



Brief communication: Ice older than a century at Triglav Glacier and Skuta Glacier – isotopic characteristics of glacier remains in Southeastern Alps, Slovenia

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Abstract. The Triglav Glacier and Skuta Glacier are the last remaining, although disappearing, surface ice masses in Slovenia. Based on environmental tracer profiles, the ice between 0–100 cm predates the 1960s at Triglav, suggesting negative net accumulation since the early 1960s. Ice below 1 m is older than 70 years. Skuta Glacier shows similar patterns, though deeper layers are affected by percolation water. Skuta Glacier shows relatively stable deposition (~5.5 cm/year) from the 1860s to 1960s, while Triglav Glacier had lower and declining rates (3.8 cm/year before 1900, dropping to 2.1 cm/year by the 1960s).

1 Introduction

Over the past decade, climate change has led to the retreat of many glaciers and the fragmentation of larger glaciers into smaller ones, often referred to as glacierets if they still show at least minimum motion or ice deformation or ice patches when the ice masses became completely static (Hughes and Woodward, 2009). As sensitive indicators of climate change, glacierets respond rapidly and visibly to temperature variations while still preserving hydroclimatic archive information, making them important targets for palaeoclimate and hydrological studies (Bahr and Radić, 2012; Grunewald and Scheithauer, 2010; Del Gobbo et al. 2016;). However, the unique nature and locally varying impacts of current global climate change necessitates more evidence from various proxies and from earlier periods.

Since 1850, the Alps have lost about 50% of their ice (Reinthal and Paul, 2025). This rapid glacier decline is evident in European mountain systems, including Slovenia, Austria, Italy, Switzerland, and the Balkan countries. Currently, the Triglav Glacier and Skuta Glacier are the only remaining surface ice masses in Slovenia since the last extensive Pleistocene glaciation (Zorn et al. 2020). Due to their relatively low altitude (<2500 m asl), these ice masses are highly vulnerable to climate change, particularly temperature increases and changes in precipitation patterns. As a result, they no longer exhibit all the characteristics of Alpine glaciers and are now considered as a glacieret (Skuta Glacier) and an ice patch (Triglav Glacier).

The effects of climate change are also evident from the fact that all ten warmest melting seasons recorded have occurred in this century, with four out of the five warmest since 2012. The other ice mass, located under Skuta mountain, is the most southeastern glacier remnant in the Alps. It retreats more slowly than the Triglav Glacier because it is surrounded by a mountain ridge from the south and remains in the shadows for longer periods (Triglav Čekada et al. 2020).

Although both Slovenian ice masses now measure only 1.7 hectares and have significantly declined, they still offer valuable information on the past glacier behavior. Here, we study the last remnants of glaciers in Slovenia to understand how climate



has changed over time and how glaciers have responded to these changes. Knowing the age of ice masses and their historical behavior allows us to predict how they might respond to current and future climate change.

In the present study, we have applied stable and radioisotope techniques to date ice layers retrieved from two Slovenian glacier remnants that are at risk from disappearing. Our results on dating glacial remains in the Alps provides significant information
45 for climate science, environmental studies, and understanding the Earth's history and environment. The results of such studies based on the multi-isotopes approach can be used to assess how changes in glacial extent and volume affect local ecosystems, including freshwater availability and habitat for various species.

2 Site description

The Triglav Glacier and the Skuta Glacier (SE Alps) are the last two remaining surface ice masses in Slovenia that originate
50 from the last Pleistocene glaciation (Triglav Čekada et al., 2020; Triglav Čekada and Zorn, 2020; Lipar et al., 2021). These ice masses are the southeasternmost glacial remnants in the Alpine region (Fig 1.). The Triglav Glacier is located at the rock wall base of the northeast face of Mount Triglav (2,864 m a.s.l.) in the Julian Alps (NW Slovenia) at elevations between 2,430 and 2,500 m a.s.l. (Gabrovec et al., 2013). The Skuta Glacier is located in the cirque below the northern walls of Mount Skuta (2,532 m a.s.l.) and Mount Kranjska Rinka (2,445 m a.s.l.) in the Kamnik-Savinja Alps at elevations between 2,050 and 2,150
55 m a.s.l. The bedrock around both glaciers consists mainly of Upper Triassic limestone and dolostone.

