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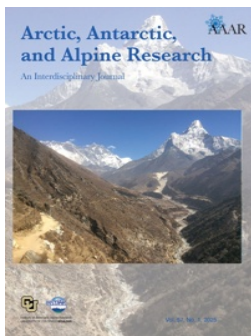
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Did a global heatwave have a lasting impact on the snowpack and the annual glacier mass balance? The example of a small glacial basin observatory in the High Arctic (Brøgger Peninsula, Spitsbergen)

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ABSTRACT

Simultaneous heat waves occurred on March 2022 in both Antarctic and Arctic regions. The impact of this extreme weather event is investigated from the perspective of a north-facing polar glacier in the Brøgger Peninsula of Svalbard, Arctic Norway. Original measurement systems including time-lapse cameras and an automated ablation stake acquiring the ice melt with hourly resolution were deployed for a couple of years during and after the event. The results of these measurements demonstrate that the liquid precipitation accompanying the warm event led to a significant impact on the snowpack structure. It resulted in an earlier snowpack disappearance. Consequently, the glacier surface was exposed earlier, resulting in ice melting earlier than it did in 2023, which is considered as a reference state. This in turn contributed to a more negative mass balance. This study highlights the strong negative influence of winter liquid precipitation on glacier mass balance.

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Heat wave; rain on snow; Svalbard; automated cameras; automated ablation stake



Introduction

Over the past thirty years, it has been widely accepted that temperatures in the Arctic have increased (van Pelt et al. 2019). The region has undergone significant changes (Box et al. 2019) associated with the phenomenon that has been defined as Arctic amplification (Overland 2021).

This climatic trend implies substantial alterations in precipitation patterns, both in their temporal distribution and in their frequency and intensity (Perkins 2015; Russo, Sillmann, and Fischer 2015; Yu and Zhong 2021). Indeed, heat waves are often associated with precipitation events, especially in winter (You et al. 2021). In continuation of this trend, more Arctic rainfall events are thus observed (Serreze et al. 2021; Vickers, Malnes, and Eckerstorfer 2022) and the total Arctic precipitation has increased by 30 to 60 percent over the last twenty years (Bintanja and Andry 2017). In parts of the Arctic, due to the significant increase of atmospheric rivers and winter cyclones (Ebell et al. 2023; Frank et al. 2023; Bednorz et al. 2024), extreme warm spells and heavy rain-on-snow (RoS) events in winter are already more

frequent and more intense (van Pelt et al. 2019; Champagne et al. 2024), although they have been reported for a long time (Dege 2004). The frequency and magnitude of RoS events has recently increased (Sobota, Weckwerth, and Grajewski 2020), with a rise in the number and size of ice layers (Bintanja and Andry 2017) in the snowpack. This trend is expected to increase further during the twenty-first century (Rennert et al. 2009).

Remarkably, though, an exceptional heat wave was detected in Antarctica and led to record-breaking temperatures in March 2022 (Blanchard-Wrigglesworth et al. 2023; Wille et al. 2024). During the first quarter of 2022, the Arctic experienced the same exceptional heat wave as well (Sabbatini 2022), accompanied by significant precipitation. According to Blanchard-Wrigglesworth et al. (2023), this extreme heat wave had the most significant impacts in Antarctica, with temperature around +39°C over the normal. Although the temperature difference was smaller in Svalbard than in Antarctica, and despite the extreme events being more and more common in the Arctic, the 2022 Arctic

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heat wave was so significant that it was able to trigger, in a single event, the reactivation of the braided river system (Athulya et al. 2023; Salzano et al. 2023). This event allowed for the observation of both the processes of snowpack melting as well as the glacier response. Indeed, heat waves have been observed for a long time, as shown on weather records of stations located in the Brøgger Peninsula, including from 15 to 18 and 24 February 2021 (Appendix A), but the heavy precipitation induced by the 2022 event makes it unusual over most other records in addition to its worldwide extension, reaching Antarctica.

During field trips, observing the landscape and the snowpack (Figure 1) when retrieving the pictures collected by the automated cameras (see section “Automatic camera”) during the spring 2022 and 2023 seasons would not have allowed prediction of the impact of the short warm event that occurred in mid-March and led to transformations of the snowpack hidden in the deeper layers of the stratigraphy. In both years (Figure 1) uniform snow cover over the moraine and glacier was observed early in the spring season.

In this study, we present an observation-based investigation of a heat wave impact on the cryosphere. The

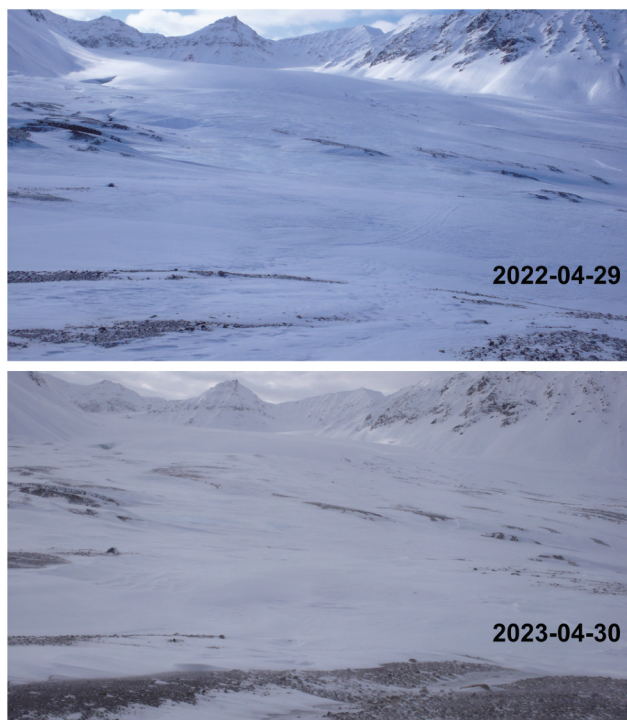


Figure 1. Automated camera observing the icings in the Austre Lovénbreen moraine: Photos acquired one year apart, around 30 April 2022 and 2023, visually similar despite the warm event that affected the snowpack in 2022. This landscape observation would not have allowed prediction of the long melting season of 2022 with respect to 2023.

analysis of the snowpack behavior after being subject to soaking by an RoS event is supported by past investigations under similar conditions (Putkonen and Roe 2003; Isaksen et al. 2007; Westermann et al. 2011). The specific objective of this study is to determine whether the recorded warm event has had a lasting impact on the snowpack to assess the potential impact on the glacial mass balance later on. The original study combines results collected by both traditional (snow pit, snow coring) and modern/innovative monitoring techniques (automated cameras, automated ablation stake, automated temperature logger network) deployed over a small observatory site in Svalbard.

