ARCTIC ANTARCTIC AND ALPINE RESEARCH

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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ARTICLE HISTORY
Compiled September 22, 2024

ABSTRACT
Simultaneous heatwaves 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 timelapse cameras and an automated ablation stake acquiring the ice melt with hourly resolution have been 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. This situation led to an earlier glacier surface exposure and hence an earlier ice melt when compared to 2023 considered as a reference state, leading to a more negative mass balance. This study highlights the strong negative influence of winter liquid precipitation on glacier mass balance.

KEYWORDS
Extreme events; Snowpack; Svalbard; Rain-on-Snow; Melting processes

1. Introduction

Over the past 30 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, & Fischer, 2015; Yu & Zhong, 2021). Indeed, heatwaves 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, & Eckerstorfer, 2022) and the total Arctic precipitation has increased by 30-60% (Bintanja & Andry, 2017). In parts of the Arctic, due to the significant increase of atmospheric rivers and winter cyclones (Bednorz, Tomczyk, Czernecki, & Piekny, n.d.; Ebell et al., 2023; Frank, Jonassen, Skogseth, & Vihma, 2023), extreme warm spells and heavy rain-on-snow (RoS) events in winter are already more frequent and more intense (Champagne, Zolina, Dedieu,

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Wolff, & Jacobi, 2024; Van Pelt et al., 2019), although they have been reported for a long time (Dege, 2004). The frequency and magnitude of RoS events has recently increased (Sobota, Weckwerth, & Grajewski, 2020), with an effect on the number and size of ice layers (Bintanja & Andry, 2017) in the snowpack. And as has already been stated by (Rennert, Roe, Putkonen, & Bitz, 2009), this trend is expected to increase further during the 21st century.

Remarkably though, an exceptional heatwave was detected in Antarctica and led to record breaking temperatures in March 2022 (Blanchard-Wrigglesworth, Cox, Espinosa, & Donohoe, 2023; Wille et al., 2024). During the first quarter of 2022, the Arctic experienced the same exceptional heatwave as well (Sabbatini, 2022), accompanied by significant precipitation. According to (Blanchard-Wrigglesworth et al., 2023), this extreme heatwave 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 Arctic, the 2022 Arctic heatwave was so significant that it was able to trigger, in a single event, the reactivation of the braided river system (Athulya, Nuncio, Chatterjee, & Vidya, 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, heatwaves have been observed for a long time as shown on weather records of stations located in the Brøgger Peninsula, including from Feb. 15–18 and 24, 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 (Fig. 1) when fetching the pictures collected by the automated cameras (see section 3.1) during the spring 2022 and 2023 seasons would not have allowed to predict the impact of the short, warm event that occurred mid-March and led to transformations of the snowpack hidden in the deeper layers of the stratigraphy. In both years (Fig. 1), a 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 heatwave impact on the cryosphere. The analysis of the snowpack behavior after being subject to soaking by a RoS event is supported by past investigations under similar conditions (Isaksen, Sollid, Holmlund, & Harris, 2007; Putkonen & Roe, 2003; Westermann, Boike, Langer, Schuler, & Etzelmüller, 2011). The specific objective of this study is to determine if the recorded warm event has had a lasting impact on the snowpack, in order 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.

2. Geographical settings

This study was carried out over an observatory site located at 78.9°N (Fig. 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 km^2 in a 10.45 km^2 basin, with an elevation ranging from 100 to 550 m above mean sea level (a.m.s.l). According to the definition exposed by (Eckerstorfer & Christiansen, 2011), this area of Svalbard is under the influence of a maritime snow climate, which is heavily influenced by the ocean, which contributes a considerable amount of humidity.