The size of the Triglav Glacier was app. 45 hectares 100 years ago and 14 ha in 1946. Over the past decade alone, from 2013 to 2022, the Triglav Glacier lost almost three times of its volume and is under threat of disappearing (Gabrovec et al., 2013; Del Gobbo et al., 2016; Triglav Čekada and Zorn, 2020). The extent of the Triglav ice mass at the time of sampling in August 2022 was less than 1 ha, while the extent of the Skuta ice mass was about 1 ha (~3 ha in the late 1940s). Ground penetrating
60 radar (GPR) measurements indicated that the average ice depth on Triglav Glacier was 1.4 m (maximum 5.5 m), and the average ice depth on Skuta Glacier was 4.9 m (maximum 9.5 m) (Supplementary Figure S1). The reasons for the decline of glaciers can be mainly attributed to the lower average snow depth in the last 30 years compared to the 130-year period before, the increase in summer air temperatures and duration of solar radiation from May to August over the last decades. The persistence of the Skuta Glacier, despite its much lower elevation compared to the Triglav Glacier, is attributed to the sun-
65 protecting topography of the cirque.

The climate at both glaciers is largely determined by the influx of moisture-bearing air masses from Mediterranean cyclones, especially in autumn and late spring, and by frequent freeze-thaw cycles (Lipar et al., 2025). It is characterized by high mean annual precipitation for the Triglav Glacier with 2059 mm/year in the period 1991–2020 (at Mt. Kredarica meteorological station (2,513 m) app. 300 m from the glacier; ARSO, 2023). At the Skuta Glacier, the mean annual precipitation is 1689
70 mm/year in the period 1991–2020 (at Mt. Krvavec meteorological station (1,748 m) app. 7.8 km SW from the glacier and app. 400 meters lower; ARSO, 2023), and the mean annual snow accumulation is 10.67 m. The maximum depth of seasonal snow cover on Kredarica is usually 3.79 m (1955–2023), which is usually reached in the first decade of April (ARSO, 2023) (Supplementary Figure S2).

The mean annual air temperature is -0.7°C at Kredarica and 3.8°C at Krvavec (ARSO, 2023), with February being the coldest
75 month and August the warmest. Long-term precipitation trends for the last 30 years, calculated for the period 1991–2020, show no significant changes in annual and seasonal precipitation amounts for Krvavec (Supplementary Figure S2). However, for Kredarica there is a decrease of 3.9% per decade in meteorological summer (June–August; ARSO, 2023) compared to the period 1950–2020. Long-term trends of snow accumulation at Kredarica show a decrease in seasonal maximum snow depth and mean new snow accumulation.

80 There is a clear and significant downward trend in snow cover and new snow accumulation between 1961–2020 in Slovenia (Hrvatín and Zorn, 2026), especially in the northwestern mountain region. During this period, the decrease in seasonal snow



depth in Kredarica is 20–30% and in mean new snow accumulation 10–20%. The obvious consequences are fewer days with snow cover and a shortening of the time in which precipitation falls as snow. The increase in temperatures has caused the snow line to be higher for each precipitation event.

- 85 Long-term temperature trends show, that mean annual air temperatures near the two glaciers increased by 1.3 °C between the 1951–1980 and 1991–2020 periods (up to 2 °C in some summer months; ARSO, 2023).

3 Materials and methods

- Ice cores were manually drilled by a hand auger (Mark II, Kovacs Ice Drilling and Coring Equipment) in August 2022. The retrieved ice cores were cut into 10 cm long sections samples for different isotope analysis (Supplementary Table S1) (Nigro et al., 2026). A plant stem was found in the upper part of the rocky layer, of which a sample was taken for ¹⁴C analysis. More details of sampling are presented in the Supplementary.

- Isotopic composition of hydrogen ($\delta^2\text{H}$) and oxygen ($\delta^{18}\text{O}$) was determined in all 152 collected ice core samples at JSI on a dual inlet isotope ratio mass spectrometer (Vreča et al., 2024). For analysis of tritium concentration (³H) in 31 merged ice core samples (Supplementary Table S2), the ³He-ingrowth method was used in HUN-REN Institute for Nuclear Research, Debrecen, Hungary (ATOMKI) (Palcsu et al., 2010). Caesium-137, beryllium-7 as well as lead-210 were analyzed in 20 combined ice core samples with gamma-spectrometry in ATOMKI. The radiocarbon (¹⁴C) content of the plant stem collected in the rocky layer at Triglav Glacier was analyzed by accelerator mass spectrometry (AMS) (Molnár et al., 2013) in ATOMKI. Technical details of the isotope measurements can be found in the Supplementary.