Geographical settings

This study was carried out over an observatory site located at 78.9° N (Figure 2) in the Brøgger Peninsula on the west coast of Spitsbergen. Austre Lovénbreen (AL) is a small land-based valley and cold/polythermal glacier covering an area of 4.5 km² in a 10.45-km² basin, with an elevation ranging from 100 to 550 m above mean sea level (a.m.s.l.). According to the definition by Eckerstorfer and Christiansen (2011), this area of Svalbard is heavily influenced by the ocean, which contributes a considerable amount of humidity.

In Svalbard, the North Atlantic current moderates the temperature compared to other regions at the same latitude (Maturilli et al. 2019). This resulted in a mean annual air temperature in Ny-Ålesund, close to the study site, of −4°C between 1991 and 2020. The snowpack period typically extends from mid-September or early October until June.

This location was in the path of an atmospheric river (Gong et al. 2024) that, owing to the Clausius-Clapeyron relationship between temperature and vapor pressure, led to heavy precipitation events throughout Arctic and Antarctic regions during the second half of March 2022 with the consequences mentioned in the following section. In this article, we discuss the response of the snowpack and then the consequence of melting of this exceptional event and how these consequences relate to those of previous or future warm events observed in Svalbard during the spring season.

Materials and methods

The AL observatory site has been instrumented and continuously monitored since 2007. Measurements of glaciological balances are carried out in conjunction with regular snow and climatic parameter data acquisition (i.e., snow profiles, air temperature). The set of measurement instruments used for this work is summarized in Figure 3.

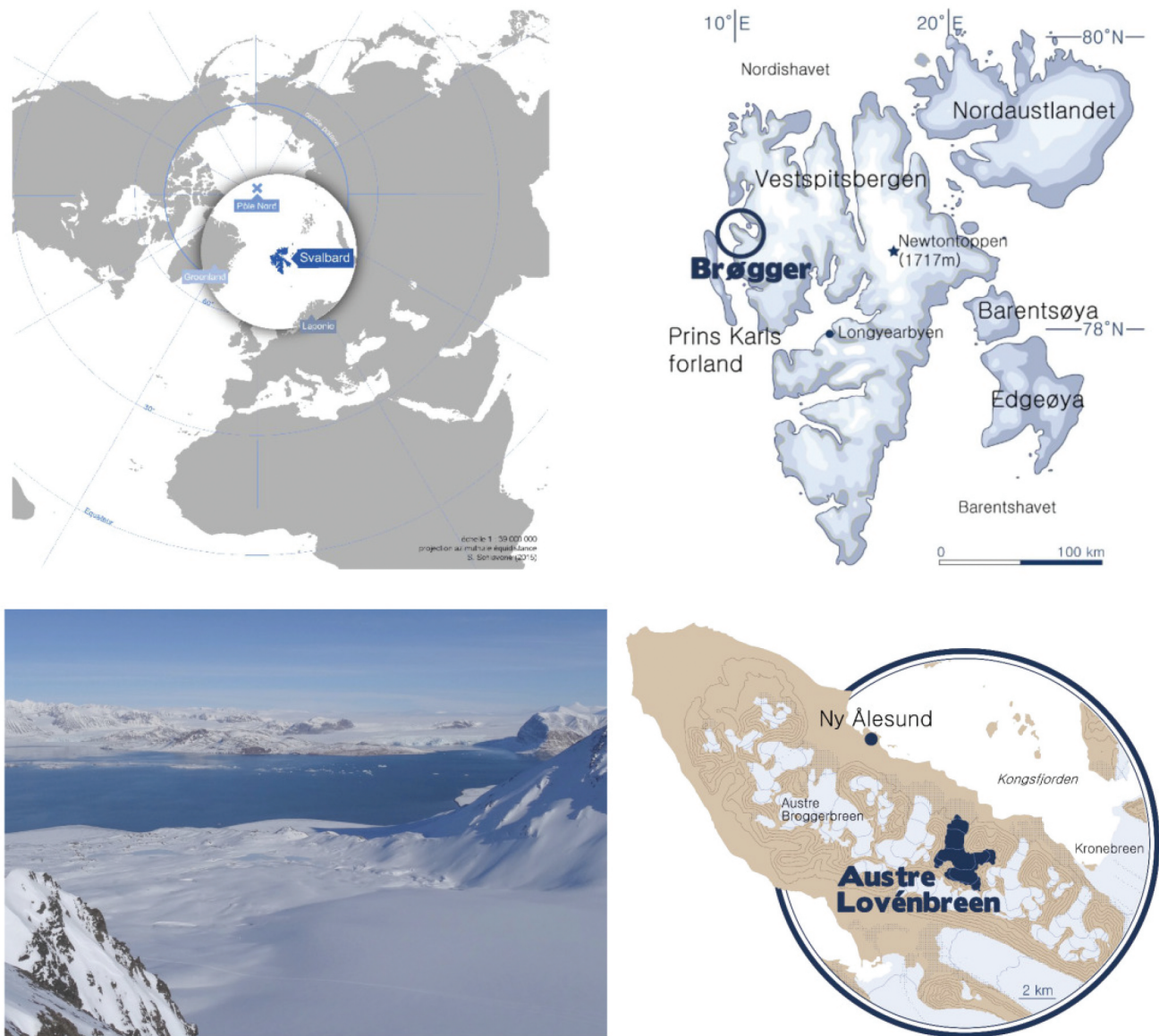


Figure 2. Austre Lovénbreen observatory site location in the Brøgger Peninsula on the west coast of Spitsbergen, 78.9° N, with increasing magnification from top left to bottom left clockwise. This area in Svalbard exhibits a typical polar maritime climate.

Automatic camera

To establish an accurate monitoring system of glacial and periglacial processes, a network of custom automated digital cameras (Laffly et al. 2012) has been deployed in the AL basin since 2010. To compensate for the absence of monitoring staff during the late spring, summer, and early autumn, consumer-grade cameras (Leica DLux 3) were tightly enclosed to protect from them weather conditions and automatically triggered at 8, 12, and 16 hours every day. The acquired pictures were manually collected and analyzed every spring and autumn at the beginning (1 May) and end (1 October) of the hydrological season. This dedicated network allowed for an accurate monitoring of several

cryosphere-induced processes, more specifically on the snowpack and RoS events (Bernard et al. 2013), which is especially relevant to our study.

