Climate change is rapidly deteriorating the climatic signal in Svalbard glaciers

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Abstract

The Svalbard archipelago is particularly sensitive to climate change due to the relatively low elevation of its main ice fields and its geographic location in the upper North Atlantic, where the effect of Arctic Amplification is most significant. The largest temperature increases were observed during winter, but higher summer temperatures, above the melting point, led to increased glacier melting. Here we evaluate the impact of this increased melting on the preservation of the oxygen isotope signal ($\delta^{18}O$) in firn records. $\delta^{18}O$ is commonly used as a proxy for reconstructing past atmospheric temperature and it is a crucial parameter to date and align ice cores when preserved. By comparing four different firn cores collected in 2012, 2015, 2017 and 2019 in the upper part of the Holtedahlfonna ice field (1100 m. a.s.l.), we show a progressive deterioration of the isotopic signal and we link its degradation to the increase in frequency and intensity of melt events. Although the $\delta^{18}O$ signal still reflects the interannual temperature trend, more frequent melt events in the future could affect the interpretation of the isotopic signal, compromising the use of Svalbard ice cores. Our results highlight the impact and the speed with which Arctic Amplification is affecting Svalbard cryosphere.

Introduction

The Arctic regions are experiencing a more rapid warming than the global average due to the so-called “Arctic Amplification” (Dahlke et al., 2020). The Arctic Amplification is caused by various feedback processes in the atmosphere-ocean-ice system and has a strong impact on the Arctic region of the North Atlantic. Arctic warming is not seasonally uniform, with the greatest impact in the winter months and near the surface (Rantanen et al., 2022a; Dahlke and Maturilli, 2017). Furthermore, it is not evenly distributed across the Arctic, with the highest warming rates occurring in the Barents/Kara Seas, where autumn and winter sea-ice retreat is strongest (Lind et al., 2018; Isaksen et al., 2022, 2016). However, there is also a significant warming signal at the tropospheric level in recent decades, peaking in the Svalbard region and more generally in the North Atlantic sector of the Arctic (Dahlke and Maturilli, 2017). Rates are up to four times higher than the global average since 1979 (Rantanen et al., 2022b).

Glaciers and ice caps in the Svalbard archipelago cover an area of \textasciitilde 34,000 km$^2$, which is about 6% of the world’s glacier area outside the Greenland and Antarctic ice sheets. The Svalbard glaciers contain $7740 \pm 1940$ km$^3$ (or Gigatonnes; Gt) of ice, enough to raise global sea level by $1.7 \pm 0.5$ cm if completely melted (Schuler et al., 2020; Geyman et al., 2022; van Pelt et al., 2019). They are experiencing some of the fastest warming on Earth (Noël et al., 2020) as a result of Arctic Amplification and are located at the edge of the retreating Arctic Sea ice.
Current climate trends are also influencing Svalbard’s seasonal snowpack status (Østby et al., 2017; van Pelt et al., 2016). The number of days of snow cover on the ground has decreased from 253 (1976–1997) to 219 (2006–2018). The change in Svalbard’s climate has strong implications for the entire environment of the archipelago. There has been an increase in the frequency of Rain on Snow (RoS) events (Wickström et al., 2020) resulting in pervasive ice layers (Sobota et al., 2020) covering the ground and limiting access to food for reindeers (Peeters et al., 2019). The reduction in sea ice limits and changes the hunting area of polar bears. From a climate perspective, the transition from one regime to another is gradual and takes centuries, as shown by paleoclimatic studies, such as ice core investigations. Ice cores contain information about past climate conditions and atmospheric composition, including traces of natural events (such as volcanic eruptions), past temperature reconstructions (Wolff et al., 2010) and anthropogenic pollution (Vecchiato et al., 2020). Such studies have shown that rapid climate change has occurred in the past. During the last glacial period in the Arctic, the so-called Dansgaard-Oeschger events occurred when temperatures increased by about 5°C (Boers, 2018). However, even during these natural abrupt events, a complete transition from stadial (glacial) to interstadial (warm) conditions took about a century (Scoto et al., 2022; Steffensen et al., 2008). The current temperature increase in Svalbard is much faster than that observed during the D-O events, with the mean annual surface air temperature increasing on average by +1.3 K ± 0.7 K per decade and the mean winter temperature by +3.1 ± 2.4 K per decade (Dahlke et al., 2020; Maturilli et al., 2013).

