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Front cover photography: Alpine landscapes contain many traces of past conditions, which are also recorded in tree rings (photograph: Matej Lipar).
Fotografija na naslovnici: Alpske pokrajine hranijo številne sledi preteklih razmer, ki so zapisane tudi v letnicah dreves (fotografija: Matej Lipar).

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HOLOCENE CLIMATE VARIABILITY IN SLOVENIA: A REVIEW

Matej Lipar, Sonja Lojen, Mateja Breg Valjavec, Maja Andrič, Andrej Šmuc, Tom Levanič, Jure Tičar, Matija Zorn, Mateja Ferk

Forest vegetation changes are direct evidence of climatic variability.

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Holocene climate variability in Slovenia: A review

ABSTRACT: The Slovenian climate has undergone significant fluctuations, and an understanding of the past climate is necessary to improve models and recognise long-term patterns. The cryosphere environment, such as ice core samples, provides valuable palaeoclimate data. Palynology and dendroclimatology are also effective ways to study long-term changes in vegetation and reconstruct past climates using pollen and tree proxies. Sediment cores from various locations in Slovenia have been studied to understand past environmental changes. Borehole temperature profiles as well as historical records were also used to reconstruct past climate conditions. Studies have shown specific periods when climatic changes likely played a major role, but a complete timeline of the Slovenian climate throughout the Holocene has not yet been fully developed.

KEYWORDS: palaeoclimate, climate proxy, glaciers, pollen, tree-rings, sediment, speleothems, historical data

Holocenska podnebna spremenljivost v Sloveniji: pregled

POVZETEK: Podnebje v Sloveniji je doživljalo velika nihanja in razumevanje preteklega podnebja je nujno za izboljšanje modelov in prepoznavanje dolgoročnih vzorcev. Kriosferno okolje, kot so vzorci ledenih jeder, zagotavlja dragocene paleopodnebne podatke. Tudi palinologija in dendroklimatologija sta učinkovita načina za preučevanje dolgoročnih sprememb rastja in rekonstrukcijo preteklega podnebja z uporabo analiz cvetnega prahu in drevesnih branik. Sedimentna jedra z različnih lokacij v Sloveniji so bila preučena za razumevanje preteklih okoljskih sprememb. Za rekonstrukcijo preteklih podnebnih razmer so bili uporabljeni tudi temperature v vrtinah in zgodovinski viri. Študije so pokazale določena obdobja, v katerih so podnebne spremembe najverjetneje imele pomembno vlogo, vendar celotna časovnica sprememb slovenskega podnebja v holocenu še ni popolnoma izdelana.

KLJUČNE BESEDE: paleopodnebje, podnebni podatki, ledenik, cvetni prah, branike, sediment, siga, zgodovinski podatki

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1 Introduction

The climate has constantly changed during Earth's different geologic ages, and over the last two and a half million years of the Quaternary period (Gibbard and Head 2020) the climate has periodically oscillated between cold and warm episodes referred to as glacial and interglacial periods. We are currently experiencing climate variabilities of the warm interglacial period, also termed the Holocene epoch.

The modern climate is monitored by various agencies (e.g., the Global Observing System of the World Meteorological Organization, the International Telecommunication Union (ITU), and the European Earth Observation Programme as part of the Copernicus Programme), and climate variability and changes in Slovenia are monitored by the Slovenian Environment Agency. However, reliable data only span approximately 80 years, and to increase the reliability of models for major and minor climate variabilities, knowledge of climate variability in Slovenia in the past is needed. Holocene climate variabilities provide robustness of short-term climate events and are therefore essential for accurate predictions of future climate variabilities, including the environmental response to these changes. How the climate has evolved on a global scale during the Holocene is controversial due to large amounts of opposing palaeoclimate data from a variety of regions (e.g., Jiang et al. 2012; Marcott et al. 2013; Liu et al. 2014; Marsicek et al. 2018; Affolter et al. 2019); however, this also suggests that many palaeoclimate peculiarities and events occurred on a regional scale, and our understanding of recent climate variabilities should thus rely more on local evidence (Mayewski et al. 2004; Thornton et al. 2014; Wake 2015).

There are four main types of climate in Slovenia: a temperate humid climate in the west; a temperate continental climate in the central and eastern part; a mountain climate in the mountain areas of northwestern, northern, and part of southern Slovenia; and a sub-Mediterranean climate in the southwest (Komac, Pavšek and Topole 2020). This climate diversity would require climate reconstructions for different climate types to produce a reliable picture of the past climate of Slovenia. Nevertheless, since the reconstructions and interpretations of climate variabilities throughout the entire Holocene for the Slovenian territory are scarce, this article summarises all of them together.

The Holocene data for Slovenia come from a variety of disciplines, spanning from cryosphere (Section 2.1) to geological analyses of clastic sediments (Section 2.2), palynology (Section 2.3), dendrochronology (Section 2.4), speleothems (Section 2.5), and historical sources (Section 2.7). This article reviews up-to-date interpretations of climate variability in Slovenia during the Holocene until the beginning of modern instrumental records based on studies of the Slovenian territory, collates climate data from various proxies, and subsequently highlights the gaps in the existing literature and promotes further research. To make the timeline and dates of events consistent, we report them in kiloyears (ka) before present (BP); very recent (and mostly historical) events in the last millennium are given in years Anno Domini (AD).

1.1 The Holocene

The Holocene epoch (11.65 ka to present; the names comes from Greek ὅλος, *holos* 'entirely' + καινός, *kainos* 'new' because preserved fossils from this epoch are of species not predating *Homo sapiens*; Gervais 1847), together with the preceding Pleistocene epoch (2.58 million years (Ma) to 11.65 ka BP; the name comes from Greek πλεῖστος, *pleistos* 'mostly' + καινός, *kainos* 'new'; Lyell 1839), is part of the Quaternary (the name comes from Latin *quaternarius* 'consisting of four parts' because it is the fourth and final subdivision of the previously proposed threefold subdivision of the geological record (Primary, Secondary and Tertiary; Desnoyers 1829; Walker et al. 2019; Head, Pillans and Zalasiewicz 2021). The Holocene was initiated by the changes in insolation due to the eccentricity of Earth's orbit, and obliquity and precession of Earth's axis, termed Milankovitch cycles (Berger 1988; Hobart et al. 2023; Watanabe et al. 2023). The additional variability of hydrological and temperature conditions during the Holocene is attributed to solar variability, volcanic aerosols, changes in air circulation, changes in the extent of continental ice, and greenhouse gas concentrations (Mayewski et al. 2004; Brayshaw, Hoskins and Black 2010; Brayshaw, Rambeau and Smith 2011). Sea surface warming started around 17–20 ka in Antarctica (Rahmstorf 2002), whilst the apparent warming in the Northern Hemisphere (Greenland) was detected 14.6 ka ago, with the delay most likely due to ocean currents (Gregoire et al. 2016). The initial warming was interrupted by the cold Younger Dryas event, which ended around 11.65 ka, marking the formal beginning of the Holocene (Walker et al. 2009; 2019).

The currently adopted formal subdivision of the Holocene, ratified by the Executive Committee of the International Union of Geological Sciences (IUGS) on June 14th, 2018, is based on the universal use of geochronology constrained by a series of geochronometric methods (Walker et al. 2019; Head, Pillans and Zalasiewicz 2021). It starts with the oldest Greenlandian (Global Stratotype Section and Point (GSSP) in the North Greenland Ice Core Project ice core 2 (NGRIP2); corresponding to the Lower/Early Holocene) dated at 11.65 ka. Climate records from the Greenland area show very rapid warming, even exceeding 10°C in a decade or two (Alley 2000). The second is the Northgrippian (GSSP in the Greenland ice core 1, NGRIP1; corresponding to the Middle Holocene), dated to 8.186 ka. The last is the Meghalayan (GSSP in a speleothem from the Mawmluh Cave, northeastern India; corresponding to the Upper/Late Holocene), with a date of 4.2 ka.

Based on climate variability, the Holocene is also characterized by a variety of »periods« of global, hemispheric, or regional extent. For example, Mayewski et al. (2004) presented six global periods of significant Rapid Climate Change (RCC) during the Holocene, driven by Earth's orbital variations, solar variability, and potentially to some extent by volcanic aerosol production, causing polar cooling, tropical aridity, and major atmospheric circulation changes during 9–8 ka, 6–5 ka, 4.2–3.8 ka, 3.5–2.5 ka, 1.2–1 ka, and 0.6–0.15 ka. »Cold« periods were also identified based on regional and/or individual data-dependent studies; for example, the Misox (8.4–7.3 ka), Frosnitz (7.2–6.8 ka), and Rotmoos (6.3–5.0 ka) oscillations identified by pollen data (Zoller 1960; Patzelt and Bortenschlager 1973; Ivy-Ochs et al. 2009). The most recent cool-climate anomaly is the so-called Little Ice Age (LIA) between the Late Middle Ages and the mid-19th century (Grove 2004; Nussbaumer et al. 2011). The LIA can be subdivided into an early (AD 1260–1380), intermediate (AD 1380–1575), and main (AD 1575–1860) phase (Nicolussi et al. 2022). Shorter colder periods within the LIA are also known; for example, the Maunder Minimum of solar activity (AD 1645–1715; Eddy 1983).

A number of »warm« periods have also been identified; for example, the Holocene Climatic Optimum (HCO), a period of high insolation and generally warmer-than-present climate between 11 and 5 ka (Renssen et al. 2009; Solomina et al. 2015). Recent warmer periods are also the Minoan Warm Period with a peak around 3.3 ka, the Roman Warm Period around 2 ka, and the Medieval Warm Period about 1 ka (Easterbrook 2016). According to the Intergovernmental Panel on Climate Change (IPCC), we are currently experiencing the first human-induced global warming (IPCC 2018).

Following the Holocene subdivisions and periods, the Holocene has also been subject to short-term climatic changes, so-called »events«. The cooling 9.3 ka climatic event was probably caused by meltwater pulses to the Atlantic Ocean (Brynjólfsson et al. 2015). The 8.2 ka event briefly interrupted the trend of global warming with sudden strong cooling, attributed to the temporary weakening or disruption of the Gulf Stream caused by the spilling of huge amounts of melted ice into the North Atlantic (Thomas et al. 2007; Matero et al. 2017). The 4.2 ka event was characterised by dry and cool climatic conditions and has been accepted as the formal boundary of Northgrippian and Meghalayan, yet its exact origin remains controversial (Bini et al. 2019; Isola et al. 2019; Ran and Chen 2019). The latest 2.8 ka cold event is thought to have been driven by a grand solar minimum, with potential impacts on atmospheric dynamics and hydrology across the globe (Park et al. 2019; Harding et al. 2020).

2 Records of the Holocene climate in Slovenia

Most palaeoclimate analyses rely on indirect methods based on analyses of a variety of media from geological, chemical, biological, and historical archives (Hardy 2003; IPCC 2007; Ruddiman 2014). The following subsections are divided based on the media or environments characterised by particular types of media relevant to the Slovenian territory.