Temperature sensors network

To conduct a fine-scale spatiotemporal monitoring of temperatures and to map its distribution, a network of temperature loggers was installed. The sensors were distributed on the AL basin, from the moraine to the upper cirques of the glacier, recording with hourly time-step resolution. The record of such loggers, located at higher elevations on the glacier ranging from 255 to 314 m a.m.s.l., were compared with the

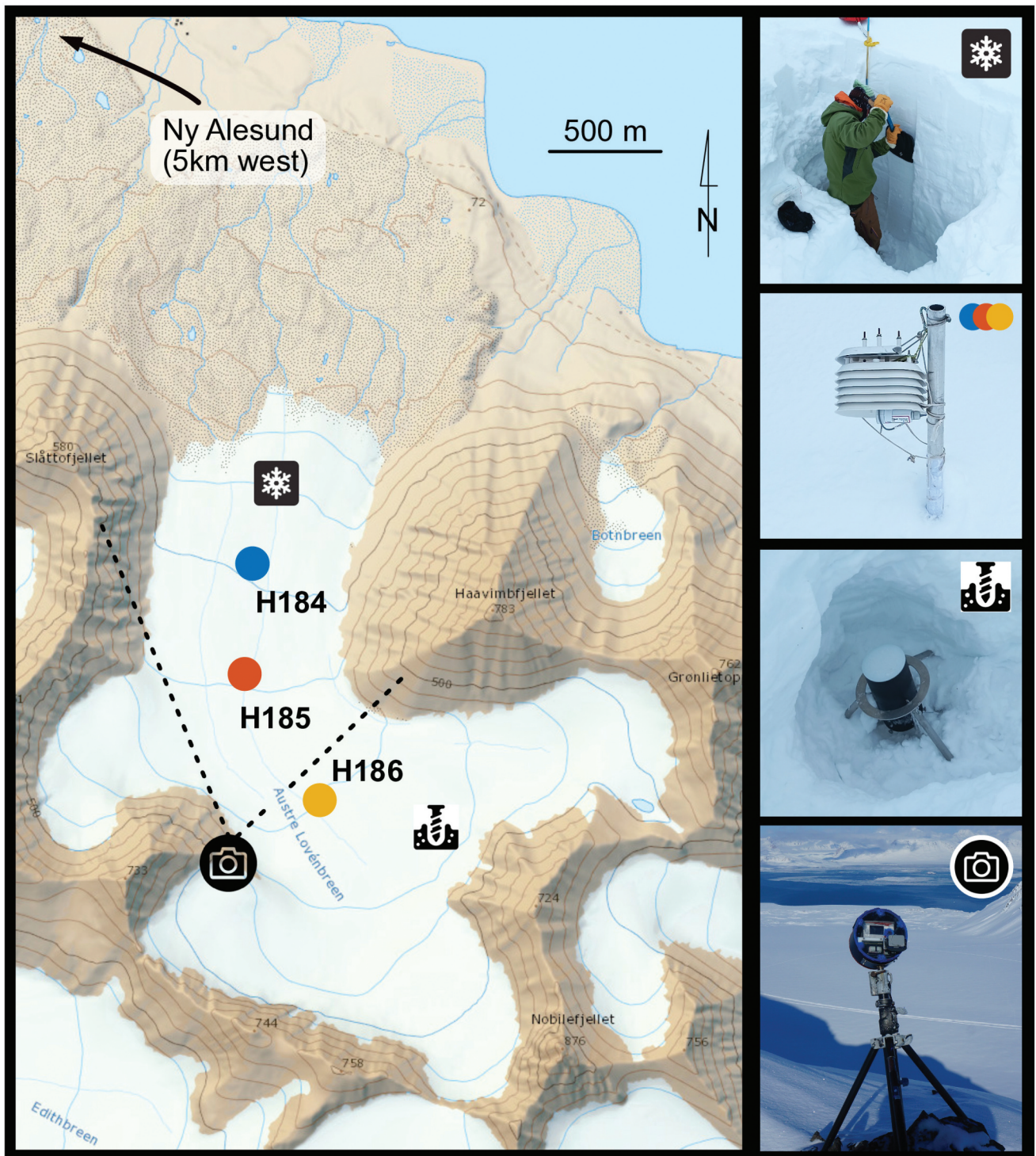


Figure 3. Location of the network of instruments used for this study on Austre Lovénbreen and the snow pit. The Smartstake for ice thickness variation monitoring is pictured third from top. The three temperature loggers follow the same color code as the graph plotted in Figure 4, namely blue for the lowest altitude sensors, orange for the mid-altitude sensors, and yellow for the highest altitude sensors. Dashed lines represent the viewshed of the automatic photo station. Background image: Topo Svalbard.

records provided by the seklima.met.no web site from the Norwegian Climate Service Center for the Ny-Ålesund measurement site (Seklina 2024; SN99910, 8 m a.m.s.l.). The latter data set was also used to

compute the positive degree-day (PDD) indicator (Bengtsson 1976) as a proxy of energy balance determining the snow and ice melt. Because only a comparison of the yearly energy balance was

assessed, we computed the sum of PDD temperatures but did not consider the multiplicative factor for converting to ice melt thickness in this study.

The temperature sensor network subset used in this investigation spanned the central flow line of the glacier and is assumed to be representative of the altitudinal gradient.

Nivology and snowpack study

Owing to the ongoing observation program over AL glacial basin, several snow profiles are carried out every year on the glacier, in different places (cirques, snout, main flow line). Beyond strictly quantitative measurements of the snowpack (density, snow water equivalent, snow depth), we also analyze its structure. Indeed, excavating the snowpack into a clean wall is a valuable strategy for assessing the structure and layers within the snowpack as well as determining the typology of snow crystals. Hence, these recurrent measurements enable the analysis of the impact of winter climatic events through the stratigraphic archive (ice layers, wet or compacted snow, etc.). All data were processed and analyzed using the online NiViz software at niviz.org (niViz 2024).

Every spring the snowpack properties were mapped by coring and weighing the extracted snow core and measuring the snowpack thickness with an avalanche probe. The mean density of the core was deduced from the ratio of the mass to the thickness times the coring tool cross section. The measurement was repeated on forty-five sites over the glacier area, spanning all elevations over which the glacier extends.