Snowmelt and water percolation at the sampling site can move the chemical constituents across the layers (Spolaor et al., 2021; Avak et al., 2019) disrupting the original signal. Prolonged events can even completely compromise the preservation of the climatic information contained in ice cores. Avak et al. (2019) showed that atmospheric composition was well preserved in an Alpine ice core during the winter, but that the melting in the spring and early summer caused a preferential loss of certain major ions and trace elements. In particular, the elution behavior of major ions is most likely controlled by redistribution processes occurring during snow metamorphism, as highlighted by a recent work investigating the distribution of impurities in the ice matrix (Bohleber et al., 2021). Differential mobility of the different chemical species has also been observed for trace elements, although it has been suggested to be better preserved than major ions (Avak et al., 2019). Antarctica and the Greenland Plateau are the best locations for such studies because the temperature is below the melting point (<0°C), although rare melting events occur in the Greenland plateau (Bonne et al., 2015). However, ice cores retrieved from these sites do not provide regional climate information. To overcome this limitation, many other drilling sites have been investigated, for example in the Alps (Arienzo et al., 2021; Gabrielli et al., 2016; Schwikowski et al., 1999) the Himalayas (Thompson et
al., 2018; Dahe et al., 2000), the Andes mountain range (Hoffmann et al., 2003), the Canadian Arctic (Zdanowicz et al., 2018) and the Svalbard archipelago (Isaksson et al., 2005; Wendl et al., 2015).

There are several ice caps in Svalbard, but due to their relatively low elevation, most are not suitable for preserving a pristine climate archive. The glacier equilibrium line altitude (ELA) varies across the different regions of the archipelago but is generally situated between 300 and 700 m asl. (van Pelt et al., 2019). In the southern part of the archipelago, the ELA is lower due to the higher winter snow accumulation, while in the northern part, the ELA rises to 600-700 m. Signal preservation requires drilling to be above the ELA to ensure regular snow accumulation, but also, so that summer percolation only moderately affects the upper firn layers.

Several drilling campaigns have collected ice core records in the archipelago, particularly in the northern part. The longest (in time coverage) ice-core record was collected from Lomonosovfonna, at 1230 m asl, covering ~1200 years of Svalbard climate history (Divine et al., 2011). Other ice cores have been collected from Austfonna (750 m a.s.l.), covering approximately 900 years (Watanabe et al., 2001), Vestfonna (600 m a.s.l.) covering approximately 500 years (Matoba et al., 2002) and Holtedahlfonna (1140 m a.s.l.) covering approximately 300 years (Beaudon et al., 2013).

To assess the robustness of Svalbard ice cores for future climate studies, we have analysed the oxygen isotope composition (δ¹⁸O) of a sequence of four shallow ice cores collected from the top of the Holtedahlfonna ice field in different years, each covering an overlapping atmospheric deposition period, to provide an overview of the evolution of the isotope stratigraphy through time. We focus our study on δ¹⁸O because it is the most widely used parameter in the ice core science for reconstructing past temperature change (Divine et al., 2011; Stenni et al., 2017) and, compared to the other chemical parameters analysed in ice cores, it is least affected by melting and percolation events (Pohjola et al., 2002). Several studies dealing with different elements and compounds have already been carried out using shallow cores from the top of the Holtedahlfonna ice field, demonstrating the importance of the site for climate studies (Burgay et al., 2021; Barbaro et al., 2017; Ruppel et al., 2017; Spolaor et al., 2013). The results were linked to glacier mass balance measurements and snowpack modelling. Based on our results, we observed that the climate signal is progressively deteriorating, although long term (>5 years) climate variability still seems to be preserved. This highlights the urgency for obtaining records to understand climate processes in one of the most rapidly changing environments on Earth.