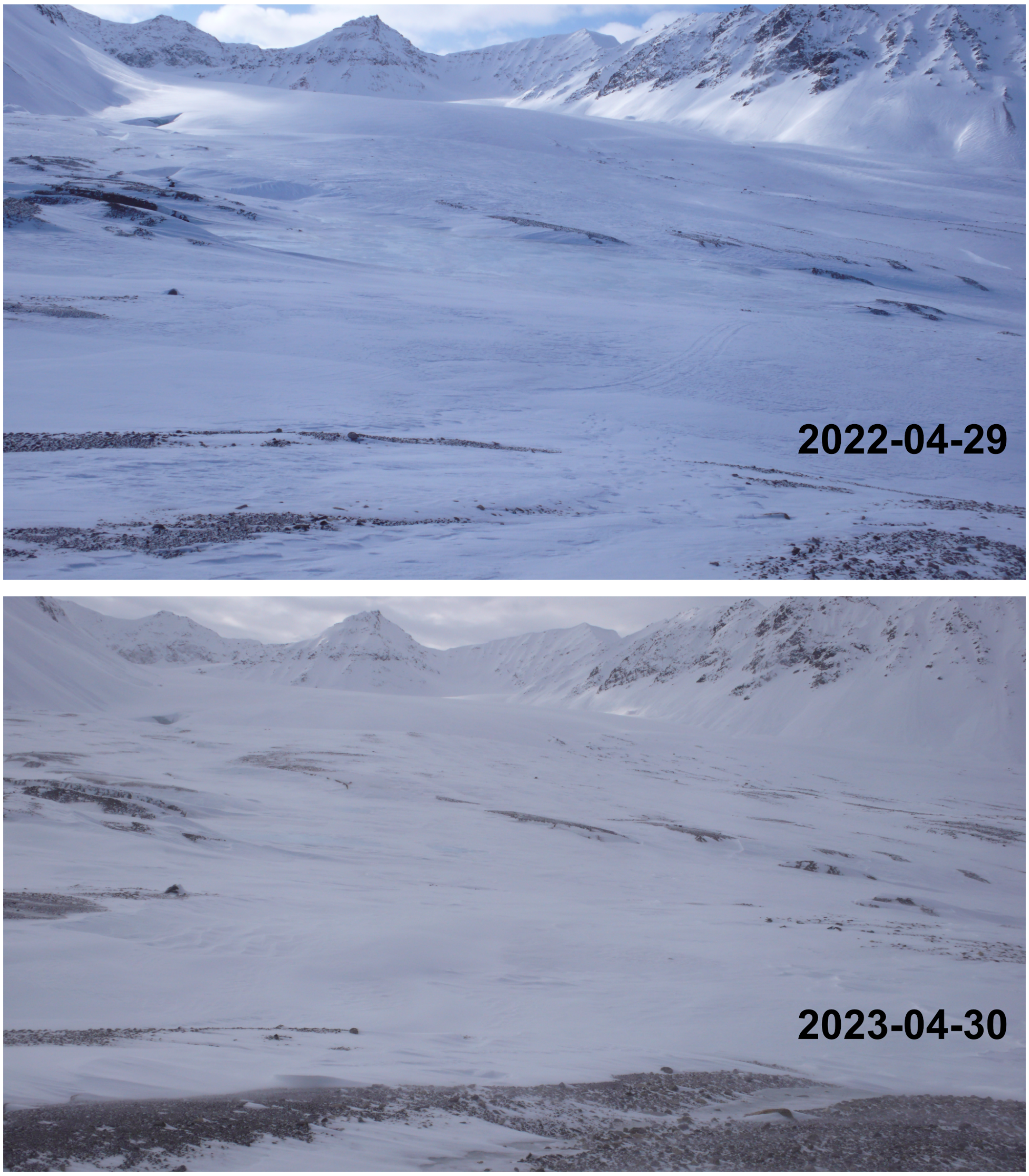

Figure 1. Automated camera observing the icings in the Austre Lovénbreen moraine: pictures acquired one year apart, around April 30 2022 and 2023, visually similar despite the warm event that affected the snowpack in 2022 and not allowing to predict the long melting season of 2022 with respect to 2023.

In Svalbard, the north Atlantic current moderates the temperature compared to other regions at the same latitude (Maturilli, Hanssen-Bauer, Neuber, Rex, & Edvardsen, 2019). This results in a mean annual air temperature (MAAT) in Ny-Ålesund, close to the study site, of $-4°C$ between 1991 and 2020. The snowpack period typically extends from mid-September or beginning of October, until June.

This location was in the path of an atmospheric river (Gong, Zhong, Hua, & Feng, 2024) that, thanks 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 below. In

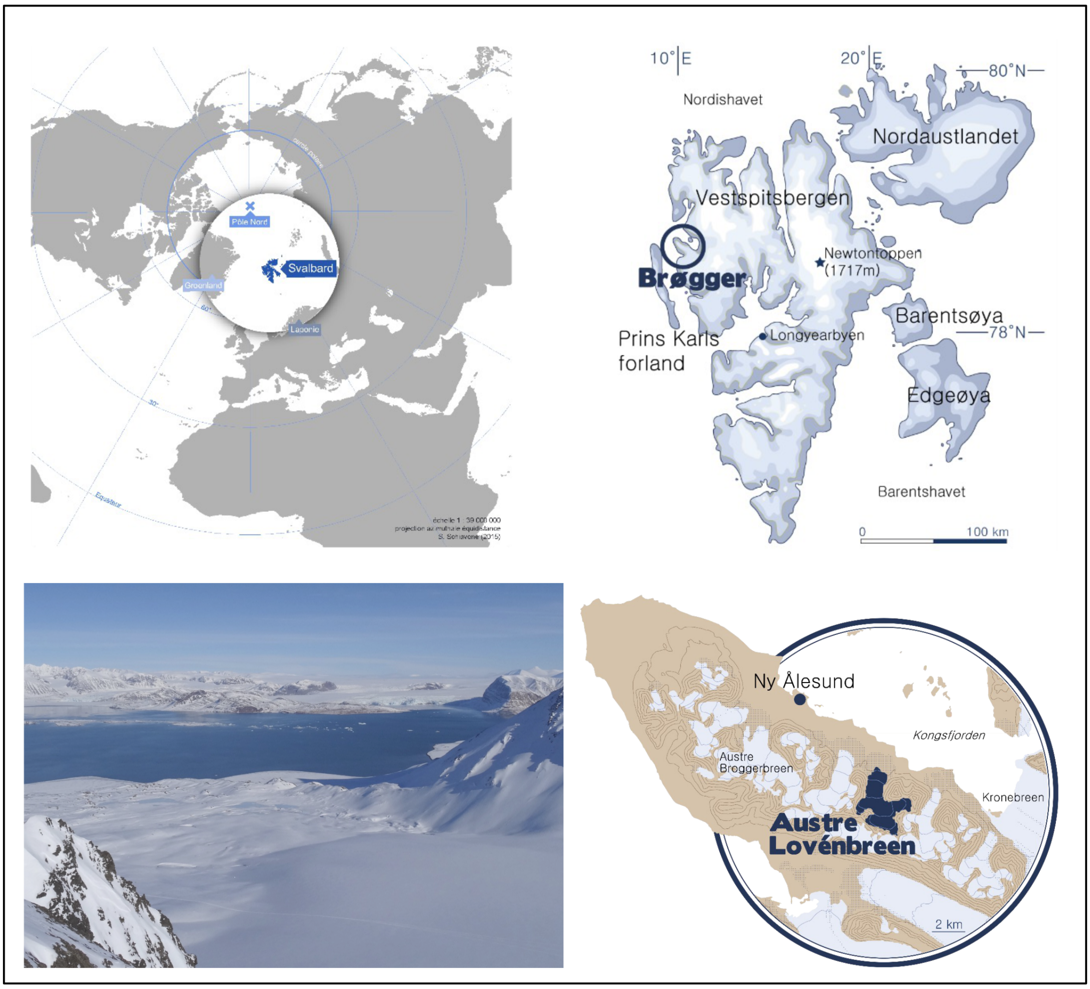

Figure 2. Austre Lovénbreen observatory site location in the Brøgger Peninsula on the west coast of Spitsbergen, 78.9°N, with increasing magnification from top-left to bottom-left clockwise. This place in Svalbard exhibits a typical polar maritime climate.

this paper, we discuss the response of the snowpack and then the melting consequences of this exceptional event, and how these consequences relate to those of previous or next warm events observed in Svalbard during the spring season.