Long term glacier mass balance recording

In addition to a conventional network of ice stakes distributed over the AL glacier (Friedt et al. 2012), an

automated ablation stake located at 372 m a.m.s.l. continuously measured the ice thickness variation at one location of the AL glacier. Because the automated probe was positioned on the surface of the glacier, the snowpack properties and thickness were not measured because the snow covers the probe, and only ice melt is measured by this instrument. A weight at the end of a 6-m-long rope was inserted in a steam-drilled vertical pipe in the glacier, and as the probe standing on the melting ice surface was lowered closer to the fixed weight, an angular encoder recorded the rope length winding on a pulley. The advantage of such an instrument is that it provides not only the total ice melt but, more important, the rate of this melting throughout the entire hydrological season.

Results

According to the elevation difference between sensors, the temperature logger network on the glacier exhibits significantly colder periods than the seklima database (Figure 4). However, both detect the warm event characterized with positive air temperatures during 13 to 17 March, as highlighted by the red ellipse.

The records from the higher elevation loggers, with respect to the sea level station, demonstrate that the whole glacier was subject to positive air temperatures (ATs) and hence rainfall during the warm event, not just the low-elevation moraine area shown in Figure 5.

Though the literature referring to the Antarctic warm event discusses two heat waves during 15 to 19 March 2022, our observations demonstrate that the first temperature rise above 0°C occurred as early as 13 March and that the warm spell ended 18 March.

The warm March 2022 event was first investigated on AL by analyzing the pictures collected by the custom automated cameras and, most significantly, the one located in the moraine at 40 m a.m.s.l., where the rain

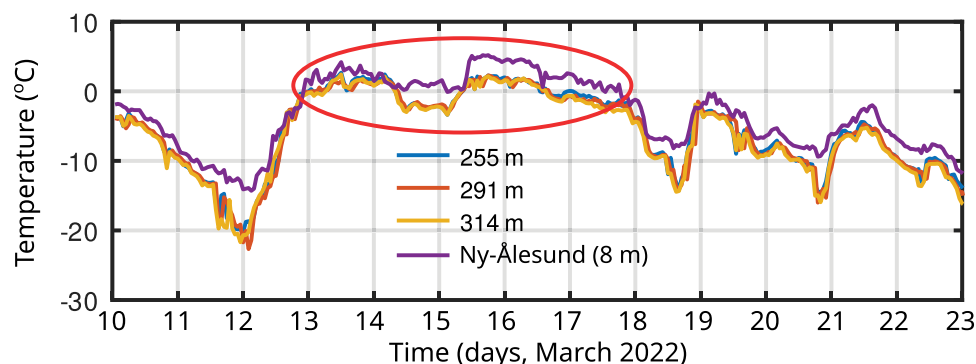


Figure 4. Hourly temperature records during mid-March 2022 collected by the reference station in Ny-Ålesund and provided by the seklima.met.no database (site SN99910, 8 m a.m.s.l.) and glacier sensor network measurements at various elevations indicated in the legend, highlighting how even the highest parts of the glacier were subject to positive temperatures and hence liquid precipitation during the heat wave.

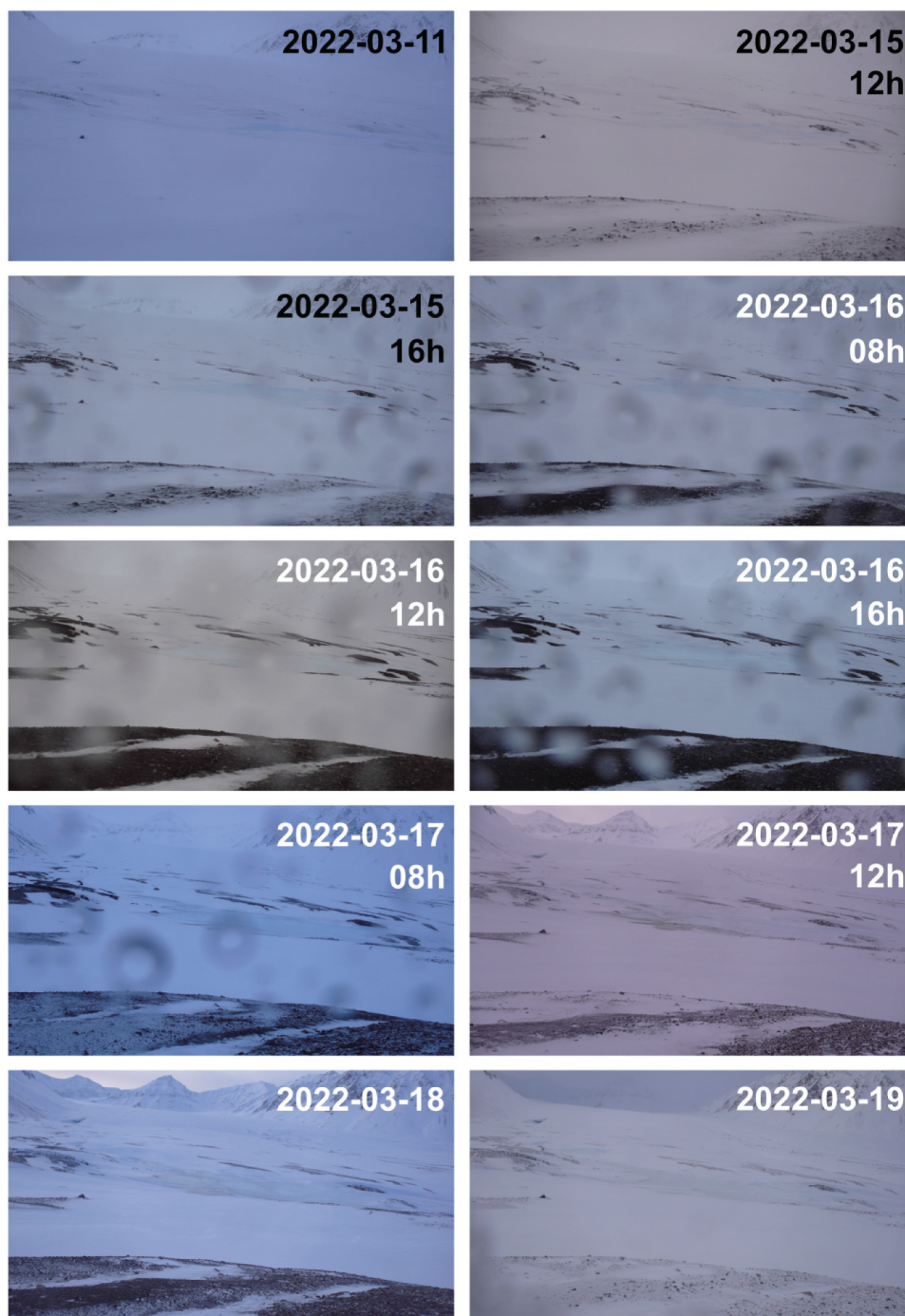


Figure 5. Automated camera image acquisition before, during, and after the warm event that occurred between 15 and 16 March 2022.