100 4 Results

- A total of 152 samples were analyzed for their stable isotope composition, 80 samples from Triglav Glacier and 72 samples from Skuta Glacier (Figure 2., and Supplementary Table S2). The Triglav Glacier has slightly lower $\delta^{18}\text{O}$ values compared to Skuta Glacier, with values ranging from -11.56 to -7.06 ‰ and from -10.32 to -5.92 ‰, respectively. The sample from the topmost 10 cm at Triglav Glacier, representing recent snow (see Discussion) has lower values than the firm below it. The lowest measured $\delta^{18}\text{O}$ values (-11.56 ‰) were found at the bottom sample at Triglav Glacier, that was cored to the base and was likely affected by the subglacial water fluxes. Such a situation is not observed at Skuta Glacier, which was not cored to the base, albeit the general shift to higher $\delta^{18}\text{O}$ values compared to Triglav Glacier might be due to increased meltwater circulation along the whole ice sequence, as observed during coring. On the other hand, Skuta Glacier is located at a lower altitude than Triglav Glacier.

- 110 Both Triglav Glacier and Skuta Glacier have similar $\delta^{18}\text{O}$ patterns (Figure 2). At both ice masses there is a general decrease to more negative values down to a depth of 80–100 cm, followed by slight increase in values and another shift to more negative values observed at depth of ~205 cm at Triglav Glacier and ~385 cm at Skuta Glacier. The $\delta^2\text{H}$ values show similar pattern to $\delta^{18}\text{O}$, while the d-excess values are generally lower with narrower range at Triglav Glacier compared to Skuta Glacier. The highest d-excess values at both ice masses are observed at the sections with significant shift to more negative $\delta^{18}\text{O}$ values.

- 115 A total of 27 ice samples were measured for ³H content, 15 samples from Triglav Glacier, and 12 samples from Skuta Glacier, with measured ³H concentrations between 0.05 to 6.9 TU. The topmost 0.8–1.0 m of both Triglav Glacier and Skuta Glacier have similar tritium concentration (5.5–6.9 TU), while the lower parts differ (Figure 2). At Triglav Glacier the values range between 0.05 and 0.015 TU below 1 m, while Skuta Glacier has significantly higher tritium content of 2.5 to 3.4 TU (Supplementary Table S3).

- 120 Radiocarbon analysis of the plant stem collected at depth of 0.9–1.0 m at Triglav Glacier (sample DeA-39760) gave $F^{14}\text{C}$ value of 1.018 ± 0.002 (Supplementary Figure S4). Based on this value several calibrated ages were obtained using the CALIBomb



calibration based on the NHZ1 calibration data set (Supplementary Table S4). Within 95% confidence interval, three ages are obtained: 1955.55 ± 0.20 , 2017.06 ± 1.08 and 2018.64 ± 0.13 cal AD. Significant amounts of ^7Be , ^{137}Cs and ^{210}Pb can be found only in the top 0.5 m of ice, while the deeper layers show low activity concentrations (Supplementary Table S5).