3. Materials and methods

The AL observatory site has been instrumented and continuously monitored since the year 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 Fig. 3

3.1. *Automatic camera*

In order 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

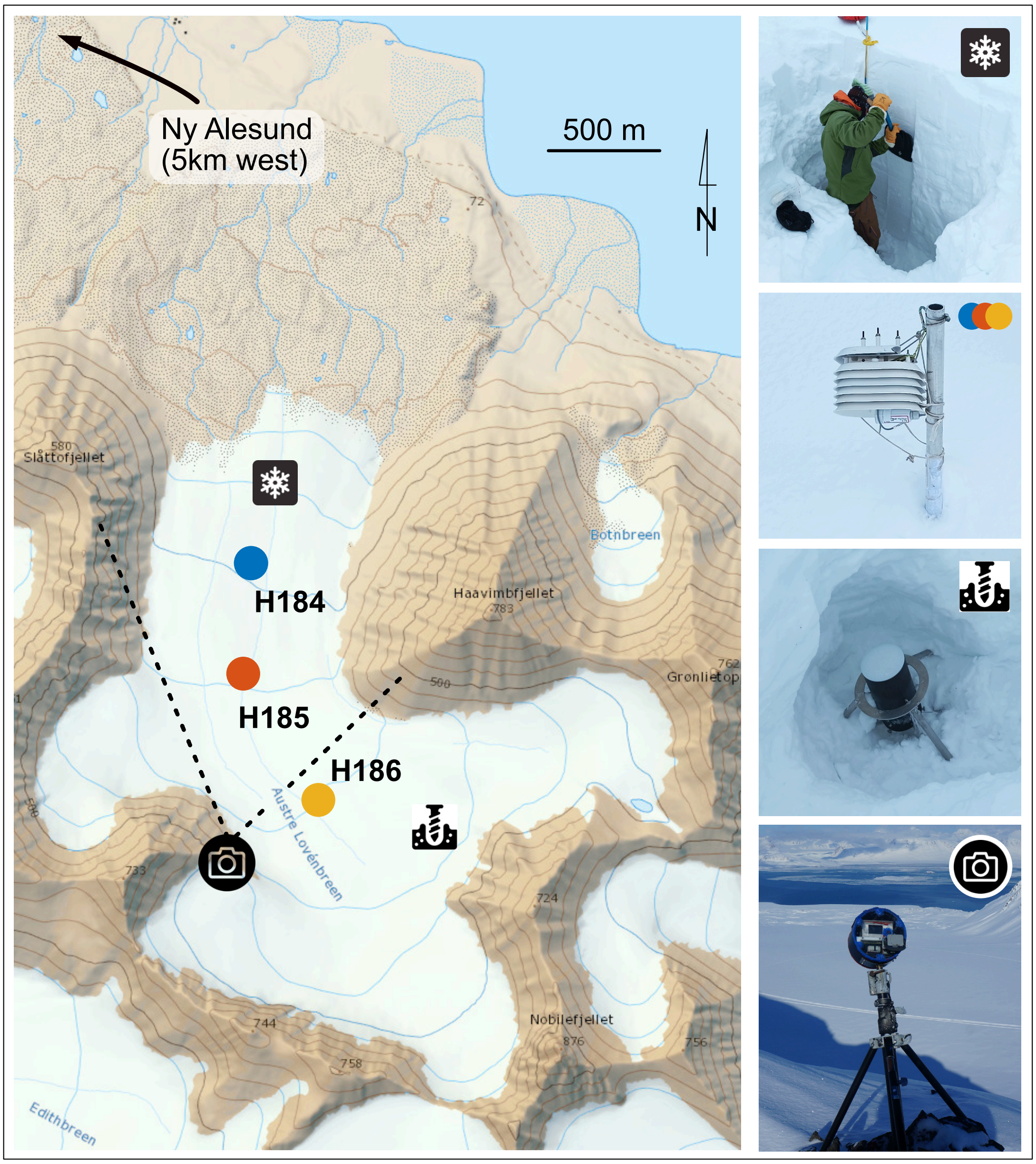

Figure 3. Location of the network of instruments used for this study on Austre Lovénbreen and the snow pit. The Smartstake for ice thickness variation monitoring is pictured third from top. The 3 temperature loggers follow the same color code as the graph plotted on Fig. 4. Dashed lines represent the viewshed of the automatic photo station. Background image: Topo Svalbard.

in the AL basin since 2010. In order to compensate for the absence of monitoring staff during the late spring, summer and early autumn, consumer grade cameras (Leica DLux 3) are tightly enclosed to protect from weather conditions, and automatically triggered at 8, 12 and 16 h every day. The acquired pictures are manually collected and analyzed every spring and autumn, at the beginning (May 1st) and end (October 1st) 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.

3.2. *Temperature sensors network*

In order to conduct a fine-scale spatio-temporal monitoring of temperatures and to map its distribution, a network of temperature loggers (Onset Hobo, Bourne, MA, USA) has been installed. The sensors are 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 m to 314 m a.m.s.l, are compared with the records provided by the `seklima.met.no` web site from the Norwegian Climate Service Center for the Ny-Ålesund measurement site (SN99910, 8 m a.m.s.l). The latter dataset is also used to compute the Positive Degree Day (PDD) indicator (Bengtsson, 1976) as a proxy of energy balance determining the snow and ice melt. Since only a comparison of the yearly energy balance is assessed, we compute the sum of positive degree day temperatures but do not consider the multiplicative factor for converting to ice melt thickness in this study.