and its impact on the moraine snowpack is the most impressive (Figure 5). This camera was aimed toward the glacial river and allowed for hydrological observations such as river discharge and icing processes. This proglacial area was extremely sensitive to sudden climatic changes. It exhibited a very short response time, typically less than one day, during heavy rainfall or when temperatures rose above 0°C. Prior to 11 March 2022, the snowpack was homogeneous, with hardly any bare

rock visible from wind-blown snow. A mix of rain and snow started falling on 15 March at noon, based on the time resolution of picture acquisition of 4 h, and some bare rock started appearing as the snow melted. Precipitation quickly turned into rain on 15 March at 16 h and the most dramatic impact of rain on the snowpack was observed during 16 March 2022, with the heaviest rainfall. The warm event was completed by 17 March at noon, when a light snowfall covered the

moraine again, returning to a visually uniform snow covered landscape by 19 March 2022 (Figure 5, bottom right) but potentially leaving a long-term impact on the underlying snowpack, especially on the glacier visible in the background of these pictures, as will be demonstrated later. Looking at the background, we observed the hydrological response with the main glacier river flow resuming, resulting from moistening of the snowpack. This resulted in an early spring breakup, pushing the snow in blocks and transforming the outwash plain into a large snow slush area (Figure 5, light blue areas). All areas saturated with water then refroze and expanded the icing areas as seen in Figure 5 (bottom right). The later visual impact of this event (Figure 1) is nearly imperceptible without the images from the automatic photo stations.

We also analyzed morphological properties (Figure 6) and, in the case of this work, the impact of the heat wave on the snowpack structure with the introduction of a significant amount of liquid water, which has presumably refrozen. The snow pit measurements were completed on a site at lower elevation than the automated ablation stake, at 211 m a.m.s.l., on the upper part of the glacier snout. Each year, the snowpack exhibits several ice layers, witnessing the effect of rainfall due to different warm events that occur during the winter and spring seasons on the existing snowpack. In both 2022 and 2023, the snow thickness at this site was equivalent (around 1 m). In both stratigraphies, ice layers are observed, paradoxically thicker in 2023 than in 2022. Furthermore, for both seasons, the ice layers closest to the surface have a comparable thickness.

In 2023, the snowpack profile showed a lightly transformed and dry snow, interspersed with three large ice layers attributed to successive warm events. Furthermore, the snowpack was characterized by a low temperature gradient, meaning that the snow metamorphism was weak. Furthermore, in 2023, the snow profile (Figure 6) showed snow grain structures corresponding to cold snow, and the warm events could only be detected through the presence of ice layers. The non-transformed cold snow has just been compacted, and the snow grains have not undergone any significant transformation throughout the entire snowpack depth.

The 2022 snowpack profile was interspersed with several (four) ice layers as well but thinner and more closely spaced in the stratigraphy. However, the snowpack consisted of a higher proportion of transformed snow as a result of multiple phases of wetting. We consequently observed a succession of thick layers composed of multiple types of melt form (MF) layers intercalated with ice layers. The total thickness of all of these layers is approximately 30 cm, including ice layers (Figure 6; MF layers are

represented by the layers in red on the 2022 profile). This indicates that the snowpack has been considerably moistened. Thus, the snow has undergone irreversible transformations through the combined action of an increase in AT and the influx of liquid water that percolates between the snow grains. The middle part of the snowpack exhibited a high liquid water content (LWC) during the stratigraphy measurement.

These MF layers are therefore the snow-related consequence of the March 2022 warm event and its associated heavy rainfall. They also explain the unusually high snowpack density, with a mean value of 0.64 in 2022 compared to the usual 0.45 observed in 2023 and years prior to 2020.

We have observed that this process of strong and successive snowpack humidification significantly accelerates the melting rate, as highlighted by several previous works (Koch et al. 2014; Salzano et al. 2023). Thus, disappearance of the snowpack was faster and, as a consequence, the glacier surface was exposed earlier. Due to induced snow slush formation, larger flows were generated that leached the glacier surface. As an example, the saturated snowpack can instantly break its cohesion with the glacier surface and then be flushed away downstream. This phenomena was observed several times during field campaigns.

The Smartstake instrument recorded the ice melt season during 2022 and 2023 (Figure 7). The measurement is assumed to be representative of the whole glacier because the probe is located on the historical equilibrium line altitude. By comparing the data sets, we observed a difference of one month between the first day of melting from one year to another. The consequence was a much longer melting period in 2022 than in 2023 (seventy days versus forty). As expected, this resulted in a significant difference in total melt: the 2022 ice melt was more than twice that of 2023, at $-1,560$ mm compared to -620 mm, respectively.

The impact of the short warm event over the whole season is emphasized by extending the sklima record analysis to all of 2022 (Figure 8, blue) and 2023 (Figure 8, orange), including temperature (bottom), precipitation (middle), and snow depth (top). The 2022 heat wave is highlighted by the light blue rectangle. Heavy precipitation associated with positive AT during the event led to a visible impact, though relatively slight in relation to its thickness: we observed a difference of only a few centimeters, attributed to melting and/or settling of the snow. However, a strong impact on the snowpack in terms of both melt and morphology was observed on the snow pit stratigraphies; that is, the MF layers identified in 2022 but not in 2023.

