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Heinrich summers

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Abstract :

Millennial-scale climate oscillations of the last ice age registered in Greenland and Antarctic ice cores did not always vary in unison. A striking example is that the strongest Antarctic warming episodes occurred during Heinrich episodes in the North Atlantic region. Although the bipolar seesaw affords a possible explanation for such anti-phasing, it does not account for the equally striking observation that climate varied in unison between the hemispheres about half the time. Such phasing differences suggest the need for an alternative hypothesis in which the polar regions at times responded in unison to common forcing, and at other times left the impression of a bipolar seesaw. We posit that this impression arose from the effect of warmer-than-usual summers on continental ice sheets adjacent to the North Atlantic Ocean during each Heinrich episode. The relatively warm Heinrich summers produced discharges of meltwater and icebergs of sufficient volume to stimulate very cold winter conditions from widespread sea ice on a freshened ocean surface. The intervals between Heinrich episodes featured relaxation of sea-ice-induced winter severity from reduced summertime influx of meltwater and icebergs, indicating relatively cooler summer conditions. It is postulated that the causative variations in freshwater fluxes were driven by a climate signal most evident in Antarctic ice cores but also recognized in other paleoclimate records in both polar hemispheres. We suggest that this widespread signal arose from changes in the latitude and strength of the austral westerlies and the resulting effect on the western Pacific tropical warm pool, a mechanism dubbed the Zealandia Switch.

Highlights

► Bipolar synchrony of millennial-scale glacier melt during the last glaciation. ► Interhemispheric glacier signal inconsistent with 'bipolar seesaw' hypothesis. ► Northern 'stadials' attributed to warm summers paired with extremely cold winters. ► Enhanced melt-induced northern seasonality obscured global ice-age climatic signature. ► Differentiating summer from winter effects key to interpreting paleoclimatic proxies.

Keywords : Climate dynamics, Glacial, Glaciation, Seasonality, Heinrich stadials, Termination, Pleistocene, Paleoclimatology, Antarctica, Greenland, North Atlantic, North America, Western Europe, Cosmogenic isotopes, Geomorphology, Ice cores, Sedimentology-marine cores

Introduction

The origin of recurring millennial-scale climate oscillations in both polar hemispheres during the last ice age and its termination remains elusive. Figure 1 illustrates these oscillations as they appear in the isotopic signatures of Greenland and Antarctic ice cores. A determination of why changes represented in these records did not always vary together lies at the heart of understanding the relationship of ice-age climate oscillations between the hemispheres. It has long been noted that the warming phases of Antarctic Isotopic Maxima (AIM) coincided with Greenland Heinrich stadials (HS) (e.g., Pedro et al., 2018 and references therein). However, less commonly highlighted is the observation (Steig and Alley, 2002) that Antarctic and Greenland climate oscillations during the last glacial cycle showed such anti-phased behavior only about 50% of the time, interspersed with in-phase changes, particularly during cooling ramps that followed warm peaks (Figure 1). Moreover, there is an important structural difference between the ice-core isotopic signatures of the two polar hemispheres in that the Greenland oscillations featured fast climate shifts, unlike the Antarctic oscillations.

Any hypothesis for the origin of climate oscillations as registered in ice-core records should account for the structural difference, as well as for the temporal relationships, between Greenland and Antarctic oscillations. A prominent hypothesis for the temporal linkage features a "bipolar seesaw" in which cooling in one polar hemisphere was countered by warming in the other polar hemisphere, and vice versa. We investigate the origins of ice-age millennial-scale climate variations through the comparison of mid-latitude glacier-derived records, one from the Northern Hemisphere comprising meltwater-sourced sediment deposited offshore from the mouth of the ice-age Channel River between France and England, the other from Southern Hemisphere glacial moraines in the Southern Alps of New Zealand. Together with other proxy records, we re-evaluate whether the bipolar seesaw still offers an adequate explanation of millennial-scale climate shifts, or whether there are better alternatives.

Channel River discharge record

During the maximal phase of the last glaciation [i.e., Last Glacial Maximum – LGM; 26.5-19 ka (Clark and Mix, 2002; Clark et al., 2009)], when the sea was at or near its lowest level, the coalescence of the Scandinavian and British-Irish ice sheets (northwest European ice sheets - EIS) over the area of the present-day North Sea caused rearrangement of western Europe fluvial drainage. Runoff from the southern parts of the EIS merged with drainage from the northwestern part of the Alps to create the west-flowing Channel River, which discharged into the Bay of Biscay (Figure 2). With a catchment area similar to that of North America's Mississippi River, the Channel River was a dominant contributor of fresh water input to the eastern North Atlantic Ocean (Gibbard, 1988; Zaragosi et al., 2001; Ménot et al., 2006; Toucanne et al., 2009, 2010; Boswell et al., 2019).