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

3.3. *Nivology and snowpack study*

Thanks 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 flowline). 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 are processed and analyzed through the online NiViz software at `niviz.org`.

Every spring the snowpack properties are mapped by coring and weighing the extracted snow core, and measuring the snowpack thickness with an avalanche probe. The mean density of the core is deduced from the ratio of the mass to the thickness times the coring tool cross-section. The measurement is repeated on 45 sites over the glacier area, spanning all elevations over which the glacier extends.

3.4. *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 (Smartstake, A2 Photonic Sensors, Grenoble, France) located at 372 m a.m.s.l continuously measures the ice thickness variation at one location of the AL glacier. Since the automated probe is positioned on the surface of the glacier, the snowpack properties and thickness are not measured since 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 is lowered closer to the fixed weight, an angular encoder records 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 importantly, the rate of this melting throughout the entire hydrological season.

4. Results

The comparison chart between temperature sensors on the AL basin and Ny-Ålesund weather station is exhibited in Fig. 4. According to the elevation difference between sensors, the temperature logger network on the glacier exhibits significantly colder periods than the `seklima` database. However, both detect the warm event characterized with positive air temperatures during March 13 to March 17, 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 (AT) and hence rainfall during the warm event, and not only the low-elevation moraine area shown in Fig. 5.

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

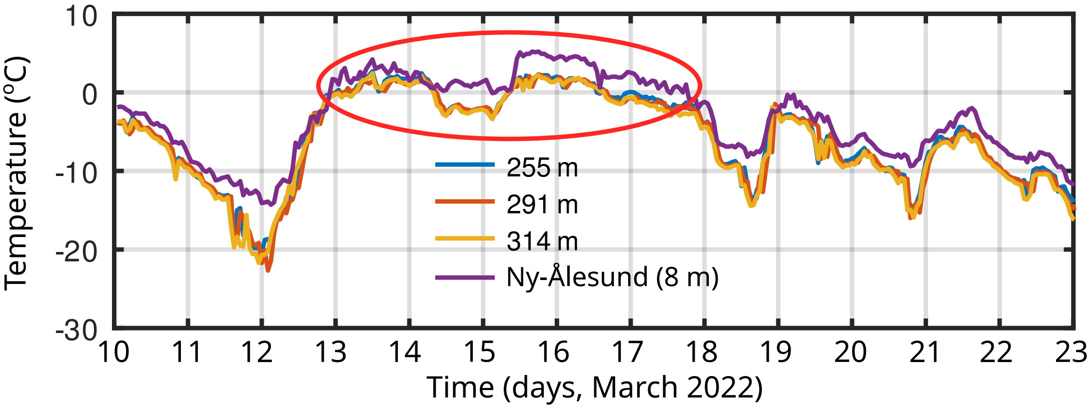

Figure 4. Hourly temperature records during mid-March 2022 collected by the reference station in Ny-Ålesund and provided by the `seklima.met.no` database (site SN99910, 8 m a.m.s.l elevation), and glacier sensor network measurements at various elevations indicated in the legend, highlighting how even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

The warm March 2022 event is 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 and its impact on the moraine snowpack is the most impressive (Fig. 5). This camera is aimed towards the glacial river and allows for hydrological observations such as river discharge and icings processes. This proglacial area is extremely sensitive to sudden climatic changes. It exhibits a very short response time, typically less than one day, during heavy rainfall or when temperatures rise above 0°C. Prior to March 11, 2022, the snowpack is homogeneous with hardly any bare rock visible from wind blown snow. A mix of rain and snow starts falling on March 15 at noon, considering the time resolution of picture acquisition of 4 h, and some bare rock starts appearing with snow melting. Precipitation quickly turns into rain on March 15 at 16h and the most dramatic impact of rain on the snowpack is observed during March 16, 2022, with the heaviest rainfall. The warm event is completed by March 17, noon, when a light snow fall covers the moraine again, returning to a visually uniform snow covered landscape by March 19, 2022 (Fig. 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 can observe the hydrological response with the main glacier river flow resuming, resulting from moistening of the snowpack. This results in an early spring break-up, pushing the snow in blocks and transforming the outwash plain into a large snow slush area (Fig. 5, light blue areas). In a next step, all areas saturated with water will then re-freeze and expand the icing areas as see on Fig. 5, last picture, bottom right. The later visual impact of this event (Fig. 1) is nearly imperceptible without the images from the automatic photo stations.

Then, we also analyze morphological properties (Fig. 6) and, in the case of this work, the impact of the heatwave 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 shows a lightly transformed and dry snow, interspersed with 3 large ice layers attributed to successive warm events. Furthermore, the snowpack is characterized by a low temperature gradient meaning that the snow metamorphism is weak. Furthermore, in 2023, the snow profile (Fig. 6) shows snow grain structures corresponding to cold snow, while 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 is interspersed with several (4) ice layers as well, but thinner and more closely spaced in the stratigraphy. However, the snowpack consists of a higher proportion of transformed snow as a result of multiple phases of wetting. We consequently observe a succession of thick layers composed of multiple types of melt form (MF) layers intercalated with ice layers. The total thickness of all these layers is approximately 30 cm, including ice layers (Fig. 6, MF 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 besides 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 work (Koch, Prasch, Schmid, Schweizer, & Mauser, 2014; Salzano et al., 2023). Thus, the snowpack disappearance is faster and as a consequence, the glacier surface is exposed earlier. Due to induced snow slush formation, larger flows are generated that leach 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 (Fig.