2.1 Cryosphere

The cryosphere environment, including glaciers, ice sheets, sea and lake ice, and even seasonal snow cover, provides a number of possibilities to extract palaeoclimate data. Some of the most important ice cores on a global scale were drilled in the thick ice sheets of Antarctica and Greenland, where the

Figure 1: Relevant localities in Slovenia where palaeoclimate studies were done. ➤ p. 11


Europe
Slovenia
Austria
Hungary
Italy
Croatia
Murska Sobota
Mura
Ljutomer
Ravne na Koroškem
Drava
Maribor
Slovenska Bistrica
Ptuj
Triglav Glacier
Jesenice
Lake Bled
Skuta Glacier
Snežna Cave
Upper Savinja Valley
Velenje
Savinja
Celje
Upper Soča Valley
Lake Planina pri Jezeru
M-17 Cave
Kranj
Sava
Kamnik
Škofja Loka
Domžale
Trbovlje
Soča
Paradana Cave
Ljubljana
Sava
Krško
Nova Gorica
Šempeter
Vrhnika
Ljubljana Marsh
Krakovo Forest
Planina Cave
Postojna Cave
Krka
Novo Mesto
Bay of Trieste
Adriatic Sea
Bay of Strunjan
Bay of Koper
Slovenian Istria
Izola
Bay of Piran
Reka
Kočevje
Bela Krajina
Kolpa
N
Legend
Cryosphere site
Clastic sediment site
Palynology site
Dendrochronology site
Cave sediment site
Historical evidence site
0 5 10 20 30 40 50 km
Cartography: Jure Tičar
© ZRC SAZU Anton Melik Geographical Institute

slow and continuous accumulation of ice over thousands or even millions of years provides an important interconnected palaeoclimate archive. The European Project for Ice Coring in Antarctica (EPICA), for example, has obtained a climate record for the past 740,000 years (Augustin et al. 2004), but stratigraphical sections spanning more than 2 Ma have also been found, and some are still being evaluated (Higgins et al. 2015; Kehrl et al. 2018). Reconstruction of the palaeoclimate can be based on the thickness of individual ice layers, seasonal stratigraphy and isotopic composition of ice, abundance and molecular composition of gas inclusions (CO_2, CH_4, and N_2O) and dust particles (Hammer 2006; Jansen et al. 2007; Lemieux-Dudon et al. 2010). For dating the uppermost layers of ice, counting annual layers is usually used, whilst for deeper (recrystallised) ice, radiometric dating of mineral and/or organic dust combined with geochemical markers and/or cosmogenic isotopes, firn densification modeling, and wiggle matching of ice core records to insolation time series are used (Lemieux-Dudon et al. 2010). Palaeoclimate modelling based on ice cores has also been done on ice cores retrieved from Alpine glaciers (e.g., Schwikowski et al. 1999), small glacieretes (e.g., Grunewald and Scheithauer 2010), and ice accumulated in natural caves (e.g., May et al. 2011).

Climate change also directly affects the extent of ice sheets and glaciers. Indirectly, their occurrence in individual time periods can be inferred from the dating of moraines and formerly glaciated areas (Stroeven et al. 2006).

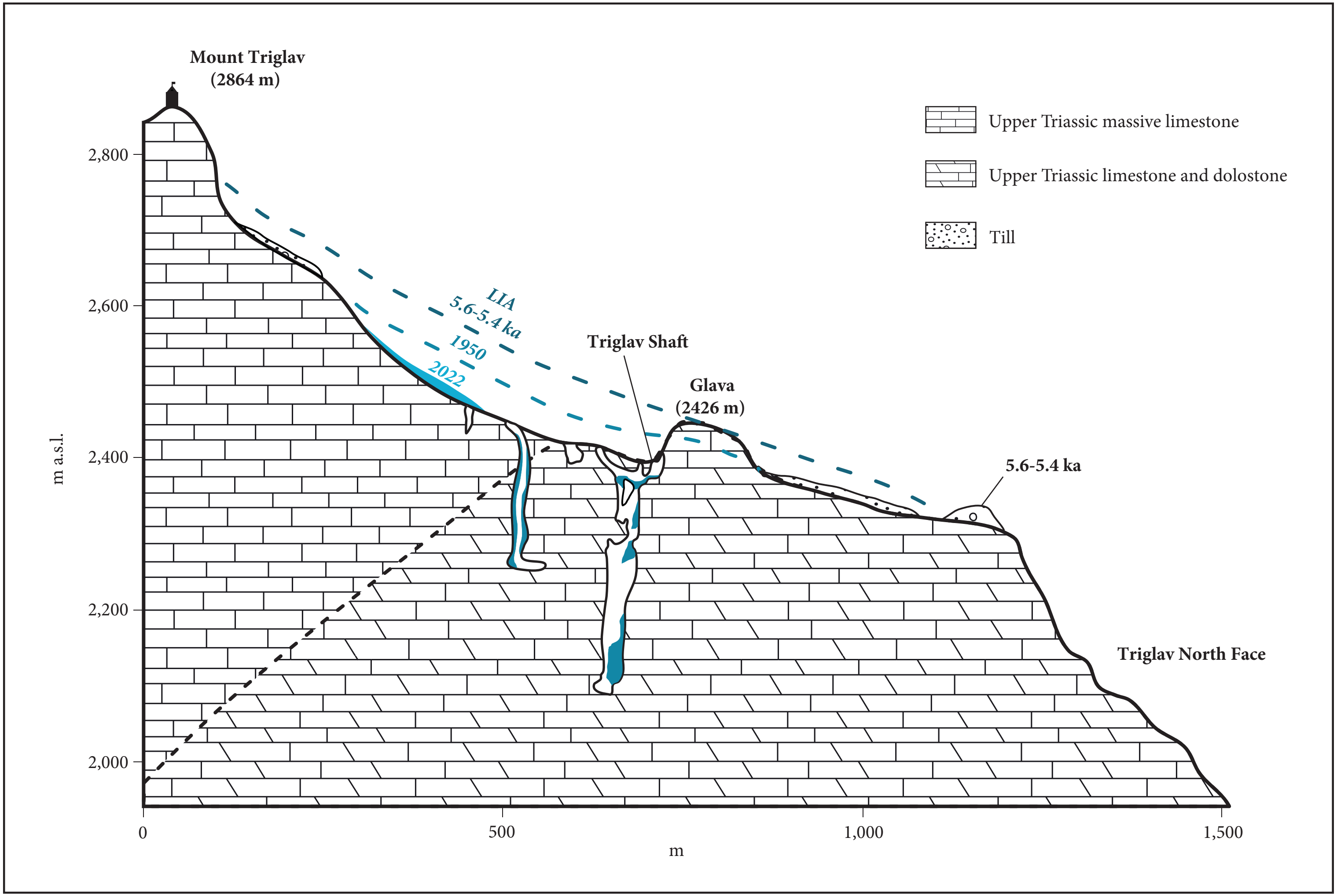
Whilst the Pleistocene glaciation played an important role in the transformation of the landscape in Slovenia (Gabrovec and Hrvatin 1998; Bavec and Verbič 2004; 2011; Ferk et al. 2015), only two remnants of glaciers persist in the present: the ice masses of the Triglav Glacier and the Skuta Glacier (Gabrovec et al. 2014; Zorn et al. 2020; 2020b; Figure 1). The Triglav Glacier is located below the peak of Mount Triglav (2,864 m) extending between 2,430 and 2,500 m in elevation and measuring around 0.7 hectares in size with a maximum thickness of around 5.5 m in 2002 (Gabrovec et al. 2013; 2014; Del Gobbo et al. 2016; Štok 2022). The Skuta Glacier is located below the peaks of Mount Skuta (2,532 m) and Mount Kranjska Rinka (2,453 m); it extends between 2,020 and 2,120 m in elevation and covers an area of about 1.5 hectares with a maximum thickness of around 7 m (Pavšek 2007; Triglav Čekada et al. 2020).

Ice core data were obtained from the remaining ice masses of the Triglav and Skuta glaciers in 2022 to provide information about the Holocene palaeoclimate, but the investigation is still ongoing. Systematic monitoring of the ice masses began shortly after the Second World War, and since the mid-1950s (Gabrovec et al. 2014) they have taken place together with systematic meteorological measurements on Mount Kredarica (2,515 m) next to the Triglav Glacier. Both data sets reflect the recent trend of climate warming (Hrvatin and Zorn 2020), but direct climate measurements are undeniably more reliable than modelling from proxies. Nevertheless, monitoring of ice masses provides valuable data on the interaction between climate and ice in recent (monitored) climate variabilities.

Archival imagery (Triglav Čekada, Zorn and Colucci 2014) of the Triglav Glacier shows its great extent and consequently indicate the presence of the LIA (i.e., colder climate conditions) in this area (Figure 2) at the end of the 19th century. Colucci and Žebre (2016) analysed the system of frontal moraine ridges of the Triglav Glacier identified by Šifrer (1963) and proposed that it was formed during the LIA; they consequently calculated the extent of the glacier to be about 44.2 hectares (compared to 0.7 hectares in 2022; Pavšek 2023) with a volume of 13.83 km^3 (compared to 2.455 m^3; i.e., 2.455×10^{-9} km^3 in 2022; Pavšek 2023). The presence of the LIA glacier extent could be also expressed by the moraine ridges in the Upper Krnica Valley (Kozamernik et al. 2018), but this is also uncertain due to the absence of ages of moraine ridges. The radiocarbon (^{14}C) analysis of the organic material sourced from a non-vegetated moraine located approximately 500 m below the present-day ice mass of the Triglav Glacier (as observed in 2022) produced an age range of 5.6 to 5.4 ka, indicating the extent of the glacier at that time similar to the LIA period and possibly suggesting another period of apparent colder climate (unpublished research conducted by Karsten Grunewald and associates; Lipar et al. 2021).

Subglacial carbonate deposits collected downward from the current extent of the Triglav Glacier suggest the presence of ice mass in this area throughout the Holocene, but it is unclear whether the HCO was not so pronounced in this area that it would have caused melting of ice mass to the present extent, or whether there are other factors that were not present in the past that are accelerating melting (Lipar et al. 2021).

Figure 2: Vertical profile of the Triglav Glacier with approximate extent of the glacier around 5.6–5.4 ka, in the LIA, in 1950, and in 2022. ➤ p. 13


Mount Triglav
(2864 m)
Upper Triassic massive limestone
Upper Triassic limestone and dolostone
Till
2,800
2,600
2,400
2,200
2,000
m a.s.l.
LIA
5.6-5.4 ka
1950
2022
Triglav Shaft
Glava
(2426 m)
5.6-5.4 ka
Triglav North Face
0
500
1,000
1,500
m

In addition to terrestrial ice masses, there are more than 260 caves in Slovenia with permanent ice masses (Cave Register 2022), which are also subject to ice mass loss as the overall climate warms (Kranjc 2009; Colucci et al. 2016; Mihevc 2021; Blatnik et al. 2023). The studies of their ice mass balance fluctuation and glaciochemistry have revealed their potential to provide palaeoenvironmental records (Mihevc 2018; Carey et al. 2019; 2020; Smith et al. 2023), but preindustrial data with dating is currently only available for the M-17 Cave located in the Tolmin Migovec massif of the Julian Alps (Racine et al. 2022). The ice mass balance of the M-17 Cave was assessed using radiocarbon dating of the organic remains embedded in ice. The developed chronostratigraphy suggests three primary phases of positive ice balance around 1.05–0.85 ka, 0.75–0.65 ka, and 0.25–0.15 ka, and a negative ice mass balance period around 0.65–0.55 ka (current ice mass loss has also been noted since its discovery in the 1980s). The overall positive ice mass balances are marked by cooler-than-average summers and wetter-than-average springs, whilst the negative mass balance indicates warmer-than-average summers and dry springs.