2. Methodology

2.1 The Holtedahlfonna ice field
Holtedahlfonna (HDF – Figure 1) is the largest ice field (ca. 300 km²) in northwest Spitsbergen, located approximately 40 km from the Ny-Ålesund research station. It covers an elevation range of 0–1241 m a.s.l. (Nuth et al., 2017) and the upper part of the glacier, located approximately at 1100 m a.s.l., has a positive annual snow mass balance of about +0.50 m w.e. a⁻¹ (Beaudon et al., 2013; van Pelt et al., 2019). The site has already been studied for long term paleoclimate reconstruction, covering the past 300 years (Divine et al., 2011; Goto-Azuma et al., 1995). In April 2005, a 125 m a long ice core was drilled using an electromechanical corer and the bottom temperature in the borehole was −3.3°C, ensuring cold ice conditions throughout the ice thickness. The ice temperature measured in the borehole featured a maximum of −0.4°C at a depth of 15 m, indicating firm warming due to the release of latent heat from refreezing (Beaudon et al., 2013).

2.2 The Holtedahlfonna shallow firn cores: collection and processing

In the spring seasons of 2012, 2015 and 2017, a total of four shallow cores were collected from the top of the Holtedahlfonna ice field (79°09′N, 13°23′E; 1150 m. a.s.l.). Shallow cores were collected using a 4" fiberglass Kovacs Mark-II ice corer driven by an electric drill, reaching depths of 7-10 m into the firm. All shallow cores were drilled from the bottom of snow pits at the interface between the annual-seasonal snowpack and previous year’s summer snow surface. The length and density of each firn core section was logged, stored in plastic sleeves and transported to Ny-Ålesund for laboratory analysis. For cores collected in 2012, 2017 and 2019, core samples were processed in a class-100 laminar flow hood at the laboratory of the Italian research station “Dirigibile Italia” in Ny-Ålesund at room temperature (15°C). Each core section (max 50 cm length) was removed individually from the freezer and immediately cut into pieces of 5 to 7 cm length using a ceramic knife. For each piece, the outer 1–2 cm layer of the firn core was removed and samples were collected from the inner part of the core. Density was measured for each core piece produced before the outer part was removed. The preparation of each core section takes approximately 5 to 10 minutes, short enough to avoid any visible melting. The core collected in 2015 was processed in a similar way, but in a freezer laboratory (−22 °C) using a thin blade band saw (Ruppel et al., 2017).

2.3 Oxygen stable isotope analysis (δ¹⁸O)

The samples for oxygen isotope analyses (δ¹⁸O) were melted at room temperature (≈20°C) and transferred to 2-mL clear glass vials filled to the top. Samples were kept refrigerated at +4°C and analyzed at Ca’ Foscari University of Venice (2017 and 2019) and Tallinn University of Technology (2012 and 2015). In both cases, the isotopic measurements were performed using a Picarro L1102-i analyser coupled to a CTC Pal autosampler. The instrument uses Cavity Ring-Down Spectroscopy (CRDS) technology, which is based on the unique near-infrared absorption spectrum of each gas-
phase molecule. The autosampler injects the melted sample into the vaporizer (set at 110°C), where it becomes gaseous and is then transferred into the cavity (nitrogen is used as the carrier), where the measurement takes place. The instrument datasheet reports an analytical precision of ± 0.10 δ‰ for δ¹⁸O. Each sample was injected eight times: only results within ± σ of the eight replicates average were kept for records, while outliers were discarded. Internal isotopic standards, periodically calibrated against IAEA-certified standards (V SMOW 2 and SLAP 2), were used for calibration.

2.4 Holtedahlfonna surface mass balance

The surface mass balance (SMB) of Holtedahlfonna is monitored by the Norwegian Polar Institute (Kohler, 2013). SMB is obtained from repeated field visits at the end of winter and summer, with winter snow-depth sounding and density measurements and repeated height readings of an array of stakes along the glacier centerline. The balance estimates are extrapolated to the entire glacier basin by determining the balance as a function of elevation and averaging them, using weights determined from the distribution of glacier area as a function of elevation. This method quantifies the glacier-wide SMB, i.e. the mass changes at the surface of the glacier and within the near-surface layers, but does not include internal mass changes below the last summer surface. SMB measurements at Holtedahlfonna started in 2003; as the drill site is in the accumulation area, these measurements provide information on seasonal accumulation, but neglect the internal accumulation that can occur due to refreezing of meltwater in layers below the last summer surface. The uppermost part of the Holtedahlfonna (HDF) has a consistently positive mass balance and is therefore expected to retain most of its annual snow accumulation.