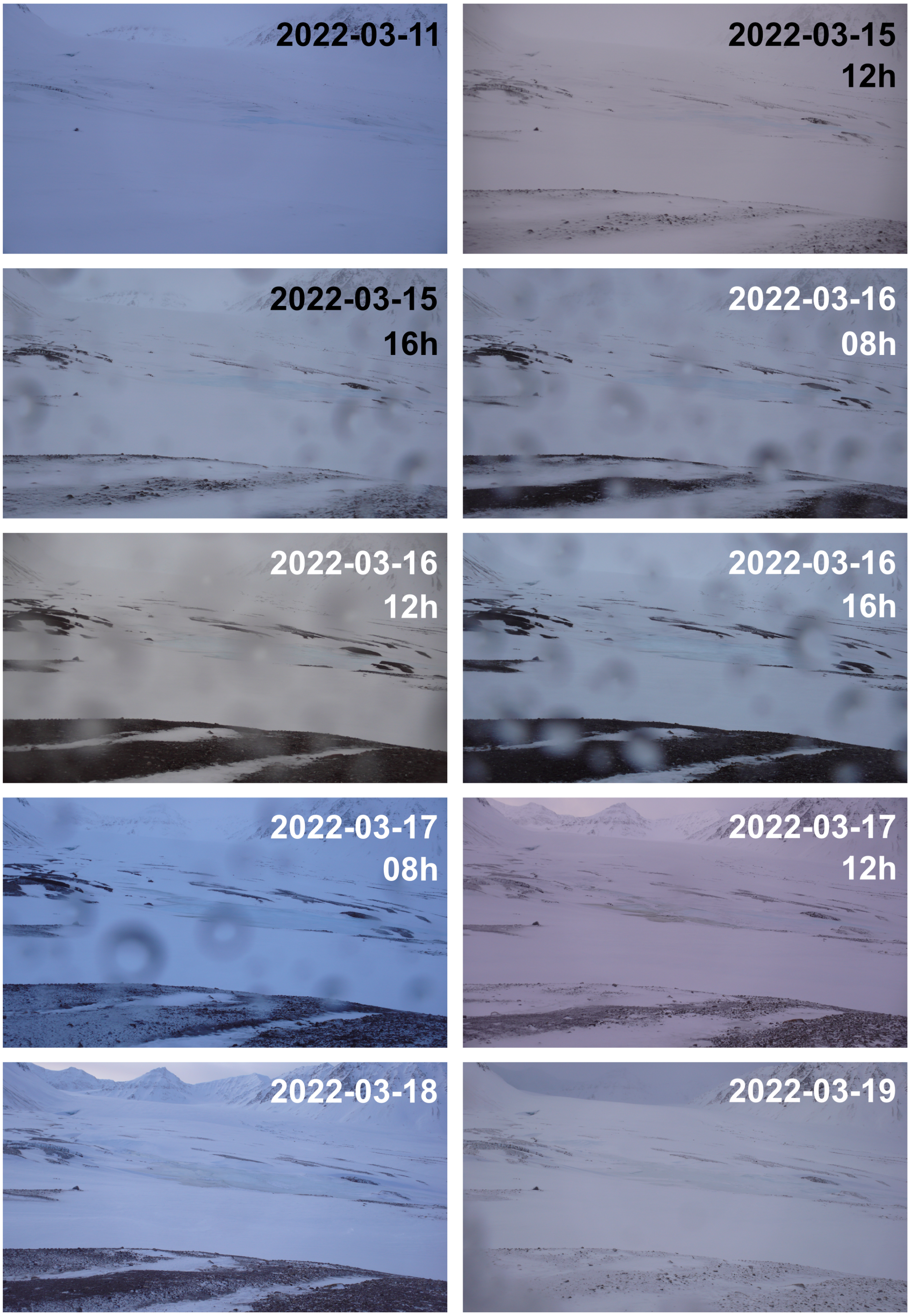

Figure 5. Automated camera image acquisition before, during and after the warm event that occurred between March 15 and 16, 2022.