2.2 Clastic lacustrine and marine sediments

Marine, lake, and other continental sediments provide an important archive from which one can reconstruct past climate, biological, and geological changes and evaluate their impact on the environment. Sediment cores obtained from lake, marine, and continental unlithified sediments using a variety of coring methods (gravity and piston corers) provide a unique opportunity to obtain undisturbed successions, where all primary sedimentary structures, textures, and compositions are preserved down to the level of individual laminae. By analysing sediment cores, it is possible to observe both gradual and rapid changes in sediments, which are the result of various changes in catchments: geomorphology, physicochemical changes in water bodies, bioproduction etc. In the Holocene successions, the main driver for these changes is related to climate changes. Sediment structure and texture are used to reconstruct sedimentary processes and to identify »normal« pelagic sedimentation and event beds. Sediment mineral and chemical composition are used for provenance analyses, which in some cases have also been associated with climate changes (Bradley 1999; Last and Smol 2001; Battarbee et al. 2002a; 2002b; Lauterbach et al. 2011).

The most studied areas in Slovenia in relation to reliable ages of Holocene periods/events and palaeoclimatic interpretation are the Bay of Koper (Figure 1), where Holocene post-LGM warming marine transgression has been reconstructed, and lakes Bohinj and Bled, where the Holocene human and climate impacts on lake catchment have been investigated.

The Slovenian coastal area, located in the northernmost part of the Adriatic Sea, is the southeastern part of the larger Bay of Trieste. In this area, a complete series of shallow (up to 3 m) and deeper (up to 45 m) cores from different parts of the bay have been analysed (Ogrinc et al. 2012; Novak et al. 2020). These include three short cores in the northern and central part of the Bay of Trieste (Covelli et al. 2006; Ogrinc et al. 2007), three long cores in the Bay of Koper (Ogorelec et al. 1997), one long core in the southern part of the bay near Sečovlje (Ogorelec et al. 1981), and four short cores near the Bay of Strunjan (Novak et al. 2020). Based on lithology (mainly carbonate content), geochemistry ($\delta^{13}C$, $\delta^{15}N$, and OC/TN ratio), biota, and radiocarbon dating of sediments, the Holocene transgression in the Bay of Trieste was reconstructed (Ogorelec et al. 1981; 1997; Ogorelec, Mišič and Faganeli 2000; Covelli et al. 2006; Ogrinc et al. 2007; 2012; Mautner et al. 2018; Novak et al. 2020). The earliest evidence of the Holocene marine transgression is found in the cores from the Bay of Strunjan, dated to ~11.3 ka (Novak et al. 2020). Northward transgression progressed at a rate of between 1 and 3 km per century (Chiocci et al. 2017), and in a few hundred years most of the Bay of Trieste was already inundated by the advancing Adriatic Sea (Ogorelec et al. 1981; 1997; Ogorelec, Mišič and Faganeli 2000; Covelli et al. 2006; Ogrinc et al. 2007; 2012; Mautner et al. 2018; Novak et al. 2020). According to Ogrinc et al. (2012), this transgression pulse was followed by another pulse around 3 to 2 ka.

The oldest reliable climate reconstruction based on the lake core successions supported by dates is from Lake Bled, elevation 475 m (Andrič et al. 2009; Figure 1) and is based on geochemical parameters ($\delta^{18}O$, $\delta^{13}C$), pollen, and biota. The conclusion was that in the Oldest Dryas the larger area around the lake was influenced by a cold and dry climate, with a trend towards wetter conditions. A period of climate warming was observed at the beginning of the Late Glacial Interstadial at ca. 14.8 ka, followed by another period of warming at ca. 13.8 ka. After 12.8 ka (and throughout the Younger Dryas), the climate was colder and drier. A warmer climate marks the onset of the Late Glacial–Holocene transition.

In Lake Bohinj, elevation 526 m (Figures 1, 3), the sedimentary characteristics (provenance analysis) of the lake succession were used to reconstruct the Holocene wetter climate periods and associated increased flood activity (Andrič et al. 2020). These periods were marked by high terrigenous input at 6.1–6.0 ka, 5.7–5.55 ka, 5.0–4.6 ka, 3.9 ka, 3.7–3.55 ka, and 2.3–2.2 ka. These flood patterns match with periods of increased flooding in the wider Alpine region (Wirth et al. 2013), and the particular timing of 5.7–5.55 ka can also be correlated with the extreme floods in the Planina Cave based on the radiocarbon dating of a flowstone layer on the flood sediments (Stepišnik et al. 2012).

Small glacial Lake Planina pri Jezeru, located at an elevation of 1,430 m in the Eastern Julian Alps, has been the subject of ecological, geochemical, and palaeoenvironmental research in recent decades. Whilst geochemical studies have mainly focused on eutrophication (Muri et al. 2004; 2013; 2018; Muri, Wakeham and Rose 2006; Vreča and Muri 2006; 2010; Muri 2013) and its implications for the local ecosystems (Brancelj 2021 and references therein), the long-term changes in vegetation and sedimentary processes during the last 13,000 years were investigated using mineralogical, geochemical, and palynological methods by Caf et al. (2023). The radiocarbon method was used for dating the sediment core, and the climate change was reconstructed from sedimentological and vegetation parameters. Along with the pollen records (see Section 2.3), the warming at the beginning of the Holocene induced a transition from a wetland to a eutrophic lake surrounded by forest (*Picea, Larix, Ulmus*). Sedimentological characteristics and elemental records showed dry conditions after the Last Glacial Period with aeolian deposition of silty siliciclastic material. Between 12.45 and 12.2 ka, increased sedimentation of carbonate and decreased sedimentation of amorphous material suggests the onset of a more humid and warmer climate. Between 11.7 and 10.2 ka, rapid accumulation of amorphous organic material occurred as a result of increasing algal biomass in the lake, leading to anoxic conditions in the sediment and formation of pyrite (FeS_2). Between 10.2 and 4.5 ka, the area around the lake was heavily forested, as concluded from the high proportion of terrigenous detrital

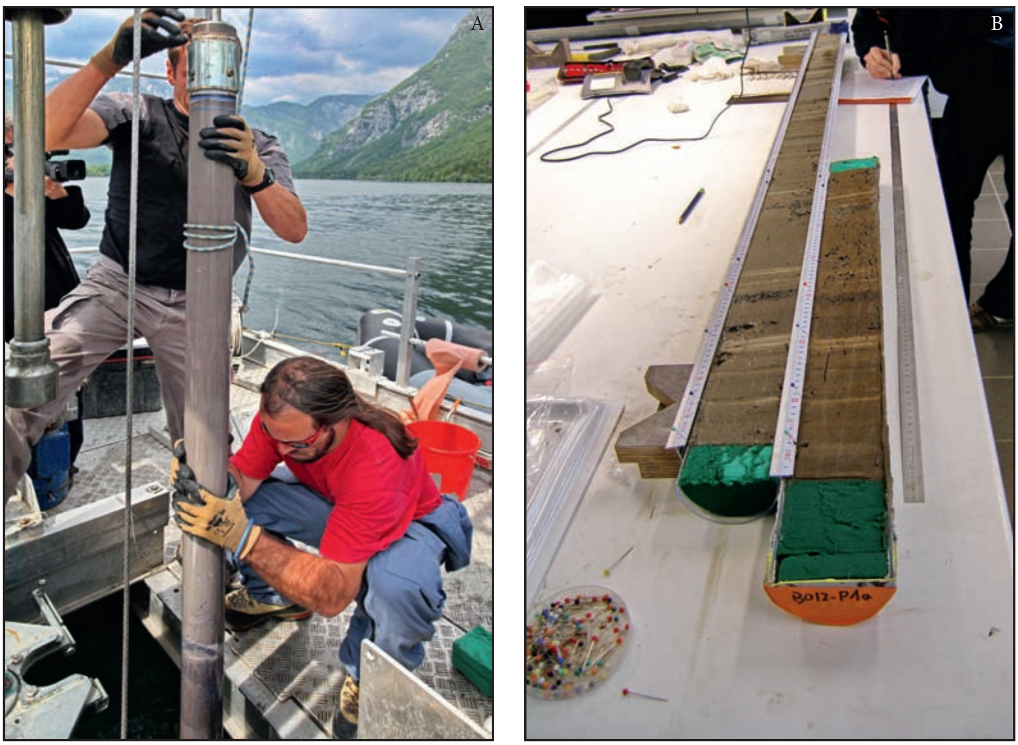


Figure 3: Sediment core from Lake Bohinj, published in Andrič et al. (2020). A: The length of the sediment core was 12 m. B: optically visible lamination of the core, indicating a change in lake hydrology as a consequence of climatic changes or events.

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organic matter with a high OC/TN ratio in the sediment. Periodical pulses of increased input of detrital dolomite point toward several consecutive periods with increased precipitation, alternating with periods of droughts. The 8.2 ka event and the cooling at 5.3–4.9 ka which were recorded in the pollen profile (see Section 2.3), remained unnoticed in sedimentological and mineralogical records. The subsequent fluctuations of geochemical parameters are attributed to changing land use rather than climate change (e.g., metallurgy since Roman times, and migrations in the Late Antiquity and the Early Middle Ages), when the settlements were located at lower elevations, whilst the pastures above the lake were used only during the summer (Caf et al. 2023).

2.3 Palynology

Palynology is an established approach to the study of fossil pollen produced by former plants and deposited in lake/marsh sediments, where it can survive for thousands or even millions of years. By analysing pollen in sedimentary cores, long-term changes in vegetation can be reconstructed (Traverse 2007; Birks 2019; Chevalier et al. 2020). Plants respond to climate variability, internal vegetation dynamics (e.g., succession), and human impact on the environment. Since the vegetation has not been affected solely by climate fluctuations, pollen analyses cannot provide direct evidence of climate change. However, in combination with other palaeoclimate proxies (e.g., sedimentological, geochemical, and stable isotope characteristics of lake, ice, and marine cores, speleothems, and tree rings – see Sections 2.2, 2.4, 2.5), it is possible to better understand the impact of climate on the vegetation and reconstruct long-term climate variability.

Major climate variabilities triggered significant changes in Pleistocene and early Holocene vegetation, whereas it is often difficult to distinguish between anthropogenic and climate impacts in the middle/late Holocene because the human impact on the environment was more pronounced (Birks 1981; Bennett and Willis 2001). Also important was the resilience of vegetation, which did not respond to minor changes in temperature or precipitation. Compared to northwestern Europe, where many palaeoclimate studies have been conducted (e.g., Dansgaard et al. 1993; O'Brien et al. 1995; Bond et al. 1997; Dahl-Jensen et al. 1998; Mayewski et al. 2004; Wanner et al. 2011), in Slovenia the vegetation changes associated with the colder/wetter climate may have been less pronounced due to the warmer climate and proximity to glacial tree refugia (e.g., Willis, Rudner and Sümegi 2000; Petit et al. 2003; Willis and Vanandel 2004; Magri et al. 2006).

In Slovenia, palynological research in the 1960s focused on sediment cores from the Ljubljana Marsh, a tectonically active basin (Mencej 1990; Brenčič 2007; Bavec and Pohar 2009; Verbič and Horvat 2009), where Šercelj (1966) investigated pollen which had been deposited in colder and warmer periods of the Pleistocene and the Holocene. The results of palynological research on study sites in the Ljubljana Marsh (Šercelj 1966; Culiberg 1991; Andrič et al. 2008), Bela Krajina (Andrič 2011), the Julian Alps at Lake Bled (Andrič et al. 2009) and Lake Planina pri Jezeru (Caf et al. 2023; Figure 1) indicate that towards the end of the last Ice Age (Late Glacial ca. 15–11.7 ka), when the climate in Europe was cold and presumably dry (Peyron et al. 2005; Feurdean et al. 2008; Ivy-Ochs et al. 2008; Kerschner and Ivy-Ochs 2008), the landscape was covered by a steppe with few trees (e.g., *Pinus, Betula, Larix, Picea*), but during warmer periods, mesophilous deciduous trees (e.g., *Quercus, Tilia, Corylus, Ulmus*) spread. These climate variabilities and subsequent changes in vegetation are evident in sedimentary cores of Lake Bled (Andrič et al. 2009), where colder and drier conditions have been suggested on the basis of multi-proxy data (sediment $\delta^{18}O$, pollen, microcharcoal, and cladocera and chironomid fauna) for the Oldest Dryas (ca. 18.5–14.8 ka) and Younger Dryas (ca. 12.8–11.7 ka). Climate warming occurred during the Late Glacial Interstadial (ca. 14.8–12.8 ka) and at the beginning of the Holocene (after ca. 11.7 ka). Similar fluctuations of Late Glacial climate and vegetation have also been detected elsewhere (e.g., Vescovi et al. 2007; Feurdean et al. 2008 and references therein). During the Late Glacial Interstadial, for example, greater inter-seasonal variability and enhanced continental conditions (colder winters) compared to the present-day climate were detected in central and eastern Europe (Feurdean et al. 2014).