125 5 Discussion

5.1 Estimation of the age of the ice from radioisotopes

The difference in ^3H concentration at Triglav Glacier between the top and bottom parts (Fig. 3 and Supplementary Figure S5) indicates that the lower layers are older than 70 years, since it takes more than 70 years for natural level of tritium (5–8 TU) to decay below 0.15 TU (Palcsu et al., 2018; Vreča et al., 2022; Vreča et al., 2024). The bomb peak of 1963 cannot be obviously seen in the top 1 m of the record. To estimate the expected ^3H concentrations at Triglav Glacier from precipitation carrying the 1960s bomb-peak signal, the tritium record of Vienna (winter period) precipitation can be used, decay-corrected to the glacier sampling year (Supplementary Figure S5). Based on this, at the time of sampling in 2022, the precipitation fallen in the 1960s would have a mean ^3H concentration of 19 TU, while the precipitation fallen from 1980 to 2010 would have about 3–4 TU. The calibrated radiocarbon age of the plant fragment collected from the rocky layer at depth of 0.9–1.0 m, indicates that the plant stem grew either in 1955 or between 2016 and 2018 (Supplementary Figure S4 and Table S4). However, the later period is unlikely, as it would indicate that the top 1 m of firn ice accumulated in the last few years, which is contradictory with the observed melting and retreat of the ice mass. The calibrated radiocarbon age of 1955 AD at depth of ~1m is also in agreement with the observed ^3H concentration in the layers above (~6–7 TU), which is comparable to the decadal average of precipitation of the colder period (October to March) as recorded in the Vienna ^3H time series (Supplementary Figure S5). ^7Be , ^{137}Cs , and ^{210}Pb can be found in significant amounts only in the top 0.5 m of the ice. The presence of ^7Be only in the top layers can be explained by fall-out. ^{137}Cs can be derived either from the thermonuclear weapon tests of 1950s and 1960s or the Chernobyl disaster in 1986, and its highest concentrations in the top layers is contradictory to the observation from the other radioisotopes (i.e., no bomb peak detected). The radioisotopes representing recent fallout are related to dust layers found on the surface of the top 10 cm represented by recent snow (winter 2021/2022), as well as at bottom of the snow layer, at the contact with the firn ice (depth datum 0 cm). With parts of the dust layer at 0 cm depth likely collected in both top samples (-10 to 0 cm and 0 to 30 cm), possible explanation for the contradictory distribution of radioisotopes is that the dust layer at 0 cm depth is the carrier of the bomb-peak or Chernobyl ^{137}Cs signal, as the ice originating from the 1960s and younger has already melted. The melting is also consistent with the observed trend of increase in air temperatures for the region since the 1980s (Supplementary Figure S2). At Skuta Glacier, the top part has similar concentrations of radioisotopes, and likely is of similar age as the top part at Triglav Glacier (younger than 1950s). However, contrary to Triglav Glacier, the ^3H concentration in the lower part is much higher, and reflects subsequent contamination by percolating meltwater. The later was observed during coring, and might also explain the slight shift of stable isotope composition to higher values.

5.2 Age-depth modelling by tuning the $\delta^{18}\text{O}$ record.

To constrain the age of the lower part of the ice cores, the reconstructed temperature from lake Jezero v Ledvicah app. 6.5 km SE from the Triglav Glacier (Battarbee et al., 2002) was used to tune the age-depth model, based on the observed similarity to the Triglav Glacier and Skuta Glacier $\delta^{18}\text{O}$ pattern. Composite $\delta^{18}\text{O}$ records were created for each ice mass by averaging the values of the different extracted cores according to their depth, excluding the top and bottom samples at Triglav (snow at the top and meltwater affected at the bottom). The tie-points used were defined by the ^{14}C determined age (1955.55 cal AD) at depth of 95 cm at Triglav Glacier, and by visually defined tie-points compared to the Jezero v Ledvicah record (Supplementary Table S6).



The obtained age-depth models (Figure 3) were evaluated using cross-wavelet coherence and Bayesian change points. They show an enhancement in the coherence between the records and detection of masked change points in the records (Supplementary Figure S6).

165 Based on the obtained model, the ice in the bottom parts is estimated to have deposited in the 1840s at Triglav Glacier and 1850s at Skuta Glacier. As the lowermost part of Skuta Glacier was not cored to the base, the ice there might be even older. However, the age-depth relationship of the sections below and above the bottom and top tie-point, respectively, are not fully constrained, and are extrapolated from the age-depth model of the neighboring section. For the upper part at Triglav Glacier, the tuning-based age of 1955 to 1999 AD is not likely, as indicated by the absence of the bomb peak in the ^3H record of this
170 section. The age of this section, as demonstrated above, is constrained between the ^{14}C -obtained date of 1955.55 cal AD and the beginning of the 1960s (bomb peak), reflecting melting of the top parts of the glacier in the last 60 years. The extrapolated growth rate for the lower sections might be more realistic, especially given the constant growth rate during the 20th century at Skuta Glacier. Nevertheless, the modelled age for the oldest parts should be taken with caution.