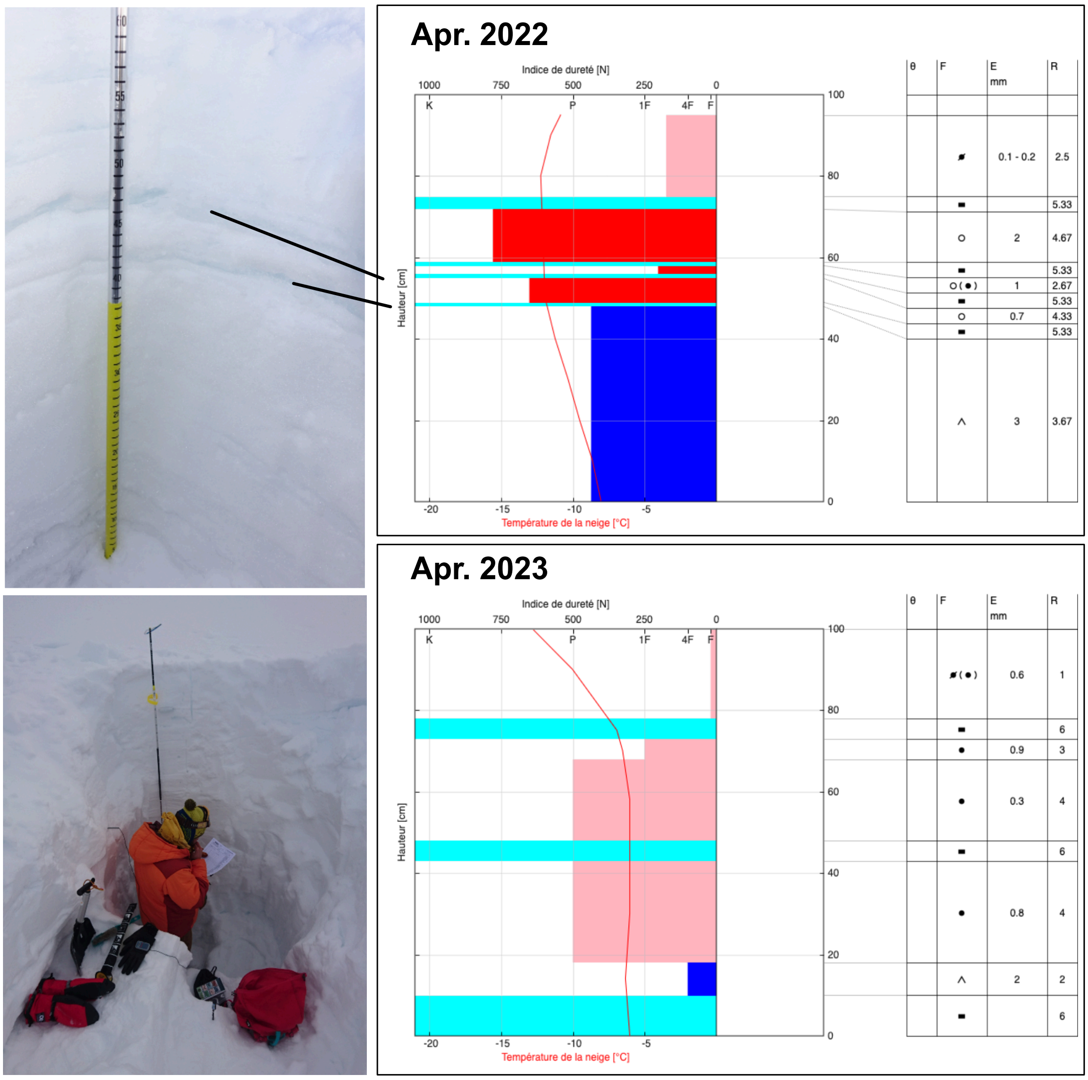

Figure 6. Snow pit stratigraphy comparison at the same sampling point in 2022 (top) and in 2023 (bottom). Several ice layers (light blue) are pointed into the snowpack in both years, but melt form (red) layers irreversibly recorded the liquid precipitation associated with the 2022 warm event only..

7). The measurement is assumed to be representative of the whole glacier since the probe is located on the historical equilibrium line altitude (i.e. ELA). By comparing the datasets, we observe a difference of 1 month between the first day of melting from one year to another. The consequence is a much longer melting period in 2022, than in 2023, (70 days versus 40). As expected, this results in a significant difference of total melt: the 2022 ice melt is more than twice that of 2023, with −1560 mm compared to −620 mm, respectively.

The impact of the short warm event over the whole season is emphasized by extending the `seklima` record analysis to the whole 2022 year (Fig. 8, blue) and 2023 (Fig. 8, orange), including temperature (bottom), precipitation (middle) and snow depth (top). The 2022 heatwave is highlighted with the light-blue rectangle. Heavy precipitation associated with positive AT during the event have led to a visible impact, though relatively slight in relation to its thickness: we observe a difference of only a few centimeters attributed to melting and/or settling of the snow. However, a