At the transition to the Holocene the climate became markedly warmer. The seasonality of the early Holocene was driven by high summer insolation and therefore increased summer temperatures and drier conditions, leading to an increase in wildfire activity at 40°–50° N (Kutzbach and Guetter 1986; Feurdean et al. 2014). Temperate deciduous forests (*Quercus, Ulmus, Tilia, Corylus, Fraxinus*) were widespread in all phytogeographic regions of Slovenia. The increased microcharcoal concentration found at several study sites can be linked to the increase in natural forest fires, although the possible influence of local hunter-gatherer populations cannot be completely excluded (Andrič and Willis 2003; Andrič 2007).

The late successional shade-tolerant taxa *Fagus* and *Abies* are thought to have spread throughout Europe later in the Holocene, when the climate became less seasonal (i.e., less continental) and colder/wetter due to changes in solar insolation (Tinner and Lotter 2006). Both taxa are sensitive to drought, late frosts, and frequent disturbance such as forest fires in the early Holocene (Ellenberg 1988), and in most regions of Slovenia both taxa did not spread until after ca. 8.9–8.8 ka (Andrič and Willis 2003; Andrič 2007). In the Julian Alps at Lake Planina pri Jezeru, the 8.2 ka event is expressed as a short cold period with decreased drought stress, which is reflected in the pollen profile of the lacustrine sediment as expansion of *Abies* and *Fagus*, outcompeting the *Corylus* sp. (Caf et al. 2023).

However, the differences in vegetation development between the different regions of Slovenia were significant. At the current level of research, it is difficult to estimate whether these differences were a result of different regional climates, human impact, bedrock, or a combination of all these factors. Therefore, independent palaeoclimate research is needed to better understand changes in vegetation and the environment.

In the Ljubljana Marsh, for example, *Fagus* spread very early in the Holocene (ca. 11.4 ka), whilst *Abies* spread only after ca. 9.2 ka (Andrič et al. 2008). At the same time, the proportion of planktonic diatom taxa increased, indicating a deeper lake, which may be associated with a colder/wetter climate (9.3 and 8.2 ka events; Meese et al. 1994; Alley and Ágústsdóttir 2005). Between 6.75 and 6.0 ka, *Abies*, *Fagus*, and planktonic diatom taxa declined, which can possibly be related to a drier climate (Andrič et al. 2008). Palaeoclimate studies using other proxies need to be conducted in Slovenia to confirm these assumptions; however, a similar decline in lake levels has been noted at other study sites in Switzerland, Germany, and Croatia (Haas et al. 1998; Kalis, Merkt and Wunderlich 2003; Balbo et al. 2006). The diatom and geochemical record of the central Austrian alpine lakes suggests climate warming between 7.3 and 6.0 ka (Schmidt et al. 2006). Furthermore, the $\delta^{18}O$ records at Lake Geneva (6.35–6.0 ka; Anadón et al. 2006) and at the Ernesto Cave (*Grotta di Ernesto*, 6.8–6.0 ka; McDermott et al. 1999) suggest a warmer and drier climate. Between 6.8 and 5.7 ka a major climate reversal has also been reconstructed in Scandinavia with more meridional flow patterns and anticyclonic summer conditions, and thus a drier climate and lower lake levels (pollen-based reconstructions of temperature and precipitation; Seppä and Birks 2001). Another change in vegetation in the Ljubljana Marsh occurred after 6.0 ka, when *Fagus* and later *Abies* began to increase again, and human impact on the vegetation (forest clearance and farming) was moderate. This change in forest composition can be associated with a cold and wet period (Haas et al. 1998; Mayewski et al. 2004), elevated lake levels (Magny 2004; Magny and Haas 2004), glacier advance after 5.8 ka (Denton and Karlén 1973; Seppä and Birks 2001), ice rafting (O'Brien et al. 1995; Bond et al. 1997), and peat formation between 5.1 and 4.4 ka (Seppä and Birks 2001). Late Holocene palaeoenvironmental changes in the Ljubljana Marsh are only partly investigated due to sedimentary hiatuses caused by water erosion (flood layers at 6–5 ka and at ca. 3.7 ka; Andrič 2020) and anthropogenic activities (peat cutting; Zorn and Šmid Hribar 2012). In the following millennia, human impact on the environment increased and »masked« potential palaeoclimate signals in the sense that it was more important for vegetation development than climate fluctuations.

In Bela Krajina, *Fagus* appeared later in comparison to the Ljubljana Marsh, (ca. 8.9 ka), *Abies* was less abundant, and human impact (forest clearing and burning, which significantly affected forest composition) was much stronger. Lower proportions of *Fagus* and *Abies* in Bela Krajina were possibly a consequence of a drier regional climate and the human impact of Neolithic farming communities (forest cutting and burning; Andrič 2007). The prevailing taxon after ca. 8.9 ka was *Fagus*. Here, an earlier decline and later recovery of *Fagus* (after ca. 7.5 and 5.7 ka, respectively) was observed compared to the Ljubljana Marsh, possibly due to a drier climate and greater human impact. *Abies* did not spread until after 4.5 ka BP (4.5–2.0 ka), and a landscape similar to that of the present day formed after 1 ka when human activities had completely overridden potential palaeoclimate signals.

In the late Holocene (after 4.5 ka), the global climate became wetter and presumably colder (Wanner et al. 2011). Due to minima in solar activity, lakes south of the Alps experienced high lake levels and higher flood frequency between 4.2 and 2.4 ka (Vannière et al. 2013; Wirth et al. 2013; Sabatier et al. 2017; Rapuc et al. 2019). Some of these floods were also detected in the Ljubljana Marsh (Andrič 2020) and at Lake Bohinj (Andrič et al. 2020). At Lake Bohinj, *Fagus*-dominated forests spread after 3.3 ka, presumably due to the wetter climate, whereas *Picea* and *Abies* started to decline, together with increasing Bronze Age human impact on the environment (grazing). A major soil erosion event in the Iron Age (2.6 ka) was triggered by human impact (forest cutting, metallurgical activities, and grazing; Andrič et al. 2020), but it cannot be ruled out that it was further strengthened by the wet climate (ca. 2.8–2.3 ka; Haas et al. 1998; Bond et al. 2001; Magny 2004; Wanner et al. 2011; Magny et al. 2012; Rach et al. 2017).

In at least the last 1–2 ka, intensive human impact on the vegetation has been the most important factor shaping vegetation in all regions of Slovenia. Therefore, short-term (minor) fluctuations of the climate (e.g., the Medieval Warm Period and the LIA) are not clearly visible on pollen diagrams. Climate change was presumably not strong enough to cause significant changes in forest composition (at the lowland study sites), and human activities have altered forest composition more than climate. In addition, sampling resolution at many study sites was not detailed enough to detect these short-term changes; high–resolution studies at high-elevation sites at the tree line might yield better results.

2.4 Dendrochronology

Dendroclimatology, a subfield of dendrochronology, focuses on finding the relationship between climate and tree growth and on climate reconstruction, once the relationship between tree-ring proxy (a surrogate for measured climate data) and climate is established (Martinelli 2004; Ruddiman 2014). Classical dendroclimatology is based on establishing the relationship between tree-ring widths and climate; however, in recent times several other tree-ring proxies for climate reconstructions based on the wealth of information stored in tree-rings have been used. These new climate proxies include tree-ring density (maximum ring density), stable isotope ratios (carbon, oxygen, and hydrogen), and various anatomical traits of tree rings and blue intensity (a surrogate for X-ray-based tree-ring density measurements), to name a few (Siegwolf et al. 2021).

There are only a few long (ca. 2 ka) tree ring–based climate reconstructions in the world with some potential to go back to 6 ka (e.g., Wilson et al. 2011). However, there are several climate reconstructions of 1 ka or more based on tree-ring widths that cover the spatiotemporal variability of the climate in the last millennia (Cook et al. 1991; 1999; 2010; 2015; 2016). Europe is relatively well covered in terms of tree ring-based climate reconstruction, with the Alpine region best represented in this respect (Büntgen et al. 2006; Nicolussi et al. 2009; Corona et al. 2010; Hafner et al. 2014).

Currently in Slovenia, several tree-ring chronologies, which are an absolute basis for any climate reconstruction, have been developed: for the European larch (*Larix decidua* Mill.), a long-lived species at the upper tree line in the Alps; the pedunculate oak (*Quercus robur* L.), another long-lived species of the floodplain forests in the Slovenian lowlands (as well as in the Pannonian lowland); and the European beech (*Fagus sylvatica* L.), Norway spruce (*Picea abies* Karst.), and silver fir (*Abies alba* Mill.), which are representatives of the vast forests below the tree line in the Alps and Dinaric Alps.

Climate reconstructions in Slovenia have been done at the upper tree line using tree-ring proxies of European larch. The relationship between larch tree-ring widths and climate was studied at seven locations in the Slovenian Alps. Analysis was performed for the period from 1900 to 2008. The response function analysis showed a significant positive response (wide tree ring) of larch to above-average temperatures in June and a significant negative response to above-average temperatures in March. A long tree-ring width chronology (Levanič 2005) with later updates (unpublished) was developed, covering the period from AD 914 to the present. However, this chronology has a gap between 1254 and 1414, and therefore only the part from the end of this gap (1415) to the present was used to reconstruct June temperatures for the last 559 years. Another climate reconstruction is based on stable carbon isotope ratios in European larch (Hafner et al. 2014). A 520-year stable carbon isotope chronology was tested against measured temperature and sunshine duration data. The stable isotope chronology correlates well with both studied parameters; however, further tests showed that the relationship between sunshine duration and a stable carbon isotope ratio provides a more reliable reconstruction than average monthly temperature. Based on this, a 520-year reconstruction of sunshine duration for the period from June to August was developed for the southwestern European Alps, with three years standing out with particularly high predicted sunshine values (2006, 1911, and 1705) and two summers with particularly low predicted sunshine values (1840 and 1913).

In the mid elevations, silver fir-beech forest thrives in Slovenia. Elevations between 700 and 1,300 m are optimal for the growth and development of silver fir-beech forest. In the context of the wider study, the climate growth relationship was analysed along a 1,000 km transect (Čater and Levanič 2019). For sites in Slovenia and neighbouring Croatia, it was confirmed that temperature in June (beech) and July (silver fir) plays an important and positive role in the growth of beech and silver fir, but no further attempts have been made towards climate reconstruction.