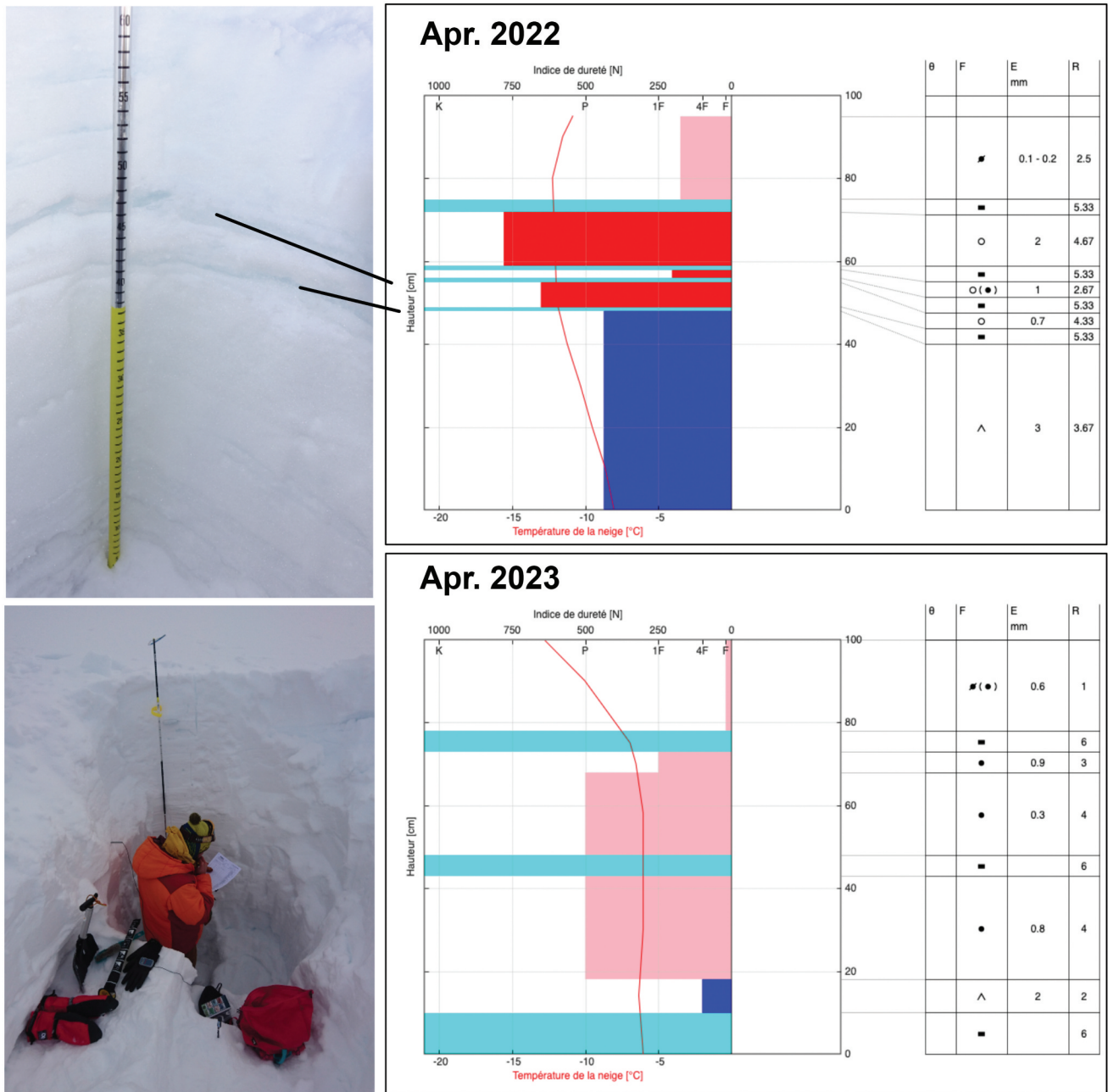


Figure 6. Comparison of snow pit stratigraphy at the same sampling point in 2022 (top) and 2023 (bottom). Several ice layers (light blue) are shown in the snowpack in both years, but melt form (red) layers irreversibly recorded the liquid precipitation associated with the 2022 warm event only.

For comparison, the 2023 complete record is overlaid, with two close heat waves highlighted by the red rectangle. Despite higher temperatures, these heat waves are not associated with heavy strong precipitation, leading to a very different impact on the snowpack than the 2022 event, as will be discussed in the next section.

The snowpack on the glacier was observed (Figure 9) under the same conditions, quantified as the fractional snow cover. Photo analysis suggests that the 2022 snowpack suddenly disappeared one month

earlier, on 29 June 2022, than in the same period in 2023, which was still fully snow covered on 29 July 2023.

Discussion

As observed during 2022, despite an initially visually similar condition with 2023 (Figure 1), the heat wave that generated intense liquid precipitation over AL