For both glaciers, based on the tuned age-depth model, the depositional rate can be estimated between the selected tie-points
175 (Figure 3C). Skuta Glacier shows higher and more stable depositional rate from 1860s to 1960s (about 5.5 cm/year). Triglav Glacier has much lower depositional rate which is estimated at about 3.8 cm/year until the 1900s, that decreases to about 2.1 cm/year between 1900s and 1960s. The difference in estimated depositional rates is consistent with the topographic setting of the ice masses, with Skuta Glacier, although located at lower elevation, better sun-protected within a deep cirque.

6 Conclusions

180 The Triglav Glacier and the Skuta Glacier in the southeastern Alps are the final two remaining surface ice masses in Slovenia that trace their origin to the last Pleistocene glaciation. Their retreat is largely linked to reduced average snow depth over the past 30 years compared with the previous 130-year period, along with rising summer air temperatures and longer durations of solar radiation between May and August in recent decades. In this study, stable isotope and radioisotope methods were used to determine the age of ice layers extracted from these two Slovenian ice masses, both of which are at risk of disappearing.

185 Based on the depth profiles of radioisotopes, the evolution of the ice layers has been reconstructed. At Triglav Glacier, the upper 10 cm seems to be recent snow of the last winter. The dark layer at 0 cm accumulates radiocaesium of the thermonuclear weapon test and the Chernobyl event, indicating that this layer was formed in the last few decades. The ice layer between 0 and 100 cm was accumulated before the 1960s. It is confirmed by a radiocarbon age of plant stem, and the lack of the tritium bomb peak. These latter indicates that after the early 1960s, the net accumulation is negative, i.e. the ice melts. Below 1 m, the
190 ice is older than 70 years. Skuta Glacier behaves similarly, although percolation water affects the deeper layers.

The age of the lower sections of the ice cores was constrained by tuning the age–depth model to the reconstructed temperature data from lake Jezero v Ledvica, based on its similarity to the $\delta^{18}\text{O}$ patterns observed in the Triglav Glacier and Skuta Glacier. Composite $\delta^{18}\text{O}$ records for each glacier were produced by averaging values from multiple ice cores by depth, excluding the top and bottom samples at Triglav Glacier due to snow contamination and meltwater influence. The age-depth model allows
195 us to estimate the variation of ice accumulation rates. Skuta Glacier shows higher and more stable depositional rate from 1860s to 1960s (about 5.5 cm/year). Triglav Glacier has much lower depositional rate, which is estimated at about 3.8 cm/year until the 1900s, that decreases to about 2.1 cm/year between 1900s and 1960s.

By now, Triglav Glacier has already fragmented and almost disappeared, while the Skuta Glacier is also constantly decreasing in size, even though it is in a more protected environment. This study provides the last opportunity to constrain the age of these
200 two ice accumulations.



Supplementary

Available online.

Code and data availability

The stable isotopic data and code for Laboratory Intercomparison used to produce the results presented in this study are
205 available at the Zenodo repository <https://zenodo.org/records/19051347>.

Author contributions

PV, LP and MT designed the study and wrote the first version of the manuscript with the help of YV and CH. LP and MT drilled the ice cores with the help of CH, MP and MN. MN, MZ, JT and ML conducted the ground-penetrating radar survey. PV, MN, KŽ, LP, DV and MT performed the isotope analyses. DV conducted the wavelet analysis. MT and DV performed
210 the age-depth profile with contributions of LP. PV, LP, MZ and CH were responsible for project administration and funding acquisition. All authors discussed and commented on the paper. All authors have read and agreed to the published version of the manuscript.