At least two long chronologies with tree-ring widths and thus climatic reconstructions have been developed for low elevations in Slovenia. The first, a 349-year reconstruction, is based on the compilation of oak wood samples collected from old houses in the Dolenjska region and samples from old-growth forest in the Krakovo Forest (Sršen 2019; Figure 1). Oak chronology was tested against several climate variables and various drought indices, and it provided statistically sound results. Based on the 349-year chronology, drought reconstruction (the Palmer Drought Severity Index, PDSI) was compiled for the region of Dolenjska. A similar reconstruction for the same region and slightly longer (506 years) was constructed for the De Martonne Aridity Index (AI; Čufar et al. 2008). This reconstruction identified both above-average June precipitation and temperature as the most critical month for pedunculate oak growth in the region.

Based on dendrochronological analyses, for example, precipitation and temperature conditions in June were reconstructed for the last half millennium for southeastern Slovenia (Čufar et al. 2008). The average temperature of a very dry June was around 20°C, with average monthly rainfall around 40 mm, and the average temperature of a very wet June was around 16°C, with average monthly rainfall around 240 mm (Zwitter 2012). Dendrochronological analyses in the Slovenian Alps show two colder summer periods, around 1770 and 1820 (Levanič 2005; Zwitter 2012).

2.5 Speleothems and other cave sediments

Caves are a characteristic feature of karst landscapes and as such act as traps for clastic, chemical, and organic sediments in the local environment (e.g., Osole 1968; Gospodarič 1988). Clastic sediments are generally allogenic and originate from the catchment, and therefore their facies reflect the water flow regime in both the cave and the catchment (Zupan Hajna et al. 2008a; 2008b; 2021; Stepišnik et al. 2012; Ferk 2016; Ferk et al. 2019). The most common authigenic chemical cave sediments generally consist of calcite, aragonite, and other carbonate precipitates in the form of speleothems or tufa. Because of the relatively stable climate conditions in caves, their growth rate and continuity are particularly important indicators for reconstructing past climate variabilities, along with their chemical and isotopic records (Ford and Williams 2007; Fairchild and Baker 2012).

Despite the abundance of karst caves in Slovenia – the national database of caves (Cave Register, Speleological Association of Slovenia) currently has 14,695 recorded – only one analysed speleothem from Slovenia is listed in the SISAL (Speleothem Isotope Synthesis and Analysis) database of speleothems with published records (Genty et al. 1998; Comas-Bru et al. 2020).

The first discrete isotope data on speleothems in several Slovenian caves (Škocjan Caves, Dimnica Cave, Divača Cave, Predjama Cave, Mačkovica Cave, and Kamnik Cave) were reported by Urbanc et al. (1985; 1987). In a stalagmite record from the Postojna Cave (Figure 1), the uppermost segment encompassing the period from about 1950 to 1995 was analysed for ^{14}C history and growth rate, which was 0.13 to 0.20 mm/a for the samples analysed (Genty et al. 1998; Vokal 1999; Genty, Baker and Vokal 2001). To establish the relationship between the stalagmite $\delta^{18}O$ and $\delta^{13}C$ values and the environmental parameters, local precipitation and drip water were analysed from 1996 to 1997; however, the sampled drip water was not associated with the stalagmite, so no direct correlation could be established (Vokal 1999; Mandić et al. 2013). The hydrogeological stable isotope study and ^{14}C modelling provided important information on the C turnover rate in soils and the mean travel time of drip water feeding the speleothem (~11 years; Vokal 1999; Mandić et al. 2013), but the carbonate precipitation appeared to be in isotopic disequilibrium, making it unsuitable for palaeoclimate interpretation. Horvatinčić, Krajcar Bronić and Obelić (2003) also analysed the C and O isotope compositions in two ^{14}C-dated stalagmites from the Postojna Cave, one recent and one roughly encompassing the last 14 ka. The fluctuations in $\delta^{13}C$ values were attributed to the changing vegetation cover over the cave. The $\delta^{18}O$ record did not reveal any anomalies that would indicate a significant change in ambient temperature; however, the temporal resolution of the isotope profile was too low to allow any plausible conclusions about the palaeoclimate.

Black layers in speleothems in the Postojna Cave were studied by Šebela et al. (2015; 2017). Remains of charred carbon were found in dripstone in the Pisani Rov passage (8.24 ka), and in the Črna Jama Cave (8.39 ka), whilst the charcoal from soil above the cave at a depth of 1 m was dated to 8.21 ka (using the ^{14}C method). These are the first findings from caves in Slovenia related to the 8.2 ka event, and they also explain the mechanism of transport of soot formed by forest fires into the cave by winter ventilation, where it was deposited as black aerosol deposits over older speleothems. Most probably, the recorded forest fire was a natural, lightning-caused fire, although an anthropogenic origin cannot be ruled out (Šebela et al. 2015).

A palaeoclimate study has been in progress since 2009 in the Postojna Cave, in the terminal Pisani Rov passage (Domínguez-Villar et al. 2015; 2018; Lipar, Drysdale and Zhao 2019), but to date no detailed palaeoclimate interpretation of the stalagmite $\delta^{18}O$ and geochemical profile has been retrieved. Only preliminary studies based on hydrochemical and isotopic analyses of drip water, stalagmite, and precipitation have been performed (Vreča et al. 2006; Vreča, Pavšek and Kocman 2022) and confirmed that (1) the cave temperature at the end of the passage at a depth of about 37 m reflects the temperature fluctuations at the surface related to global warming with a delay of 20 to 25 years; however, because of the transfer of surface atmosphere, thermal variability depends on the duration of the oscillations, so the thermal anomalies with periods of 7 to 15 years in duration have delay times < 10 years in the passage studied (Domínguez-Villar et al. 2015); (2) at the time of collection (2009), the stalagmite was in a state of dissolution and was not growing; (3) the upper 0.6 mm of the stalagmite grew from 1984 to 2003; and (4) the $\delta^{18}O$ values of speleothem in that segment are synchronous with fluctuations of averaged $\delta^{18}O$ values of drip water and local precipitation during the same period (Domínguez-Villar et al. 2018).

2.6 Borehole temperature profiles

Studies of temperatures measured in boreholes can be used to reconstruct surface temperature. Due to the relatively low thermal diffusivity of rocks, temperature change at the surface propagates downwards and the way temperature changes along a borehole at the present time can indicate how the surface temperature has changed in the past (Cermak 1971; Bodri and Cermak 2007).

In Slovenia, temperature profiles from boreholes come mostly from the northeastern part of the country and span generally up to 300 years (Rajver, Šafanda and Shen 1998). Information about temperature changes beyond the past centuries are available from the Ljutomer borehole (drilled to a depth of 4,048 m and logged to almost 2,000 m) and the Šempeter borehole (drilled to 1,541 m and logged to 1,518 m), allowing reconstruction spanning the Holocene and the last glacial period (Rajver, Šafanda and Shen 1998; Šafanda and Rajver 2001). It shows the warming occurring after the last glacial period around 10 to 15 ka and reaching a maximum around 3 to 2 ka. The maximum could be related to the HCO–11 and 5 ka based on Renssen et al. (2009) and Solomina et al. (2015) since the amplitude and timing of the borehole values are qualitative because of the diffusive nature of heat conduction and the assumptions about the parameters used in inversion routines that blur temperature changes in the distant past (Luterbacher et al. 2012).

The shallower boreholes show a cold period around 1870–1890 (possibly related to the LIA), followed by a warming trend in the past 100 years. It is estimated that the ground surface temperature rose by 2° in the last 150 years (Rajver, Šafanda and Shen 1998; Šafanda et al. 2007).

2.7 Historical sources

Written records of climate phenomena began with the advent of developed civilizations (Zorn and Komac 2007). Some of the observations were made individually or passed down through generations. Common observations included droughts and floods, freezing of water, and vegetation cycles. They were carefully recorded, especially in terms of their effects on society. Historical sources from before advances in weather instruments can therefore be considered only as secondary information regarding climate changes in recent centuries. Well-known examples of historical sources include El Niño and written evidence of rainfall and weather-related disasters in China, etc. (Carey 2012; Ruddiman 2014).

Studies dealing with climate in Slovenia in the pre-instrumental period are rare (Ogrin 2012), but for the 17th and 18th centuries they show that springs and summers with heavy rain were common between 1700 and 1720, and summers were warm in the mid-18th century. Winters were harsh between 1630 and 1650 and during the Maunder Minimum, 1680–1716. Sources suggest that the 17th century was »a rather varied period in terms of climate and weather« (Ogrin 2012, 96). In the first half of the 17th century and the first half of the 18th century, weather-related natural disasters were frequent, with their frequency comparable to that of the late 20th century (Ogrin 2007b).

Slovenian historiography for the early Middle Ages, more precisely until AD 536, reports a severe famine that also affected the areas of present-day western Slovenia (Bratož 2019). Summer temperatures in Europe in AD 536 decreased by 1.6 to 2.5°C compared to the previous 30-year average due to a volcanic eruption in Iceland (Sigl et al. 2015; Gibbons 2018). Similarly, the eruption of the Mount Tambora volcano in Indonesia in April 1815 led to a drop in temperature of approximately 1.5°C in 1816 in what is now Slovenia, and this was accompanied by above-average rainfall (Čeč 2017); the estimated average surface temperature anomalies of the northern hemisphere in the summers of 1816, 1817, and 1818 are −0.51, −0.44, and −0.29 K (Oppenheimer 2003). The year 1816 is also known as the »year without a summer« (Oppenheimer 2003), and the year 1817 as the »year of famine«. It was the 1816–1818 famine that contributed to the development of a new cultivar – the potato – in certain areas of present-day Slovenia (Čeč 2015; Studen 2018).

More detailed historical studies of sources for weather and climate for the territory of present-day Slovenia are still lacking for the Middle Ages. These studies are more common for sources from the 16th century onward. For the beginning of the 17th century, the weather data collated by the bishop of Ljubljana and several annals have been preserved (Zwitter 2013). From these data, it is known that precipitation around the new year in central Slovenia was not only from snowfall and that the rise of temperatures above freezing was not uncommon. Sources for this period also confirm the occasional occurrence of very cold and wet summers in a single year or several years in a row (Zwitter 2013).

The climate conditions in the second half of the 17th century and at the beginning of the 18th century (i.e., for the Maunder Minimum, when solar activity was at its lowest) can be inferred for Slovenian Istria or the coastal/southwestern part of Slovenia from sources on salt production. During this period, severe storms with hail and strong winds were statistically more frequent than in earlier or later periods (Paliska et al. 2015). Between the first half of the 17th century and the first half of the 18th century, salt production was at its lowest in the mid-17th century (Bonin 2001).

An important climate indicator is frost damage to olive trees because olive trees in southwestern Slovenia grow at their northern climate limit. In the 20th century, the average recurrent period of frosts in the olive groves was 20 years, whilst in the 18th century it was shorter (10–15 years; Ogrin 2007a). For southwestern Slovenia, the occurrence of droughts was also reconstructed using historical sources. These were more common between 1540 and 1562, in the first half of the 18th century, and between 1820 and 1848. The droughts in the first half of the 18th century sometimes coincided with plagues of locusts (Ogrin 2003).

Historical sources for the LIA in southwestern Slovenia indicate two periods with a higher frequency of colder winters: (1) between 1300 and 1570 with peaks between 1400 and 1450, and between 1475 and 1570, and (2) between 1680 and 1865 with a peak in the first half of the 18th century (Ogrin 2005). Colder winters were also present between AD 800 and 865. Winter temperatures were 0.8°C lower at the end of the 15th century, and about 0.5°C lower in the first half of the 18th century than average temperatures at the end of the 20th century (Ogrin 1994).

The LIA is characterised by localized accusations of bad weather magic among the population. Witchcraft processes in Slovenia reached a high point during the second peak of the LIA at the end of the 17th and beginning of the 18th century (Rajšp 1988; Zwitter 2012).