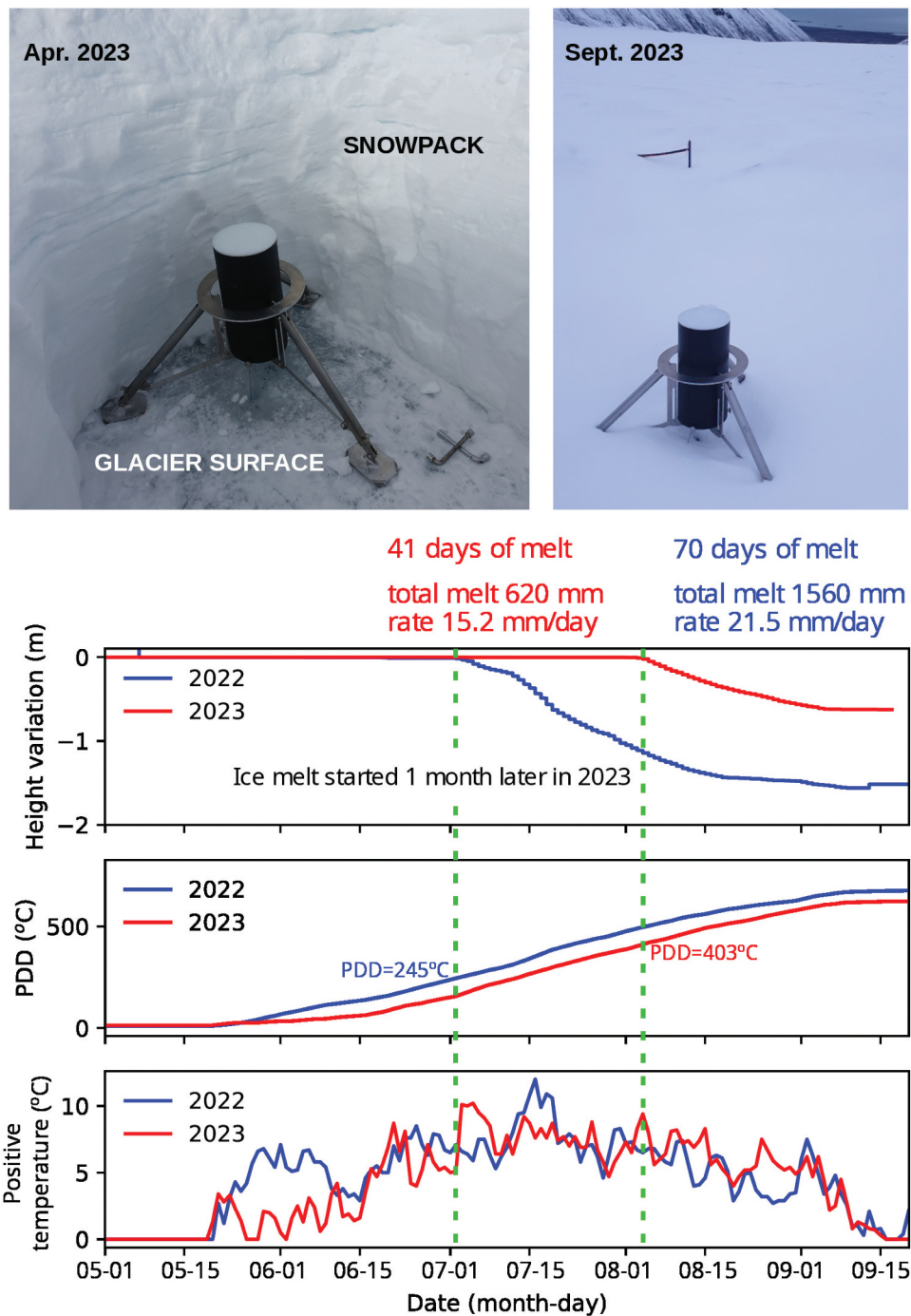


Figure 7. Top: Experimental setup for continuous ablation monitoring in spring (left) and autumn (right). The first chart displays the automated ablation stake ice thickness variation measurement in 2022 (blue) and 2023 (red) referenced to the same baseline on 1 June of each year, when the sensor was still covered with snow protecting the ice from melting. The ablation season duration defined as the first ice thickness variation due to the stabilization of the ice thickness is indicated for each year, emphasizing how the melt season duration was extended in 2022 with respect to a typical year represented by 2023. Middle: Sum of PDD temperatures in 2022 (red) and 2023 (blue). The PDD values at the onset of the melt (top) are indicated for 2022 (blue) and 2023 (red) as 245°C and 403°C, respectively. Bottom: Positive temperature records in 2022 (blue) and 2023 (red).

(Figure 4) mainly induced transformations of/into the snowpack (Figure 5).

The consequence of the heat wave on the snowpack is not the same in the glacier and in the periglacial

environment: though the melt processes are the same, the mechanical instability leads to different outcomes on the protection of the underlying surface by the snowpack. Figure 8 suggests that the exceptional 2022 heat

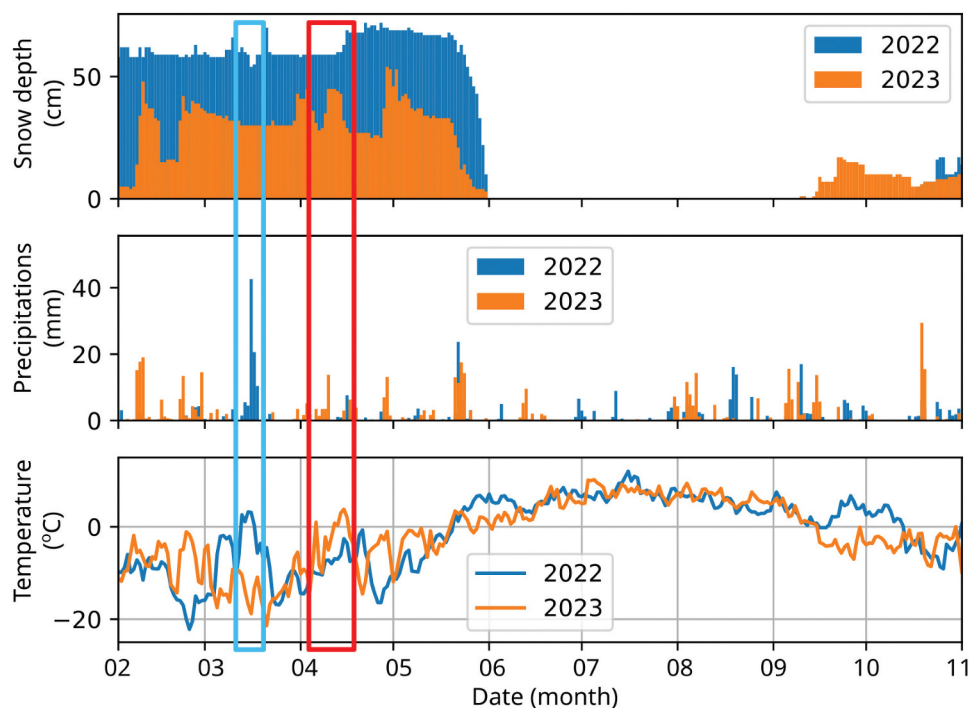


Figure 8. Weather records during 2022 (blue) and 2023 (red) from the seklima.met.no database for the Ny-Ålesund station. The warm event around 15 March 2022 is highlighted by the light blue rectangle, including the heavy precipitation (middle). Two warm events in close succession in 2023 are highlighted by the red rectangle. Higher temperatures observed in 2023 were not accompanied with heavy precipitation (middle) and yet also decreased the snowpack thickness (top).

wave event did not have an impact on the snowpack at sea level. Indeed, in periglacial environments—that is, on nonglaciated ground as shown in Figure 8—the snowpack disappeared at the same time, on 1 June, in both 2022 and 2023.

This result contrasts with observations of the snowpack on the glacier (Figure 9). Indeed, the glacier surface acts as a sliding plane that facilitates the disappearance of the snowpack when it exhibits low mechanical resistance; that is, when saturated by a high LWC. This corroborates the measurements of the Smartstake data, analysis of which demonstrated the earlier melt of the ice as the glacier surface was exposed earlier.

Despite the temperature rising above 0°C one month earlier in 2022 than in 2023, the PDD curves exhibit a parallel evolution for both years, indicating a similar trend. This leads to similar snow- and ice melt potential. Indeed, temperatures above the melting point of snow are considered as a proxy of melt potential, summarizing the impact of incoming and outgoing radiations. However, under similar snowpack depth and PDD, the structure of the snowpack dictates how the fractional snow cover evolves and how long the glacier remains protected from melt by the snowpack. Though the snow mass could explain the melting duration—the heavier snowpack induced by the higher 2022 density than in 2023 for a similar snowpack thickness requires more

energy to melt—the observation here contradicts this conclusion because the heavier snowpack vanished earlier. Hence, the factor driving snowpack coverage duration over the glacier is considered as the mechanical characteristics. This observation strengthens the argument that the early snowpack disappearance in 2022 was due to the snowpack sudden rupture rather than progressive melt.