2.5 Estimation of Meteorological condition at the summit of the Holtedahlfonna ice field

In absence of in-situ meteorological measurements at the drill site, we obtained long-term seasonal (DJF, MAM, JJA and SON) temperature and precipitation series from the high-resolution CARRA dataset (Copernicus Arctic Regional Re-Analysis, Schyberg et al., 2020). This 2.5 km resolution product, covering the period 1991-2020, is downscaled from ERA5(Hersbach et al., 2020) using the state-of-the-art weather prediction model HARMONIE-AROME (Bengtsson et al., 2017). CARRA has several improvements compared to ERA5, including the assimilation of a large number of additional surface observations, extensive use of satellite data, and improved representation of sea ice, and is therefore likely to provide the best estimate of meteorological conditions in the Barents Sea region. The CARRA reanalysis is also used to force the CryoGrid community model (Westermann et al., 2023) to simulate glacier mass balance, seasonal snowpack evolution and meltwater runoff over...
Svalbard Franz-Joseph Land and Novaya Zemlya. The model couples the surface energy balance and a multi-layer subsurface module to resolve meltwater production, percolation, storage, refreezing and runoff, taking into account the interaction with local density and temperature stratigraphy. The vertical discretization includes 47 layers of variable vertical extend to cover the top 20 m below the surface (Steffensen Schmidt et al., 2023).

3. RESULTS

3.1 Shallow firn core dating and alignment

To date the core, we use the seasonal cycle (where available) of the δ¹⁸O data together with the mass balance data available since 2003. Core depths have been converted to water equivalent using the density data acquired during the core processing. The density for the 2015 core is taken from Ruppel et al., (2017), the 2012 values are published in (Spolaor et al., 2013), and the density for the 2017 and 2019 cores are presented in this paper. The density profiles of the four shallow cores (Figure S1) all show a similar pattern/ range of values.

The cores were collected within 50 m of the mass balance stake HDF-10. The stake measurements, which show a consistently net positive mass balance, provide a historical record of snowpack accumulation that can be used to directly assign a specific year to a range of firn core depth (Figure 2).

Oxygen stable isotopes (δ¹⁸O) can be used independently to date the ice annually, but only in ice core archives where the seasonal signal is well preserved. This means that snow accumulation must be sufficiently high, and the summer ablation should not compromise the stratigraphy by redistributing and smoothing the original atmospheric signal. The thinning of the firn layer at the top of the Holthedalhoffna glacier can be considered negligible for the depth coverage of our shallow cores (max 15 m). By combining the annual accumulation and the core depth expressed in water equivalent and the seasonality of δ¹⁸O (where available and preserved), we can date and align all four cores (Figure 3).

The cores cover 14 years (2004 to 2018). The time coverage for each core is shown in Table 1, along with additional information for each firn core. The 2012 core had an average δ¹⁸O value of -15.3 ± 1.0 ‰, the 2015 core a value of -15.1 ± 0.8 ‰, the 2017 core an average value of -14.4 ± 0.7 ‰ and the 2019 core an average value of -14.1 ± 1.2 ‰. All the cores have an overlap period and show a general increasing trend in δ¹⁸O from 2004 to 2018 (Figure 3). In particular, the 2012 and 2015 cores show similar trends, especially in 2005-2006, which is also useful for core alignment. They also show similar trends in the remaining periods that they each cover, albeit with minor differences. The high values of δ¹⁸O found in the 2013 and in the 2015 core are also clearly found in the 2017 core, helping...
to synchronize the records. The alignment of the 2019 core with the previous cores could only be done using mass balance values, as the $\delta^{18}O$ values did not show the same peaks as the other records. In particular, the decrease in $\delta^{18}O$ values recorded in the period representing 2016 was not present in the 2017 core.

3.2 Meteorological condition at the Holtedahlfonna ice field summit

The meteorological conditions at the summit of the Holtedahlfonna ice field from 1991 to 2020 were retrieved from model re-analysis and provide a clear overview of the ongoing changes at the site. The annual mean winter temperatures (DJF) at the HDF summit (located at 1100 m a.s.l.) ranged from -25°C to -15°C and show an increasing trend of 2.37°C per decade for the period 1991–2020 (Figure 4a - blue line). The annual mean spring and summer temperatures (MAM) ranged from -17°C to -12°C (Figure 4a - green line) and -5°C to -1°C (Figure 4a - red line), respectively. The average temperature increase per decade since 1991 was 0.38°C for spring and 0.51°C for summer. The temperature during fall (SON) increased by 1.47 °C per decade and ranged between -15°C and -5°C (Figure 4a - brown line).