For northern Slovenia, more precisely in the Upper Savinja Valley, it is known from historical sources that several consecutive cold and rainy summers led to the short-term abandonment of some high-elevation farms in the last decade of the 17th century (Zwitter 2012). The highest located farms in the Slovenian Alps were probably established towards the end of the Medieval Warm Period (i.e., during the time of secondary, high-elevation settlement), many of which were later abandoned (Ogrin 2012).

Data on weather and climate conditions for the 16th and 17th centuries can be found in the urbarium (or rent roll). Temperature and precipitation data are less frequently documented, but there are more data on harvests of various crops and meadows, and on the impact of weather on agricultural activities (Zwitter 2016). Based on court records from the first half of the 17th century, in the case of mountain grazing there was an awareness that in the second half of August the weather could already be cold, which influenced the earlier movement of livestock from higher to lower mountain pastures. This historical fact was still present in historical records in the mid-20th century, when August 10th was considered the last day of summer or the first day of autumn in many parts of Slovenia (Zwitter 2020). Poorer weather conditions may also have led to the introduction of new crops – in the mid-19th century, due to poor cereal harvests, the production of table potatoes became a necessity (Gestrin 1969; Zwitter 2012), along with a change in harvest time (Zwitter 2015).

The Glory of the Duchy of Carniola (Valvasor 1689) also provides weather and climate data for the 17th century, but care must be taken, as some of the statements may be exaggerated to a certain extent. Among other things, it is learned that high mountains could be covered with snow periodically, which means that the highest parts of the high mountains were not covered with permanent snow and ice during this period of the LIA, even though summers were on average colder than today (Zwitter 2014).

The harsh winters can be inferred from the ice on rivers, which the resulting floods were associated with during the melting period. In the 18th and 19th centuries, there were severe winters in northeastern Slovenia (Ptuj) in the first decade of the 18th century and in the second half of that century, as well as in the first half and at the end of the 19th century (Kolar 2020).

3 Synthesis

The reconstruction of the Slovenian climate during the Holocene is still evolving, and it would be too speculative to present an overall timeline synthesis. In addition, Slovenia is climatically diverse, and the palaeoclimate cannot simply be inserted into an overall history but should be treated on a regional scale. Nevertheless, several valuable studies have already shown peculiar periods when climate variations most likely played a major role to which the environment responded, either in terms of changes of glacier extent, lake level and flood frequency, or the spread or growth discontinuity of particular plant species, or simply through a historical remark in written records.

In terms of the regional distribution of palaeoclimatic archives studied throughout Slovenia (Figure 4), the eastern and northeastern regions characterised by the most apparent continental climate have palaeoclimatic research based on historical sources such as winter weather events in the Ptuj area in the 18th to 20th century (Kolar 2020) and borehole temperature profiles (Rajver, Šafanda and Shen 1998; Šafanda and Rajver 2001). The studied regions with a temperate continental climate are southeastern and central Slovenia, which include palynological (Culiberg 1991; Andrič 2007; 2020; Andrič et al. 2008), dendrochronological (Čufar et al. 2008; Sršen 2019), borehole temperature (Šafanda et al. 2007), and hydrological studies (Andrič et al. 2008; Stepišnik et al. 2012). Mountain climates are well represented by cryosphere archives (Gabrovec et al. 2014; Colucci and Žebre 2016; Lipar et al. 2021; Racine et al. 2022), palynological and sedimentological studies (Andrič et al. 2009; 2020; Caf et al. 2023), dendrochronological research (Hafner et al. 2014), and historical sources (Zwitter 2015; 2020). Studies in regions with a sub-Mediterranean climate mostly focus on marine sediments and transgression (Ogrinc et al. 2012; Novak et al. 2020).

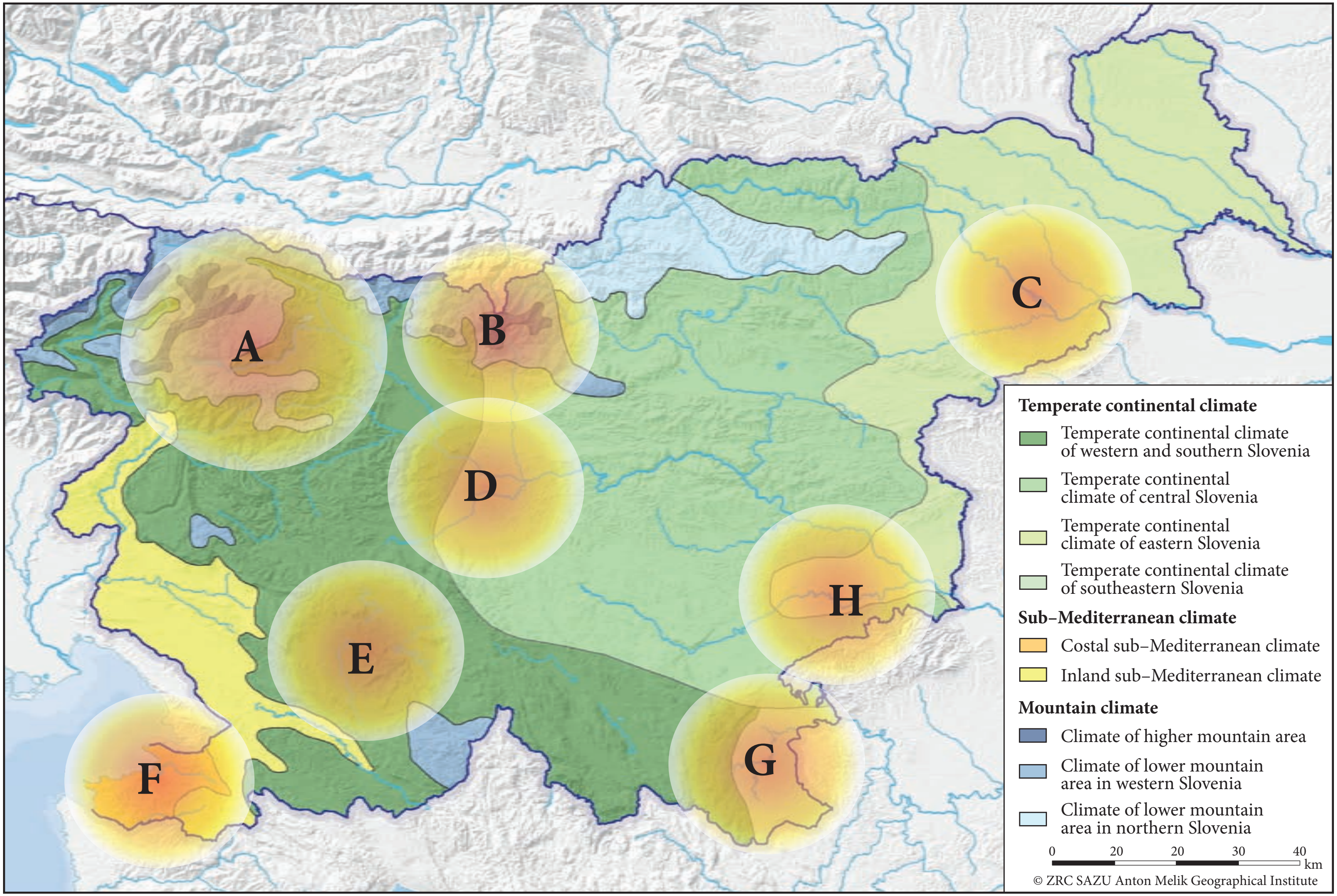
As for the period from the beginning of the Holocene to the times of modern climate monitoring, the palaeoclimate data based on archives from the Slovenian territory exist for all three subdivisions – oldest to newest, these are Greenlandian, Northgrippian and Meghalayan. The palaeoclimate from Slovenian archives of each of these subdivisions is summarised, along with the major global climatic periods/events. The summary of events is shown in Figure 5.

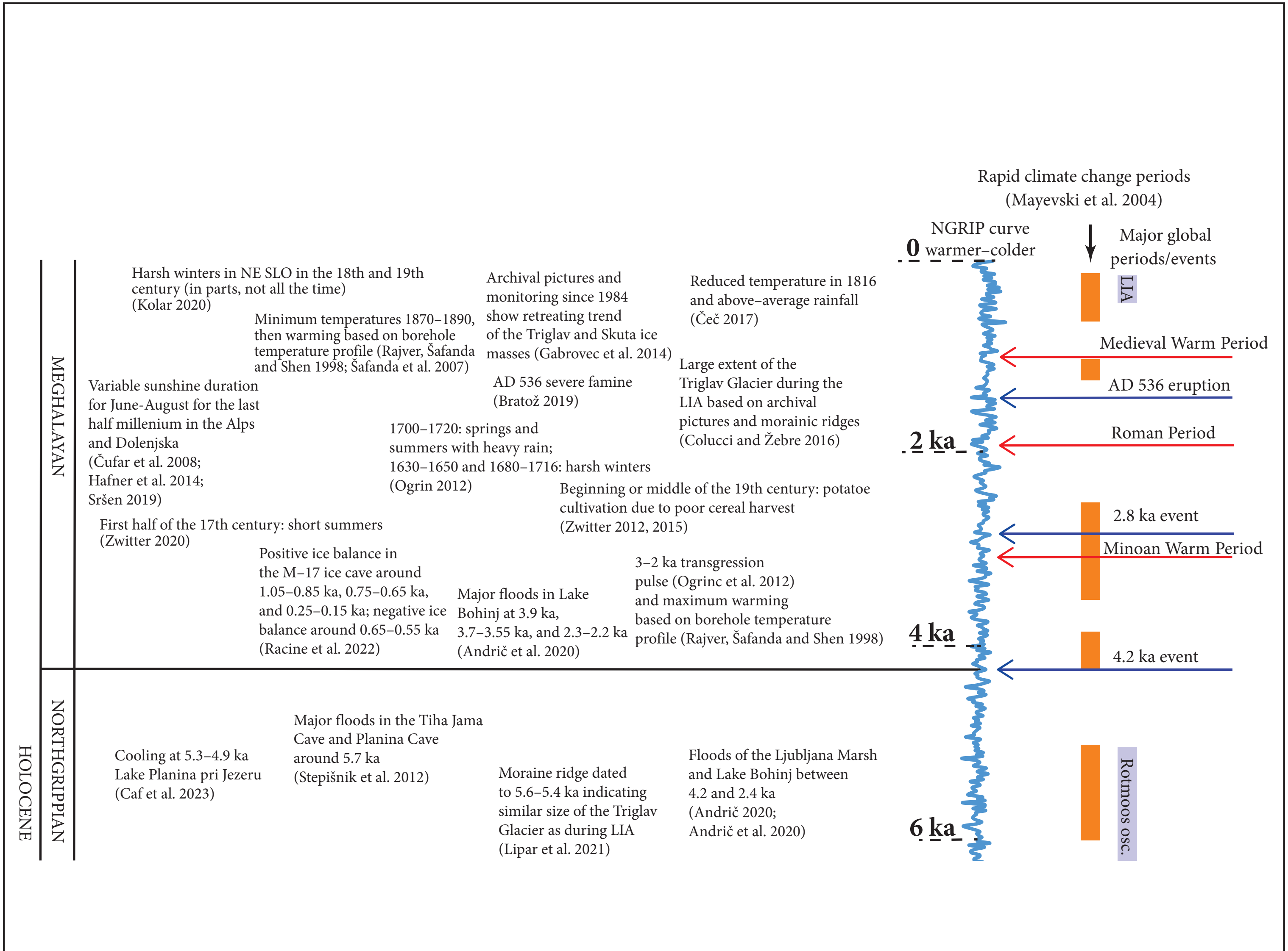
3.1 Greenlandian (11.65–8.186 ka)