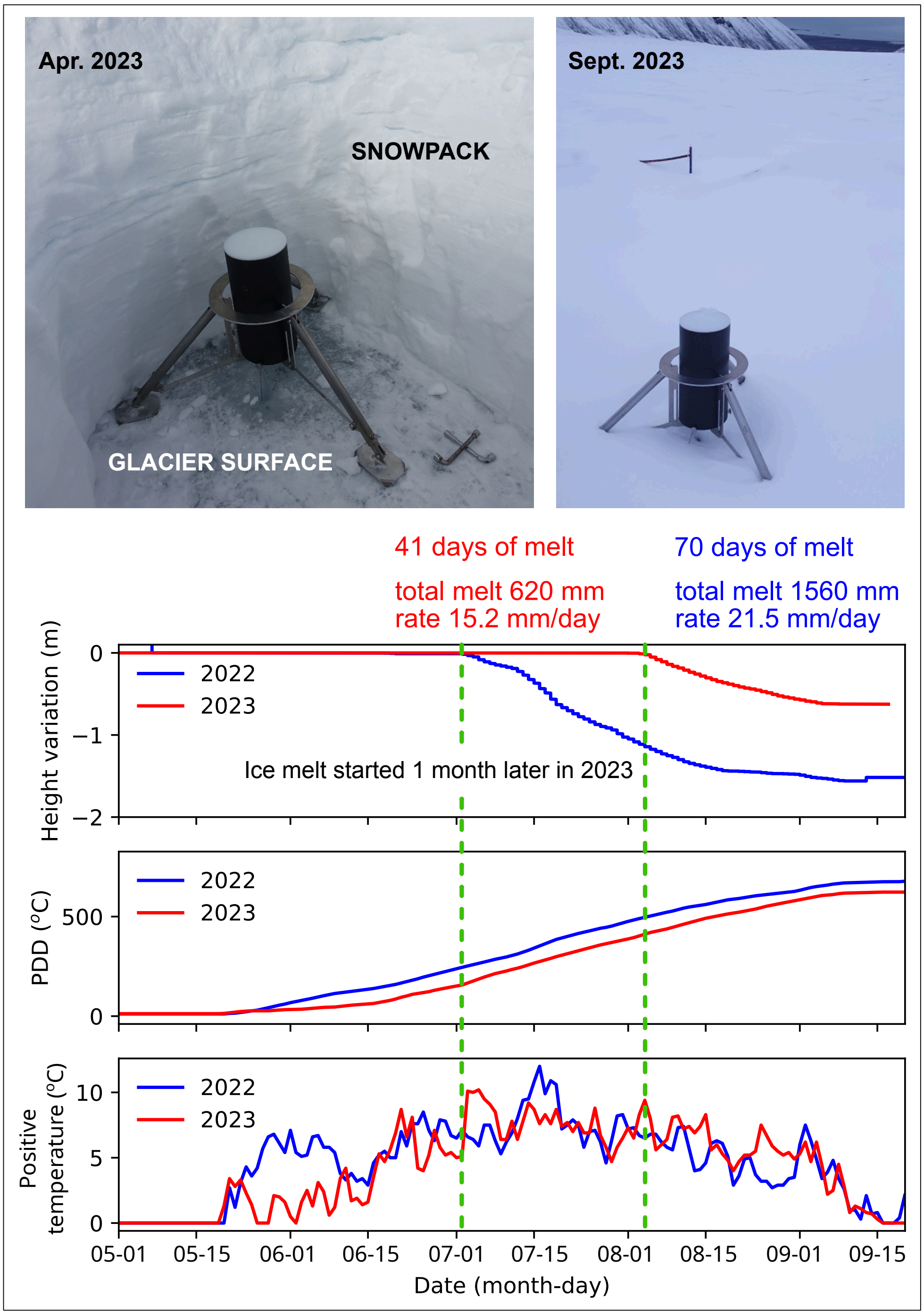

Figure 7. Top: experimental setup for continuous ablation monitoring in spring (left) and in autumn (right). The first chart displays the automated ablation stake ice thickness variation measurement in 2022 (blue) and 2023 (red) referenced to the same baseline in June 1st of each year, when the sensor is still covered with snow protecting the ice from melting. The ablation season duration defined as the first ice thickness variation 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 chart: sum of positive degree day temperatures in 2022 (red) and 2023 (blue). Bottom: temperature records in 2022 (blue) and 2023 (red). Right: experimental setup.

strong impact on the snowpack both in terms of melt and morphology is observed on the snow pit stratigraphies i.e. the MF layers identified in 2022 but not in 2023.

For comparison, the 2023 complete record is overlaid, with two close heatwaves highlighted by the red rectangle: despite higher temperatures, these heatwaves 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.

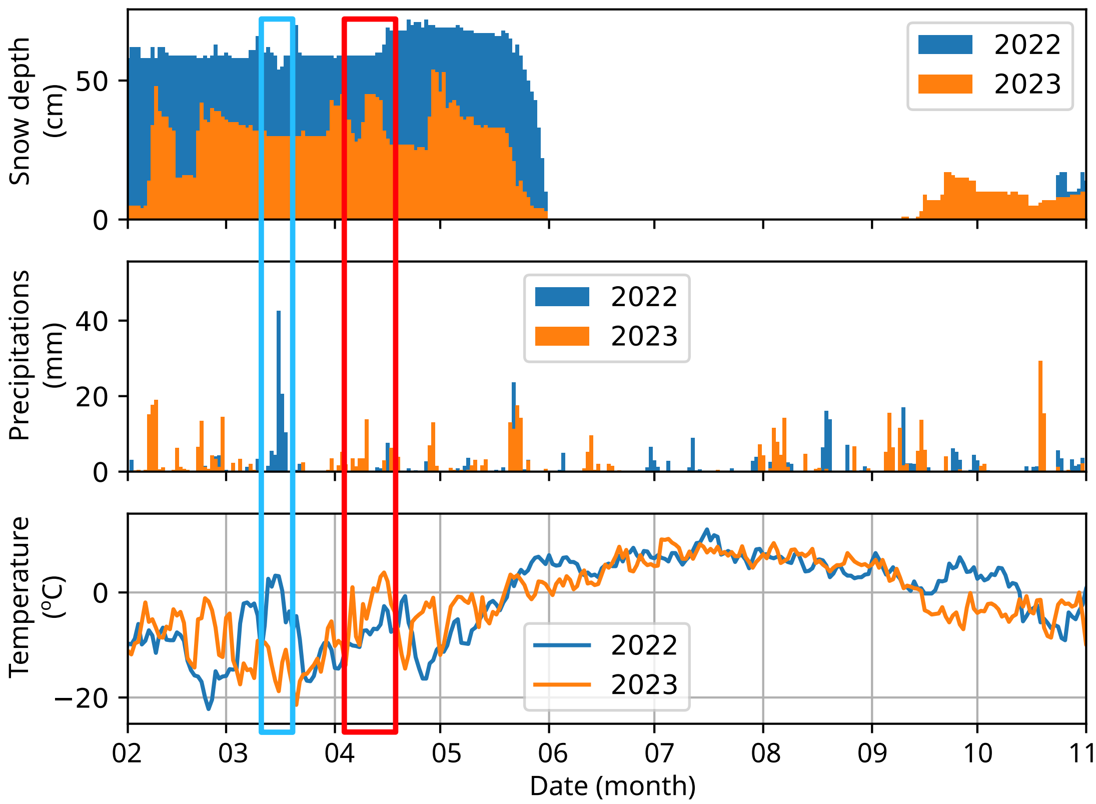

Figure 8. Weather records during 2022 (blue) and 2023 (red) from the `seklima.met.no` database for the Ny-Ålesund station. The warm event around March 15, 2022 is highlighted with the light-blue rectangle, including the heavy precipitation (middle chart). Two warm events in close succession are highlighted with the red rectangle. Despite higher temperatures reached during the 2023 event with respect to the 2022 event, the former is not characterized with heavy precipitation (middle) and yet has also impacted the snowpack thickness (top).

5. Discussion

As observed during the year 2022, despite an initially visually similar condition with 2023 (Fig. 1), the heatwave that generated intense liquid precipitation over AL (Fig. 4) mainly induced transformations of/into the snowpack (Fig. 5).