Although the mean seasonal summer temperatures were below the water melting point, positive degree days (PDD – Figure 4b, expressed as the sum of mean daily temperatures for all days during a period where the temperature is above 0°C), occurred at the summit of HDF, causing the snowpack to melt. The cumulative annual PDD, derived from the model temperature series outputs, showed a stable value for the period 1990 to 2015, although some years (1994, 1999, 2010) and periods (2001–2006) were characterized by an increased PDD. A net increase was observed from 2015 to the present. The melting of snow at the site was clearly visible and confirmed by the presence of several ice lenses in the core (Burgay et al., 2021; Spolaor et al., 2013).

The model estimated annual precipitation (1991–2020) ranged from 63.0 to 117.0 cm w.e. per year, with a slight increase in the most recent period (Figure 4d). A similar trend was also observed in Ny-Ålesund (Førland et al., 2020). Seasonal precipitation (Figure S2) was highest during fall (SON) and winter (DJF), with mean precipitation of 28.6 cm w.e. and 27.4 cm w.e. respectively, and a relative mean contribution to total deposition of 32% and 31%, respectively. The lowest precipitation occurred in spring (MAM) and summer, with mean precipitation of 17.0 cm w.e. and 14.5 cm w.e., respectively, representing a mean contribution of 20% to total deposition in spring and 17% to total precipitation in summer.

Although the annual mass balance was always positive, the summer mass balance was both positive and negative depending on the meteorological conditions (Figure 2). Winter accumulation accounted for between 60% and 100% of the net annual mass balance at the site. Although the summer mass
Balance data from 2015 to 2020 were positive, melting also occurred and water percolated into the snow and firn before refreezing.

Most of the melting occurred during the summer period (JJA), but melting events also occurred during fall and late spring (Figure S3). The estimated annual melting at the site from 1991-2020 (Figure 4c) varied between 96.0 cm w.e. (2020) and 11.7 cm w.e. (2008) and showed a clear increasing trend with increasing temperature. In addition, autumn snowmelt events, which were previously rare, became a more regular phenomenon in the period 2015 to 2019. However, spring snowmelt is sporadic (2011) and rare (Figure S3).

In addition to the meteorological reanalysis from the HARMONIE-AROME model, the CryoGrid simulation provided information on the presence of liquid water in the firn and its percolation (Figure 5). Percolation was mainly confined to the surface layer between 1991 (start of simulation) and the late 1990s (except 1999). Percolation increased significantly from 2000 onwards. In particular, the period 2004-2005 was characterized by strong surface melting events (Figure 2c and Figure S3), which caused water percolation over several metres (Figure 5). The period 2006-2014 was characterized by relatively limited surface melting and the lowest amount of percolated water, which did not exceed one (2006 and 2008) to four (2010 and 2011) annual snow accumulation periods.

Based on the model’s calculations, water percolation has increased since 2014 and has been able to reach deeper firn layers. Although the model suggests the presence of liquid water in the firn, water and elution channels are complex to simulate and are likely to have high spatial variability. Therefore, we only consider the data presented in Figure 5 in a qualitative manner to assess the possible presence or absence of liquid water in the snowpack and its theoretical penetration/percolation depth.

4. DISCUSSION

The aim of this paper is to evaluate the effect of temperature rise on the preservation of $\delta^{18}$O in the Holtedahlfonna ice core signal. Our discussion will focus only on the periods covered by the shallow cores.

Based on the $\delta^{18}$O records of the four shallow cores, it is evident that the seasonal signal has undergone considerable changes and has progressively deteriorated in the most recent cores (Figure 3). The most important parameters affecting the original atmospheric signal trapped in the snow are the amount of snow melt, which depends on the snow and meteorological conditions, and the infiltration of melt water into the snowpack.

In the core collected in 2012 (Figure 3), the seasonal variations are clear for almost the entire period except for 2004-2005, a period characterized by significant summer melt that disturbed the...
atmospheric signal trapped in the ice. However, for the period 2006-2011, the seasonality is clear and each δ18O seasonal cycle is confined within the annual snow mass balance measurements.