The onset of the Holocene and the associated warmer climate on a global scale compared to the last glaciation period at the end of the Pleistocene also led to the retreat of major glaciers in Slovenia (Bavec and

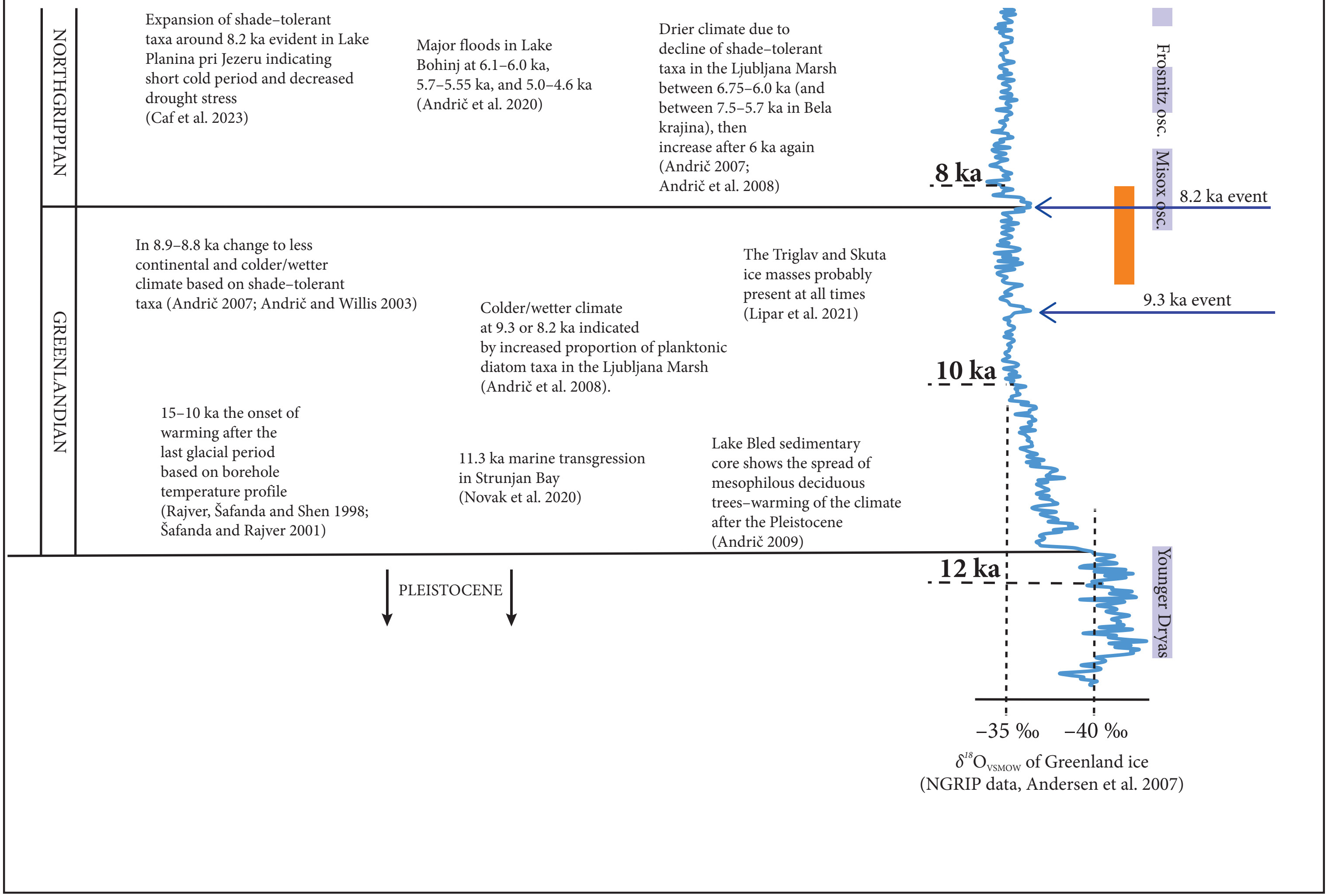
Figure 4: The present climate of Slovenia (Ogrin 2008) and the broad localities of major palaeoclimatic research. A: The Triglav Glacier (Gabrovec et al. 2014; Colucci and Žebre 2016; Hrvatin and Zorn 2020; Lipar et al. 2021), Lake Bohinj (Andrič et al. 2020), Lake Bled (Andrič et al. 2009), Lake Planina pri Jezeru (Caf et al. 2023), Vršič Pass (Hafner et al. 2014), the M-17 Ice Cave (Racine et al. 2022). B: The Skuta Glacier (Pavšek 2007; Triglav Čekada et al. 2020), the Dleskovec Plateau (Hafner et al. 2014), and the northeastern Slovenian Alps in general (Zwitter 2015; 2020). C: Ptuj (Kolar 2020) and the rest of northeastern Slovenia (e.g., Ljutomer; Rajver, Šafanda and Shen 1998; Šafanda and Rajver 2001). D: The Ljubljana Marsh (Culiberg 1991; Andrič et al. 2008; Andrič 2020). E: The Planina Cave (Stepišnik et al. 2012) and the Postojna Cave System (Domínguez-Villar et al. 2015; Šebela et al. 2017; Domínguez-Villar et al. 2018; Lipar, Drysdale and Zhao 2019). F: Strunjan Bay (Ogrinc et al. 2012; Novak et al. 2020). G: Bela Krajina region (Andrič 2007; 2011). H: Krakovo Forest (Sršen 2019), the wider region between Novo Mesto and Krško (Šafanda et al. 2007), and southeastern Slovenia (Čufar et al. 2008). ➤ p. 23

Figure 5: A summary of apparent palaeoclimatic data from the Slovenian territory, accompanied by the NGRIP curve (Andersen et al. 2007) and major climatic events (red arrows for major global periods/events – warm events; blue arrows for major global periods/events – cold events). © ZRC SAZU Anton Melik Geographical Institute ➤ p. 24–25


A
B
C
D
E
F
G
H
Temperate continental climate
Temperate continental climate of western and southern Slovenia
Temperate continental climate of central Slovenia
Temperate continental climate of eastern Slovenia
Temperate continental climate of southeastern Slovenia
Sub–Mediterranean climate
Costal sub–Mediterranean climate
Inland sub–Mediterranean climate
Mountain climate
Climate of higher mountain area
Climate of lower mountain area in western Slovenia
Climate of lower mountain area in northern Slovenia
0 20 20 30 40
km
© ZRC SAZU Anton Melik Geographical Institute



Rapid climate change periods
(Mayevski et al. 2004)
NGRIP curve
warmer–colder
Major global
periods/events
0
2 ka
4 ka
6 ka
LIA
Medieval Warm Period
AD 536 eruption
Roman Period
2.8 ka event
Minoan Warm Period
4.2 ka event
Rotmoos osc.
HOLOCENE
MEGHALAYAN
NORTHGRIPPIAN
Harsh winters in NE SLO in the 18th and 19th century (in parts, not all the time) (Kolar 2020)
Minimum temperatures 1870–1890, then warming based on borehole temperature profile (Rajver, Šafanda and Shen 1998; Šafanda et al. 2007)
Archival pictures and monitoring since 1984 show retreating trend of the Triglav and Skuta ice masses (Gabrovec et al. 2014)
Reduced temperature in 1816 and above–average rainfall (Čeč 2017)
Large extent of the Triglav Glacier during the LIA based on archival pictures and morainic ridges (Colucci and Žebre 2016)
AD 536 severe famine (Bratož 2019)
Variable sunshine duration for June-August for the last half millenium in the Alps and Dolenjska (Čufar et al. 2008; Hafner et al. 2014; Sršen 2019)
1700–1720: springs and summers with heavy rain; 1630–1650 and 1680–1716: harsh winters (Ogrin 2012)
Beginning or middle of the 19th century: potatoe cultivation due to poor cereal harvest (Zwitter 2012, 2015)
First half of the 17th century: short summers (Zwitter 2020)
Positive ice balance in the M–17 ice cave around 1.05–0.85 ka, 0.75–0.65 ka, and 0.25–0.15 ka; negative ice balance around 0.65–0.55 ka (Racine et al. 2022)
Major floods in Lake Bohinj at 3.9 ka, 3.7–3.55 ka, and 2.3–2.2 ka (Andrič et al. 2020)
3–2 ka transgression pulse (Ogrinc et al. 2012) and maximum warming based on borehole temperature profile (Rajver, Šafanda and Shen 1998)
Cooling at 5.3–4.9 ka Lake Planina pri Jezeru (Caf et al. 2023)
Major floods in the Tiha Jama Cave and Planina Cave around 5.7 ka (Stepišnik et al. 2012)
Moraine ridge dated to 5.6–5.4 ka indicating similar size of the Triglav Glacier as during LIA (Lipar et al. 2021)
Floods of the Ljubljana Marsh and Lake Bohinj between 4.2 and 2.4 ka (Andrič 2020; Andrič et al. 2020)


NORTHGRIPPIAN
GREENLANDIAN
Expansion of shade–tolerant taxa around 8.2 ka evident in Lake Planina pri Jezeru indicating short cold period and decreased drought stress (Caf et al. 2023)
Major floods in Lake Bohinj at 6.1–6.0 ka, 5.7–5.55 ka, and 5.0–4.6 ka (Andrič et al. 2020)
Drier climate due to decline of shade–tolerant taxa in the Ljubljana Marsh between 6.75–6.0 ka (and between 7.5–5.7 ka in Bela krajina), then increase after 6 ka again (Andrič 2007; Andrič et al. 2008)
8 ka
Frosnitz osc.
Misox osc.
8.2 ka event
In 8.9–8.8 ka change to less continental and colder/wetter climate based on shade–tolerant taxa (Andrič 2007; Andrič and Willis 2003)
The Triglav and Skuta ice masses probably present at all times (Lipar et al. 2021)
Colder/wetter climate at 9.3 or 8.2 ka indicated by increased proportion of planktonic diatom taxa in the Ljubljana Marsh (Andrič et al. 2008).
9.3 ka event
10 ka
15–10 ka the onset of warming after the last glacial period based on borehole temperature profile (Rajver, Šafanda and Shen 1998; Šafanda and Rajver 2001)
11.3 ka marine transgression in Strunjan Bay (Novak et al. 2020)
Lake Bled sedimentary core shows the spread of mesophilous deciduous trees–warming of the climate after the Pleistocene (Andrič 2009)
12 ka
Younger Dryas
PLEISTOCENE
–35 ‰
–40 ‰
$\delta^{18}O_{VSMOW}$ of Greenland ice (NGRIP data, Andersen et al. 2007)

Verbič 2011), although some ice masses (e.g., the Triglav and Skuta glaciers) were still present (Lipar et al. 2021). The borehole temperature profile from Ljutomer also clearly shows a warming trend at the end of the last glacial period and the beginning of the Greenlandian. The earliest evidence of marine transgression, dated to 11.3 ka, comes from Strunjan Bay (Novak et al. 2020), and the onset of a warmer – and also more humid climate compared to the late Pleistocene is also supported by increased sedimentation of carbonate and decreased sedimentation of amorphous material in Lake Planina pri Jezeru (Caf et al. 2023) and the spread of mesophilous deciduous trees evident in the sediment core of Lake Bled (Andrič et al. 2009).