The consequence of the heatwave on the snowpack is not the same whether the latter is located on the glacier or in the periglacial environment: while the melt processes are the same, the mechanical instability leads to different outcome on the protection of the underlying surface by the snowpack. Fig. 8 suggests that the exceptional 2022 heatwave event did not have an impact on the snowpack at sea level. Indeed, on periglacial environments. i.e. on non-glaciated ground as shown on Fig. 8, the snowpack disappeared at the same time, June 1st, both in 2022 and 2023.

This result contrasts with observations under the same conditions of the snowpack on the glacier (Fig. 9) quantified as the Fractional Snow Cover (FSC). Picture analysis suggests that the 2022 snowpack suddenly disappeared one month earlier, June 29, 2022, than at the same period in 2023 since still fully snow covered on July 29th, 2023. Indeed, the glacier surface acts as a sliding plane that facilitates the disappearance of the snowpack when it exhibits low mechanical resistance, i.e. when saturated by a high LWC. This corroborates the measurements of the Smartstake whose data analysis demonstrates 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 are mostly similar for both years, leading 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 FSC evolves and how long the glacier remains protected from melt by the snowpack. While 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 since the heavier snowpack vanishes 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 is due to the snowpack sudden rupture rather than progressive melt.

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 factor 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 actually the perfect experiment to demonstrate that the snowpack structure has an impact on how it vanishes, especially onto the glacier surface.

6. Conclusion

Initially focusing on the March 2022 heatwave resulting from the atmospheric river running through Arctic and Antarctic regions and its impact on the Austre Lovén glacier in the Brøgger Peninsula in Spitsbergen, Arctic Norway, we have observed a long glacier ice melting season resulting from an early disappearance of the snowpack. However comparison with the 2023 (and 2021) weather records highlights repeated similar warm events during early spring. Whereas temperature remains the main trigger of ice/snow melt, 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 heatwave. This point is corroborated by the linear Fractional Snow Cover retreat in 2023, when the snowpack was not subject to intense moisture during winter and spring.

Figure 9. Date-to-date comparison 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.

The 2022 heatwave 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.

Acknowledgements

This project has received financial support from the French Centre National de la Recherche Scientifique (CNRS) through the MITI interdisciplinary programs. This work is supported by a grant of the Franche-Comté county (France) and the French Paul-Émile Victor Polar Institute IPEV.

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Appendix A. Weather records: 2021 v.s 2022

Weather records (Fig. 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 time scale is limited to February 1st to June 15 of each year to include the melt of the snowpack (reached June 10, 2021 and June 1st, 2022) since the temperature measurement started failing mid-May in 2021 and was only resumed beginning of September, preventing a Positive Degree Day index calculation during the melt season.

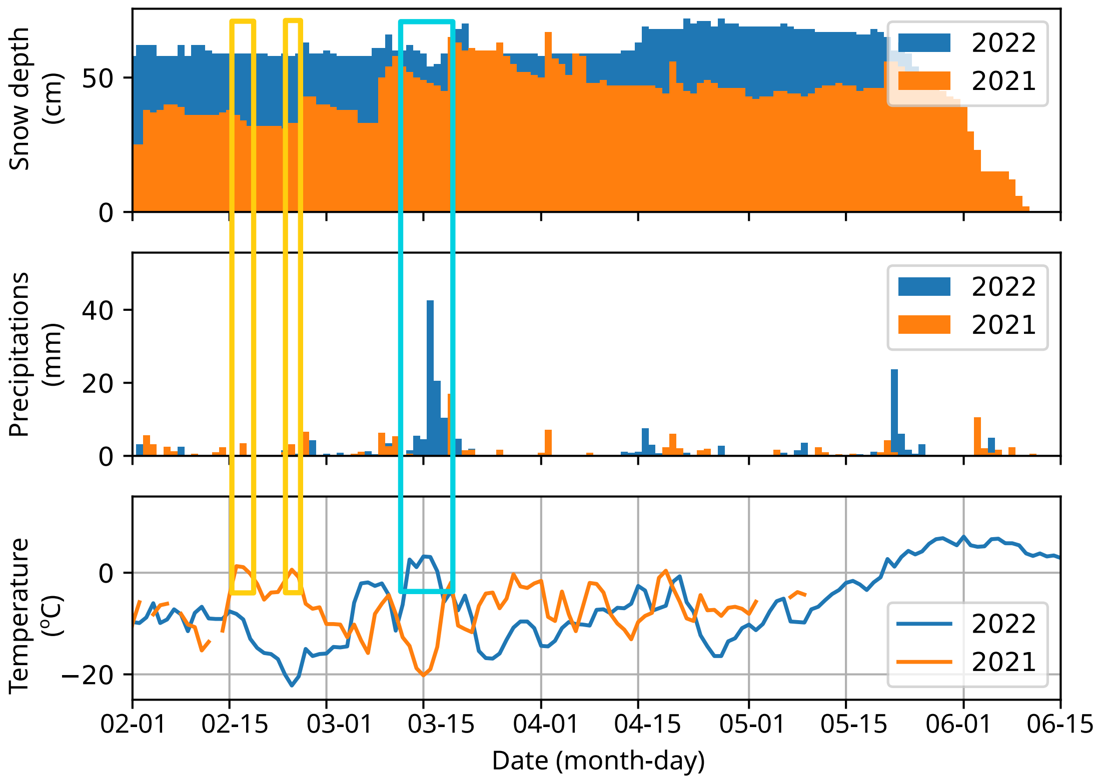

Figure A1. Weather records during 2022 (blue) and 2021 (red) from the `seklima.met.no` database for the Ny-Ålesund station. The warm event around March 15, 2022 is highlighted with the light-blue rectangle, including the heavy precipitation (middle chart). Two warm events in February 2021 are highlighted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