The 2015 core still showed the seasonal cycle in the upper half of the core, corresponding to the periods 2010-2014. However, the seasonal feature of the δ18O identified in the core 2012 for the periods 2008-2009 was no longer present, suggesting a possible elution caused by the percolation of liquid water (Figure 5). The model simulation supports the possibility that post-depositional events may have occurred within the firn due to the percolation of liquid water.

The most striking change in terms of the δ18O seasonal cycle occurred in the 2017 core. The 2017 core overlapped with the 2015 core for the period 2012-2014 and, while the seasonality for this period was well defined in the 2015 core, only the seasonal δ18O for the year 2013 was visible in the 2017 core. The δ18O seasonal cycle of 2014 has been significantly smoothed and the δ18O seasonal cycle of 2012 is no longer visible. For the period 2015-2016, the seasonal cycle was not clear, although oscillations were still present.

In the latest core, collected in 2019, a seasonal δ18O cycle was no longer detectable and particular features, such as the δ18O signal drop in 2016 (not observed in the 2017 core), were not associated with a drop in the temperature, as 2016 was the warmest year on record (Figure 6, black dots).

Two independent statistical analyses, one using the significant value of a regression model and the other using the spectral analysis, were performed on the shallow core records to test the presence of seasonal oscillation on the δ18O signal. Both statistical analyses demonstrated the disappearance of the seasonal signal in the most recent (2017 and 2019) shallow cores (full details are reported in the supplementary material - section 2).

The change in seasonality and, to a lesser extent, total precipitation, may have influenced the δ18O signal of the four cores. However, the model results show that the seasonal contribution to the total annual precipitation did not change significantly (Figure S2). This suggests that precipitation does not play a central role in explaining the degradation or possible change in the δ18O signal, and that increased melting and water infiltration may have had a greater effect. Instead, the increase in year-round precipitation may have increased meltwater formation during the summer periods. The preservation of the ice core climate signal is strongly dependent on the amount of summer snowmelt and the ability of water to percolate through the snowpack, which in turn is controlled by snow temperature. Progressive atmospheric warming, increased summer melt and water percolation, and water movement within the snowpack could have affected the δ18O signal present in the Holtedahlfonna firn/ice.

The progressive degradation and loss of the seasonality of the δ18O signal in the shallow core (2004-2018) is also supported by the results of the δ18O signal in the 2005 core. In the deep core collected...
in 2005, the seasonal signal of the δ¹⁸O was well preserved for the period 1960 to -2000 (Figure S5).

The signal determined in the 2005 Holtedahlfonna deep ice core had similar characteristics to those determined in the 2012 and 2015 shallow cores, where the seasonal oscillations were still partially present, but not to the signals determined in the 2017 and 2019 cores, where the seasonality in δ¹⁸O almost disappeared. We suggest that since 2015, the estimated melting and percolation had increased due to the evolution of the general atmospheric conditions, causing a deterioration of the climate signal preserved in the firm/ice.

Water stable isotopes are commonly used as a temperature proxy. By superimposing the water stable isotope profiles measured in the shallow cores (shown in Figure 3) and, comparing their trends to the annual mean temperature, we suggest that the general atmospheric temperature trend is still preserved within the HDF ice (Figure 6), although some clear deterioration is visible. For example, the highest annual temperature values recorded in 2016 were not reflected in the δ¹⁸O record from the 2017 and 2019 cores. This highlights the impact of high temperatures on the preservation of pristine atmospheric signals in ice cores, where temperature values have had a significant impact on the preservation of the atmospheric signal.

5. Conclusion

An ice core drilled at the summit of Holtedahlfonna has previously been used to provide atmospheric and climate conditions about the past 300 years (Beaudon et al., 2013). Prior to 2005, the site was characterized by moderate summer melt, but the snow and ice were shown to preserve important climate information as well as key seasonal features. The current warming of the Svalbard archipelago has clearly enhanced glacial mass loss, with an increase in the equilibrium line altitude and a shorter snow season. This study is the first to investigate the impact of rising temperatures on the preservation of climate signal within firm/ice in one of the highest ice fields in Svalbard. The direct effect of higher temperatures has been to increase summer snow melt and water percolation. In this study, we have shown that the climate signal preserved in the ice has been progressively deteriorated.