The high insolation at the beginning of the Greenlandian also aided seasonality with drier conditions and higher temperatures in summer, possibly reflected in increased microcharcoal concentrations (Andrič and Willis 2003; Andrič 2007). Toward the end of Greenlandian, the shade-tolerant taxa, which generally spread after ca. 8.9–8.8 ka (Andrič and Willis 2003; Tinner and Lotter 2006; Andrič 2007), may indicate a decline in solar insolation and consequently a less seasonal and colder/wetter climate. Notable regional differences (e.g., the spread of shade-tolerant taxa earlier in the Ljubljana Marsh than in Bela krajina) allow rare opportunities to compare the palaeoclimate on a regional scale and could indicate a drier regional climate in the temperate continental climate of southeastern Slovenia, compared to the temperate continental climate in central Slovenia.

The end of the Greenlandian and the beginning of Northgrippian are marked by the 8.2 ka event, and the very prominent expansion of shade-tolerant taxa in the Lake Planina pri Jezeru core (Caf et al. 2023) could be associated with this event, which can be characterised as a short cold period with lower drought stress. The increased proportion of planktonic diatom taxa, indicating a deeper lake possibly associated with a colder/wetter climate, was also observed in the Ljubljana Marsh (Andrič et al. 2008), although this may also be associated with the 9.3 ka event.

On the contrary, the extensive black-layered speleothems in the Črna Jama Cave are thought to be the result of massive forest fires around 8.2 ka (Šebela et al. 2017), which could indicate a drier climate at that time. This could indicate either minor regional palaeoclimatic differences in Slovenia, similar to the wider European region where this event was characterised by wet conditions in some parts and dry conditions in others (Gałka et al. 2016 and references therein), or an unclear sequence of relatively rapidly changing climatic events; for example, higher-than-average air temperatures before and after 8.2 ka in Europe (Gałka et al. 2016; Andersen et al. 2017) could also contribute to more frequent forest fires.

3.2 Northgrippian (8.186–4.2 ka)

The first apparent palaeoclimatic change after the 8.2 ka event is evident in the decline of shade-tolerant taxa recorded in the Ljubljana Marsh between 6.75 and 6.0 ka, which may be related to a drier climate; after 6 ka, the shade-tolerant taxa increased again, possibly indicating a cold and wet period (Andrič et al. 2008). In Bela Krajina, a decline in shade-tolerant taxa was recorded over a longer time interval, between 7.5 and 5.7 ka (Andrič 2007), possibly indicating a drier climate in southeastern Slovenia compared to central Slovenia, but a stronger human influence cannot be excluded. These longer periods of drier climate coexist with the HCO, which, in fact, spans from 11 to 5 ka, but, due to the variation of climatic events on a shorter timescale, the HCO period seems to be very generalised. Furthermore, temperature data from the boreholes, reaching a maximum between 3 to 2 ka, have also been considered related to the HCO (Rajver, Šafanda and Shen 1998), but the estimates of the ages do not overlap.

Nevertheless, the enhanced flood activity at 6.1–6.0 ka, 5.7–5.55 ka, and 5.0–4.6 ka indicated by terrigenous input to Lake Bohinj (Andrič et al. 2020) may be the result of decreasing insolation and the end of the HCO at around 6 ka. This could furthermore be strengthened by the advances of the Triglav Glacier (5.6–5.4 ka; Lipar et al. 2021), possibly related to the two-phased Rotmoos Oscillation between around 6.3 and 5.0 ka, when advances of small glaciers were reported in the Alps (Patzelt and Bortenschlager 1973; Ivy-Ochs et al. 2009). Cooling was also noted at 5.3 to 4.9 ka in pollen records of the Lake Planina pri Jezeru (Caf et al. 2023).

3.3 Meghalayan (4.2 ka–present)

The Meghalayan begins with the 4.2 ka event, which is almost coincident in most of the archives discussed (Sevink et al. 2011; Wanner et al. 2011), but it has not been clearly detected in proxies from the Slovenian region. Detected flooding in the Ljubljana Marsh (Andrič 2020) and Lake Bohinj (Andrič et al. 2020) may indicate a wetter and presumably colder climate in the early Meghalayan due to minima of solar activity. At Lake Bohinj, the spread of *Fagus* after 3.3 ka also suggests a wetter climate, and increased flood activity was recorded at 3.9, 3.7–3.55, and 2.3–2.2 ka, whilst a major soil erosion event between 2.8–2.3 ka could also be related to human impact (otherwise also a wetter climate; Andrič et al. 2020).

The apparent cooling was detected during the LIA, as indicated by morainic ridges of the Triglav Glacier (Colucci and Žebre 2016). It is also possible that the very low salt production on the Slovenian coast and particularly the witchcraft trials at the end of the 17th and beginning of the 18th centuries indicate the climate of the LIA. Dendrochronological data show the variability of summer insolation in the eastern Alps during the LIA until today (Hafner et al. 2014); they show that summer insolation was variable with particularly hot summers around 1705. Based on dendrochronological data from Dolenjska region, no extreme summers (featuring either extreme dryness or wetness) were observed (Sršen 2019), but relatively wet summers were observed in the early 18th century and similarly after 1797. Summers became slightly less wet in the last decade of the 18th century. Based on historical imagery since the end of the 19th century, the melting of the two remaining ice masses in Slovenia, the Triglav and Skuta glaciers, and borehole temperature profiles indicate the onset of a warmer period after the LIA (Rajver, Šafanda and Shen 1998; Šafanda et al. 2007; Triglav Čekada et al. 2014).

4 Conclusion

Studies based on climatic indicators from the Slovenian territory have revealed a number of particular periods when climate variations played a major role, whether in the form of changes in glacier extent, lake levels and frequency of floods, or the spread or discontinuity of growth of certain plant species, or simply through historical remarks in written records. Slovenia is climatically diverse, and consequently the data show that palaeoclimate cannot simply be inserted into an overall territory but should be treated on a regional scale with correlations to transboundary palaeoclimate data from broader yet similar regional features (e.g., the southeastern Alps, the Dinaric Alps, the Pannonian Basin, and the Mediterranean region).

The following list of climatic events, nevertheless, summarises all reported changes in the Slovenian territory:

- Before the Holocene: the landscape was dominated by steppes with few trees due to a colder and dry climate. Variability in climate was observed, with warmer periods allowing the spread of mesophilous deciduous trees. A warmer global climate led to major glacial retreats. A trend towards wetter conditions was noted before the climatic warming observed at around 14.8 ka.
- 14.8 ka (Lake Bled): phase of warming. Another phase of warming occurred at around 13.8 ka. The climate became colder and drier after 12.8 ka.
- 15–10 ka: approximate time gap when the borehole temperature profile data from Ljutomer and Šempeter start showing a warming trend occurring after the last glacial period, reaching a maximum temperature around 3 to 2 ka. This maximum could be associated with the HCO.
- The onset of the Holocene: the climate became warmer, leading to widespread temperate deciduous forests in Slovenia. There were increased summer temperatures and drier conditions, leading to increased forest fires.
- 11.4–8.8 ka: varieties of trees such as *Fagus* and *Abies* began to spread, and the climate became less seasonal but colder and wetter. Different regions in Slovenia showed variability in vegetation development due to multiple factors, including regional climates and human impacts.
- 11.3 ka (Bay of Trieste): the earliest evidence of Holocene marine transgression in the cores from the Bay of Strunjan. Most of the Bay of Trieste was inundated by the Adriatic Sea within a few hundred years, marking significant marine transgressions.
- 10.2–4.5 ka (Lake Planina pri Jezeru): the area around the lake was heavily forested, marking a period of lush vegetation. Intermittent periods of increased precipitation and drought were recorded.
- 8.8–6.0 ka: there were fluctuations in vegetation and climate, with indications of drier and warmer periods. These changes were influenced by various factors, including human activities such as forest clearing and farming.
- 8.2 ka: black layers found in speleothems in the Postojna Cave and Črna Jama Cave were analysed, revealing charred carbon remains. These layers suggest that soot from forest fires was transported into the caves, marking an important climatic event.

- 6.1–2.2 ka (Lake Bohinj): several episodes of increased flood activity were noted, associated with wetter climatic conditions. Specific episodes were identified at 6.1–6.0, 5.7–5.55, 5.0–4.6, 3.9, 3.7–3.55, and 2.3–2.2 ka, reflecting patterns of increased terrigenous input due to flooding.
- 5.6–5.4 ka (Triglav Glacier): radiocarbon analysis of organic material from a moraine near the Triglav Glacier indicates that the glacier extent was similar to the LIA, suggesting a colder climate during this period.
- 4.5 ka onward: there was a more significant human impact on vegetation, and the climate became generally colder and wetter. The dominance of human activities, such as forest cutting and metallurgical activities, made it challenging to clearly distinguish the impact of climate variations based on pollen studies.
- 3 to 2 ka (Bay of Trieste): another significant marine transgression pulse was identified during this period, following the earlier Holocene transgressions.
- 1.05–0.85, 0.75–0.65, and 0.25–0.15 ka (M-17 Cave): ice in the M-17 Cave shows periods of positive ice mass balances, implying cooler and wetter conditions during these times. There was also a period of negative ice balance around 0.65–0.55 ka, indicative of warmer and drier conditions.
- AD 536: severe famine due to a volcanic eruption in Iceland that caused summer temperatures in Europe to decrease by 1.6 to 2.5°C compared to the previous 30-year average.
- AD 914 onward: a study focused on European larch in Slovenia, with a notable gap from 1254 to 1414. Climate reconstruction has been mainly utilized from 1415 onward, focusing on June temperatures. Based on oak wood samples, the De Martonne Aridity Index and the Palmer Drought Severity Index were developed for the last ~500 and 350 years, respectively.
- 1300–1570, 1680–1865: historical sources from southwestern Slovenia of periods with colder winters, notably between 1300–1570 and 1680–1865, with winter temperatures being lower than the average temperatures at the end of the 20th century.
- The LIA (Triglav Glacier): the Triglav Glacier had a more significant extent during the LIA compared to its present state, indicating colder climate conditions at that time.
- 1540–1562, first half of the 18th century, 1820–1848: southwestern Slovenia experienced more common occurrences of droughts during these periods, sometimes coinciding with locust plagues.
- 1630–1650, 1680–1716: harsh winters were recorded in these years, corresponding with the Maunder Minimum, a period of low solar activity.
- Late 17th century to early 18th century: weather-related natural disasters were frequent, and, in the second half of the 17th century, climate conditions affected agricultural practices, such as the timing of moving livestock and introducing new crops.
- 1700–1720: heavy rainfall during springs and summers was common.
- 1705, 1911, and 2006: exceptional sunshine values were noted in the southwestern European Alps, based on stable carbon isotope ratios in European larch. However, in 1770 and 1820 colder summer periods were identified in the Slovenian Alps, marking distinct climatic phases.
- 18th–19th centuries: harsh winters were recorded in northeastern Slovenia, notably in the first decade of the 18th century, the second half of the 18th century, and the beginning and end of the 19th century, influencing agricultural practices and social behaviours.
- 1815: the eruption of the Mount Tambora volcano caused temperatures in Slovenia to drop by about 1.5°C, resulting in the »year without a summer« in 1816 and the »year of famine« in 1817.
- 1870–1890: borehole temperature profiles indicate a colder period within these years, possibly relating to the LIA. Then, over the past century and a half, a warming trend has been observed, with the ground surface temperature estimated to have risen by 2°C, as indicated by more recent temperature profiles from boreholes in northeastern Slovenia.
- 1950s to present (Triglav and Skuta glaciers): the Triglav and Skuta glaciers' size and volume have significantly decreased, with current sizes much smaller compared to historical extents, reflecting recent global warming trends.

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