation difference between the station and the glacier transects.

Comparison with ground-based photography at Austre Lovén supports the interpretation of major radar transitions. Pronounced radar changes occur within approximately one Sentinel-1 acquisition interval of visually observed snowline and surface-state changes. This agreement provides independent evidence for the interpretation while not excluding contributions from changes in snow structure.

Substantial inter-glacier variability is nevertheless apparent. A similarity analysis of the normalized temporal signatures identifies a dominant rapidly responding group, a smaller group with more progressive and persistent wet-snow signatures, and one individual outlier. The dominant group contains 12 glaciers (approximately 63%) and reaches H*max values close to unity, whereas six glaciers (approximately 32%) display lower maximum values (0.91 ± 0.04) and more delayed recovery. The individual outlier has a detected wet-snow duration of approximately 35 days. Because it is represented by one glacier, it should be treated as an anomalous case rather than a statistically established third regional regime.

5. DISCUSSION

The results indicate that regional atmospheric forcing provides a strong control on the timing of seasonal snowpack wetting, but that glacier-specific characteristics modulate the response. The stronger relationship with temperature for the rapidly responding group (reported $R^2 = 0.78$) than for the more buffered group ($R^2 = 0.61$) suggests that additional controls become increasingly important where snowpack persistence is greater.

Potential controls include snow depth, internal ice layers, elevation-dependent thermal buffering, topographic setting and liquid-water retention and refreezing. These mechanisms cannot be uniquely separated using Sentinel-1 backscatter alone. The observed hysteresis in radar recovery may indicate persistent liquid water or refreezing within the snowpack, but it cannot by itself distinguish deep refreezing from superficial refreezing or other structural changes in the scattering volume.

The main value of the approach is therefore regional rather than quantitative: Sentinel-1 provides spatially distributed observations that complement fixed meteorological stations and local field observations. The normalized hypsometric representation makes it possible to compare glaciers with different elevation ranges and to identify coherent and anomalous responses.

These observations also emphasize that glacier melt is not controlled solely by instantaneous air temperature. The antecedent state of the seasonal snowpack influences the timing of snow-to-ice transition and potentially the onset and spatial development of glacier ablation. The proposed indicator provides a potential observational metric for this intermediate state between atmospheric forcing and surface melt.

6. CONCLUSIONS

This study presents a Sentinel-1-based framework for characterizing seasonal snowpack wetting across small glaciers of the Brøgger Peninsula, Svalbard. Combining C-band SAR time series, hypsometric normalization, meteorological observations and local ground-based photography provides a regional perspective on the spatial and temporal variability of snowpack transitions.

Three conclusions are particularly robust. First, Sentinel-1 observations reveal a coherent seasonal transition towards a wet-snow radar state across the 19 glaciers, with a mean detected duration of approximately 78 days over 2022–2025. Second, the timing of this transition is associated with regional atmospheric forcing, particularly sustained positive temperatures and warm, wet periods. Third, substantial inter-glacier variability persists, indicating that local snowpack and topographic conditions modulate the response.

Sentinel-1 is therefore well suited to regional monitoring of snowpack state under the cloudy conditions typical of maritime Arctic environments, but radar backscatter remains an indirect proxy. Future work should combine these observations with higher-frequency ground measurements and independent information on snow stratigraphy, liquid-water retention and refreezing to determine which components of the radar-derived signal correspond to superficial wetting, deep percolation, refreezing and the transition towards glacier ice ablation.

ACKNOWLEDGEMENTS

The authors acknowledge the Norwegian Meteorological Institute for meteorological observations from Ny-Ålesund and the French Polar Institute teams supporting field observations in the Austre Lovén glacier basin.

MAIN REFERENCES

Bavay, M., Grünwald, T., Lehning, M., 2013. Response of snow cover and runoff to climate change in high alpine catchments of eastern Switzerland. Advances in Water Resources 55, 4–16. https://doi.org/10.1016/j.advwatres.2012.12.009.

Buchelt, S., Skov, K., Rasmussen, K., Ullmann, T., 2022. Sentinel-1 time series for mapping snow cover depletion and timing of snowmelt in Arctic periglacial environments: Case study from Zackenberg and Kobbefjord, Greenland. The Cryosphere 16, 625–646. https://doi.org/10.5194/tc-16-625-2022.

Eckerstorfer, M., Christiansen, H., 2011. The “High Arctic maritime snow climate” in central Svalbard. Arctic, Antarctic, and Alpine Research 43, 11–21.

Friedt, J.M., Bernard, E., Griselin, M., 2023. Ground-based oblique-view photogrammetry and Sentinel-1 spaceborne radar reflectivity snow melt processes assessment on an Arctic glacier. Remote Sensing 15, 1858. https://doi.org/10.3390/rs15071858.

Førland, E., Benestad, R., Hanssen-Bauer, I., Haugen, J., Skaugen, T., 2011. Temperature and precipitation development at Svalbard 1900–2100. Advances in Meteorology, 893790. https://doi.org/10.1155/2011/893790.

Isaksen, K., et al., 2022. Exceptional warming over Svalbard and consequences for snow and ice. Environmental Research Letters 17, 014011.

Karbou, F., et al., 2021. Monitoring wet snow over an alpine region using Sentinel-1 observations. Remote Sensing 13, 381. https://doi.org/10.3390/rs13030381.

Laska, M., Luks, B., Budzik, T., 2016. Influence of snowpack internal structure on snow metamorphism and melting intensity on Hansbreen, Svalbard. Polish Polar Research 37, 193–218. https://doi.org/10.1515/popore-2016-0012.

Lievens, H., et al., 2022. Sentinel-1 snow depth retrieval at sub-kilometer resolution over the European Alps. The Cryosphere 16, 159–177. https://doi.org/10.5194/tc-16-159-2022.

Marin, C., Bertoldi, G., Notarnicola, C., 2020. Use of Sentinel-1 radar observations to evaluate snowmelt dynamics in alpine regions. The Cryosphere 14, 935–956. https://doi.org/10.5194/tc-14-935-2020.

Peeters, B., et al., 2019. Spatiotemporal patterns of rain-on-snow events in Svalbard. Environmental Research Letters 14, 015002.

Sobota, I., Weckwerth, P., Grajewski, T., 2020. Rain-on-snow events and their relations to snowpack and ice layer changes on small glaciers in Svalbard, the High Arctic. Journal of Hydrology 590, 125279. https://doi.org/10.1016/j.jhydrol.2020.125279.

van Pelt, W.J.J., et al., 2019. A long-term dataset of climatic mass balance, snow conditions, and runoff in Svalbard (1957–2018). The Cryosphere 13, 2259–2280. https://doi.org/10.5194/tc-13-2259-2019.

Winsvold, S., Kääb, A., Nuth, C., Andreassen, L., van Pelt, W., Schellenberger, T., 2018. Using SAR satellite data time series for regional glacier mapping. The Cryosphere 12, 867–890. https://doi.org/10.5194/tc-12-867-2018.