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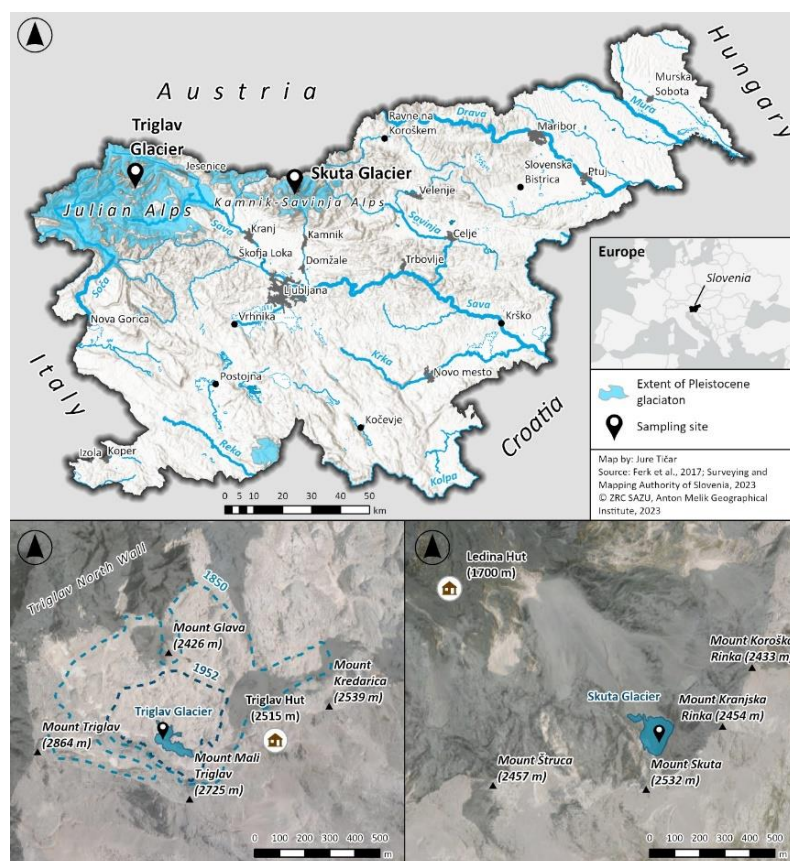


Figure 1. Locations of the Triglav Glacier and the Skuta Glacier.