Estimates derived from Figure 7 suggest that the PDD value for 2022 was approximately 250 degree-days, whereas for 2023 it rose to around 400 degree-days. Notably, due to the cooler overall temperatures during the summer of 2023, the threshold of 250 degree-days was reached approximately fifteen days later in that year compared to 2022. Consequently, the variation in average summer temperatures may account for nearly half of the one-month delay in melt onset observed between 2022 and 2023. However, there remained a residual delay in melt conditions in 2023 relative to 2022. The residual delay in melt for 2023 compared to 2022 can be attributed to the transformation of snowpack resulting from the warm and wet weather conditions experienced in March 2022. That unusually mild and moist period led to an earlier accumulation of snowpack that likely underwent significant metamorphosis, altering its density and albedo properties. As a result, the transformed snowpack reacted differently to subsequent temperature



Figure 9. Date comparisons of the glacier snow cover between 2022 (left) and 2023 (right). These images highlight a significantly faster melting and leaching of the glacier, occurring nearly one month earlier, in 2022 than in 2023.

variations, exhibiting slower melt rates due to its enhanced moisture retention. The observed delay in melt progression in 2023, in conjunction with cooler summer temperatures, emphasizes the complex interplay between weather events and snowpack dynamics, highlighting how previous seasonal conditions can have lasting effects on glacial melt patterns.

In this context, a significant amount of LWC in the snowpack and the presence of MF layers lead to a critical threshold of instability. As soon as the temperature rises above freezing, it undergoes an almost instantaneous transformation into slush before being washed away from the glacier's surface. Here, due to the impermeability of the glacier surface, which encourages surface flows, the structure of the snowpack and the snow grain type seem

to be the explanatory factors for the earlier total disappearance of the snowpack favoring the ice exposure and then the ice melt. This supports the hypothesis that the earlier disappearance of the snowpack leads to earlier exposure of the glacier, resulting in increased ice melting.

The 2022 warm event was the perfect experiment to demonstrate that the snowpack structure has an impact on how it vanishes, especially onto the glacier surface.

Conclusion

Starting with the March 2022 heat wave caused by the atmospheric river affecting the Arctic and Antarctic regions, we examined its impact on the Austre Lovén glacier in the

Brøgger Peninsula of Spitsbergen, Arctic Norway. Our observations indicate a prolonged glacier ice melting season due to an early loss of the snowpack. Furthermore, a comparison with weather records from 2023 (and 2021) revealed that similar warm events have occurred in early spring on a recurring basis. Whereas temperature remains the main trigger of ice/snowmelt, it appeared that the strong changes in the snowpack structure acted as a catalyst, accelerating the effects of melting when the temperature rose above 0°C. The fast reduction of fractional snow cover until the surface becomes completely snow free, especially on the glacier, is interpreted as a main consequence of the RoS event resulting from the exceptional 2022 heat wave. This was corroborated by the linear fractional snow cover retreat in 2023, when the snowpack was not subject to intense moisture during winter and spring.

The 2022 heat wave had an indirect impact on the early melting of the underlying glacier by altering the mechanical properties of the snowpack through the addition of liquid water, leading to the formation of ice layers and melt form snow grain structures. The resulting rapid disappearance of the snowpack, once the melting season started, led to double ice melt over the glacier area.

Disclosure statement

There are no financial or nonfinancial competing interests to report.

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Data availability

The data and processing scripts are available at <https://github.com/jmfriedt/aaar2024>. Further assistance in reproducing the results can be obtained from the authors.

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Appendix A

Weather records: 2021 versus 2022

Weather records (Figure A1) from seklima.met.no at the Ny-Ålesund station (SN99910, 8 m a.m.s.l.) comparing the snow depth (top), precipitation (middle), and temperature records

(bottom) in 2021 and 2022. The timescale is limited to 1 February to 15 June of each year to include the melt of the snowpack (reached 10 June 2021 and 1 June 2022) because the temperature measurement started failing mid-May in 2021 and was only resumed at the beginning of September, preventing a PDD index calculation during the melt season.

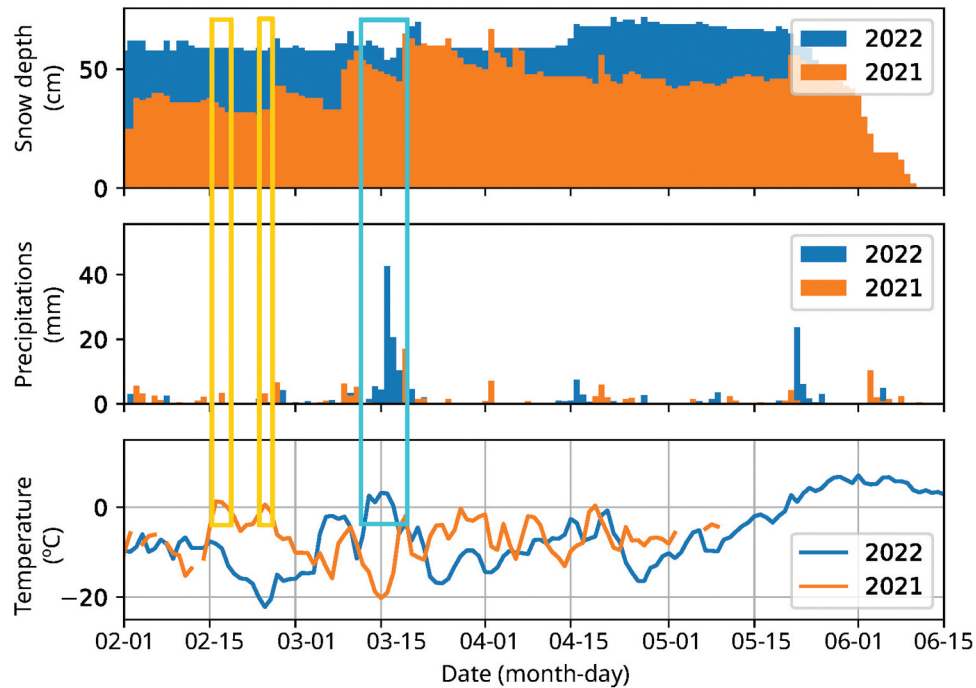


Figure A1. Weather records during 2022 (blue) and 2021 (red) from the seklima.met.no database for the Ny-Ålesund station. The warm event around 15 March 2022 is highlighted by the light blue rectangle, including the heavy precipitation (middle). Two warm events in February 2021 are highlighted by the orange rectangle.