For example, in seven years, the seasonal signal visible in the 2012 core has completely disappeared in the 2019 core, most likely due to increased snow summer melting and water percolation. However, although the δ¹⁸O seasonal signal has disappeared, the overall atmospheric warming signature is still preserved in the ice/firn, suggesting that the site is still suitable for long record paleoclimate reconstruction. However, with the current rate of warming in the Svalbard archipelago and the resulting increase in summer melt, Holtedahlfonna and other ice fields at similar altitudes may no longer provide suitable records of climate conditions. Glaciers worldwide are currently losing not only mass at unprecedented rates, but also the climatic information they contain.
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Author contribution

AS, EB, FS, JCG, CL, MB, JG, FB, and DC conceived the experiment and collected the samples and wrote the paper with the support of all co-authors; CT, TM, GD and BS analyze the samples; JK provide the field mass balance data and contribute in data interpretation; LSS and TVS provide the model data and atmospheric re-analysis; FdB and MC perform the statistical exercise and contribute in data interpretation. BL and FD contribute to data interpretation. DD and EI provide the data from previous ice core and contribute to data interpretation.

Data availability

The data will be available upon request to the corresponding author.

Competing interests

The authors declare that they have no conflict of interest.
Figure 1. Location of the drilling site (red star) within the Holtedahlfonna (HDF) ice field as compared to the Ny-Ålesund research village (NyA). Maps from https://toposvalbard.npolar.no (last access: 5th June 2023).
Figure 2. Mass balance measurements, modelled precipitation and snow melt at the drilling site. a) cumulative surface mass balance (SMB) expressed in cm of w.e., b) comparison of modeled total annual precipitation (green – in cm w.e) and modeled melt (red in cm w.e). c-e) net, winter and summer mass balance (cm w.e.) measured at the top of the Holtedahlfonna ice field, respectively.
Figure 3. Oxygen stable isotope profiles $\delta^{18}O$ of the four shallow cores. The shallow core was aligned by converting the depth to depth expressed in cm of w.e. using the annual mass balance (MB) data. The white and pink colors distinguish different years based on the MB measurements presented in Figure 2.
Figure 4. Modeled meteorological conditions at the Holtedahlfonna shallow core drilling site (1150 m a.s.l.) from 1991 to 2020 at seasonal resolution. a) winter (DJF - blue), spring (MAM – green), summer (JJA – red) and fall (SON – brown) temperatures, with increasing trend line for the period investigated; b) annual Positive Degree Days (PDD) value (grey); c) annual melting (in cm w.e in red); d) annual total precipitation (in cm w.e. – blue)
Figure 5. Evolution of the water content in the snowpack at the top of Holtedahlfonna estimated by model simulation between 1990 and 2020. The chart shows the volumetric water content (%) in the snow/firm (white to blue color), surface height evolution (black line), 0°C isotherm (red). Dashed lines show the period covered by the four shallow cores.
Figure 6. Estimated annual average temperature at the top of Holtedahlfonna ice field (black square) and the $\delta^{18}$O signal of the four shallow cores.
**Table 1. Shallow ice core descriptions.** The table reports the length expressed in cm and in water equivalent (w.e.) and the estimated (Est. start year; Est. end year) time coverage. The average density of the cores is also reported.

<table>
<thead>
<tr>
<th>Core ID</th>
<th>Length (cm)</th>
<th>Length (cm w.e.)</th>
<th>Ave density (kgL⁻¹)</th>
<th>Est. Start year</th>
<th>Est. End year</th>
<th>Drilling date</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2019</td>
<td>769</td>
<td>461</td>
<td>0.60</td>
<td>2018</td>
<td>2012</td>
<td>April 2019</td>
<td>This work</td>
</tr>
<tr>
<td>2017</td>
<td>736</td>
<td>466</td>
<td>0.63</td>
<td>2016</td>
<td>2010</td>
<td>April 2017</td>
<td>Burgay et al. 2017</td>
</tr>
<tr>
<td>2015</td>
<td>1185</td>
<td>832</td>
<td>0.70</td>
<td>2014</td>
<td>2005</td>
<td>May 2015</td>
<td>Ruppel et al. 2017</td>
</tr>
<tr>
<td>2012</td>
<td>954</td>
<td>575</td>
<td>0.60</td>
<td>2011</td>
<td>2004</td>
<td>April 2012</td>
<td>Spolaor et al. 2013</td>
</tr>
</tbody>
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