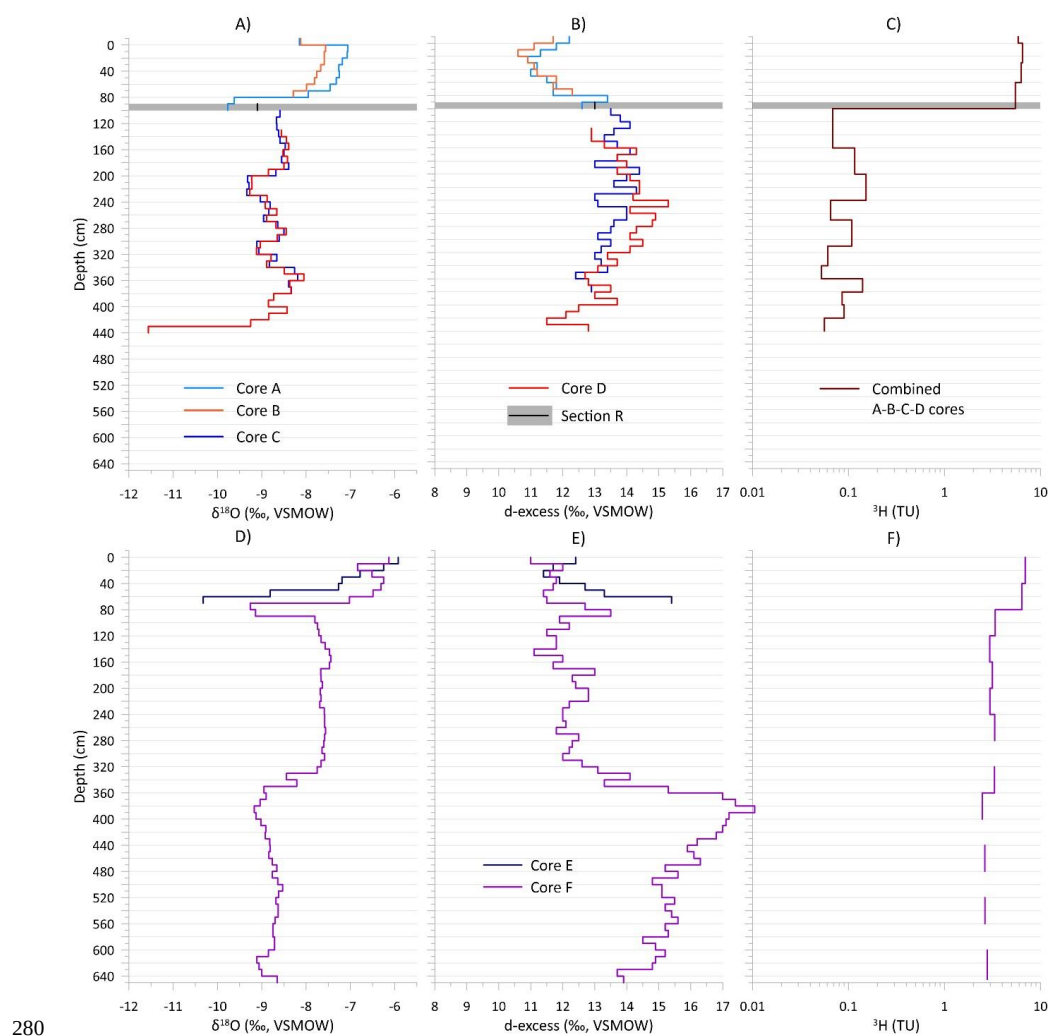


Figure 2. Stable isotope and ^3H composition of the studied ice cores from Triglav Glacier (A, B, C) and Skuta Glacier (D, E, F).

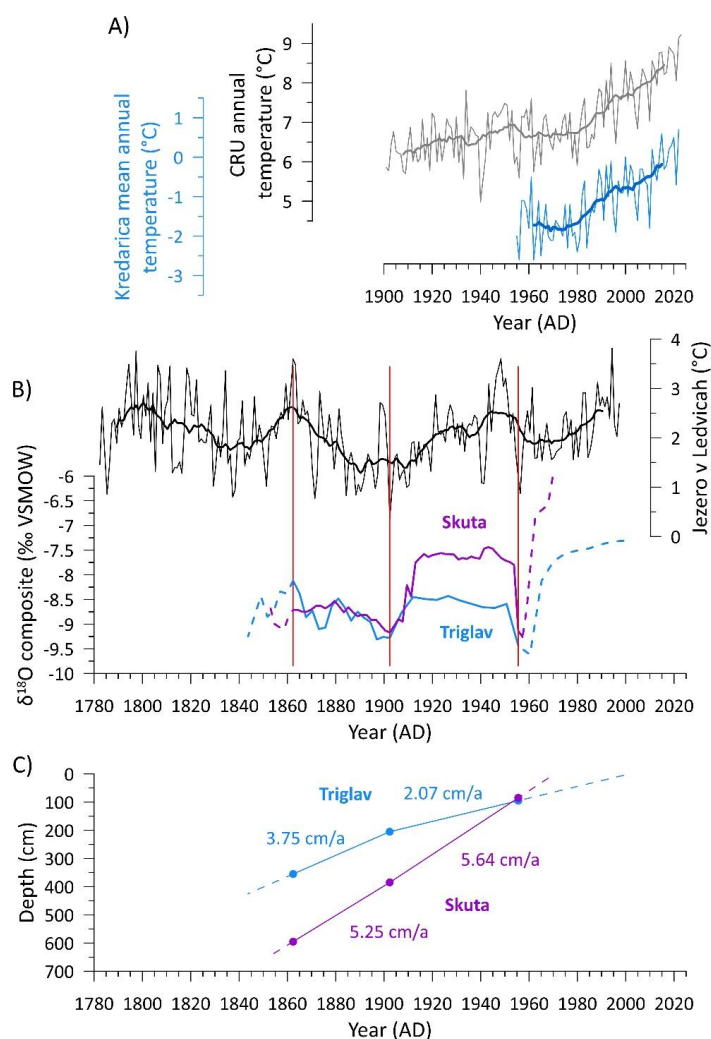


Fig. 3. Mean annual temperature at Kredarica meteorological station and CRU annual air temperature (Harris et al., 2020) for 0.5° size grid-box centered at 46.25° N and 13.75° E covering Triglav area (A); age-depth model obtained by tuning of the Triglav Glacier and Skuta Glacier $\delta^{18}\text{O}$ composite records to the Jezero v Ledvica reconstructed temperature record (B); and estimated model-based ice growth-rates (C). Thick grey and black line – 15-year average; red line – used tie-points; dashed purple and blue lines – sections constrained by only one tie-point (age-depth relationship extrapolated from neighboring section).