The records of Channel River discharge come from well-dated marine sediment cores from near the former river mouth (Zaragosi et al., 2001; Ménot et al., 2006; Eynaud et al., 2007, 2012; Toucanne et al., 2009, 2015). Particularly important is core MD95-2002 (Figure 2), whose neodymium isotope composition of the fine-sediment fraction links the detrital sediment in the core with a source along the southern sector of the EIS (Toucanne et al., 2015). Paleo-discharge variations are interpreted from the reconstruction of regional sediment flux and ratios of major elements based on XRF data measured in core MD95-2002, and in other nearby cores (Toucanne et al., 2015). The ratios of Ti/Ca and Fe/Ca register terrigenous inputs and, by extension, past discharge from the Channel River, with higher versus lower values respectively indicating increased or decreased discharge (Figure 3). The links between ice-marginal fluctuations and discharge of the Channel River come from a comparison of the core parameters with moraine chronologies in the source areas (Toucanne et al., 2015). In particular, increased meltwater flow near the end of the last glaciation coincided with ice-margin retreat. Toucanne et al. (2015) concluded that the varying flow of the Channel River monitored the melt response of the EIS to changing summer temperature. Intervals of notably greater runoff are taken to reflect warmer summer temperatures and are labeled, from older to younger, R1-R5. R1 corresponds in time with HS3, R2 with HS2, and R5 with the first half of HS1. R3 and R4 represent increased runoff episodes not recognized as Heinrich stadials. That the Heinrich stadials are interpreted as cold intervals highlights a conundrum: why did increased meltwater discharge from the Channel River occur during cold climate episodes? This problem is underscored by a similar finding that the Danube River, which drained melt from ice-age glaciers of the northeastern Alps, also had increased discharge during Heinrich stadials (Martinez-Lamas et al., 2019).

Southern Alps moraine record

A detailed chronology of alpine glacier fluctuations adjacent to the highest parts of New Zealand's Southern Alps is based on exposure-ages of boulders concentrated in moraine belts (Figure 4) or as erratics on glacially-shaped landscapes (Schaefer et al., 2006, 2009, 2015; Kaplan et al., 2010, 2013; Putnam et al., 2010a, 2010b, 2012, 2013a, 2013b; Barrell et al., 2011; Kelley et al., 2014; Doughty et al., 2015; Koffman et al., 2017; Strand et al., 2019; Denton et al., 2021). In the mid-latitude maritime climatic setting of the Southern Alps, summer melt determined by austral summer season temperature is the major driver of the annual snowline (ELA) position and hence for fluctuations of the glaciers that produced the moraine belts (Anderson, 2005; Anderson et al., 2006; Anderson and Mackintosh, 2006; Anderson et al., 2010; Anderson and Mackintosh, 2012; Lorrey et al., 2014; Purdie et al., 2014; Koffman et al., 2017; Mackintosh et al., 2017; Lorrey et al., 2022). Modeling of glacier extent targeting dated moraine belts, and employing precipitation values ranging 0-30% less than modern, indicates that temperatures necessary for glaciers to occupy moraine belts of full-glacial extent were 6-7°C cooler than modern. The late-glacial moraines farther up the catchments relate to temperatures 2-3°C cooler than present.

Construction of the moraine belts marked the culminations of glacier expansion, followed by glacier retraction that resulted in the moraine belt being preserved. The overall pattern of glacier fluctuations follows a Heinrich pulsebeat in which moraine construction occurred in intervals between Heinrich stadials, with no moraines preserved from the stadials themselves (Figure 3). This pattern of southern moraine construction between northern stadials (Strand et al. 2019) characterized not only the last glaciation but also the last termination. Rapid, large-scale, glacier retreat began at ~18 ka, with the demise of ice-age glaciers during HS1 (17.8 to 14.7 ka) equating to 75% of the glacial/interglacial climate transition in the Southern Alps, with near-interglacial conditions attained by the end of HS1 (Denton et al. 2021). This sustained glacier retraction was followed by glacier resurgence during the Antarctic Cold Reversal (ACR, coeval with the northern Bølling-Allerød interstadial) and then further retreat during HS0 (approximates Younger Dryas from 12.9 to 11.7 ka). Comparison with the isotope signature from the South Pole ice core (Figure 5) highlights a prominent southern registration of the Heinrich stadials (interpreted as warming conditions). Southern Alps moraines formed during intervening times, where the isotope signature indicates cooler conditions.

Significance of the Channel River and Southern Alps records

The two records show close alignment of reduced discharge from the Channel River (troughs in the Ti-Fe curve) and alpine glacier moraine formation in the Southern Alps (Figure 3). Insofar as the Channel River discharge comprised substantial meltwater from the EIS, minima of discharge imply minima of melt, attributable to cooler climate conditions with net ice accumulation. Southern Alps glacier expansion similarly implies cooler temperatures. Greater Channel River discharge during Heinrich stadials, and coeval absence of Southern Alps moraine formation in the full-glacial moraine belts, suggest warmer temperatures in both regions. Rather than showing a bipolar seesaw pattern, notable synchronicity is evident between the Channel River and the Southern Alps records.

Concept framework

The bipolar seesaw is a hypothesis for millennial-scale differences between Greenland and Antarctic isotopic signatures in ice cores. A favored mechanism is interhemispheric redistribution of heat through an oceanic seesaw, augmented by atmospheric components (e.g., Pedro et al., 2011, 2018; WAIS Divide Project Members, 2015). A deep-water version of the seesaw posits that the interhemispheric temporal linkage arose from alternations in ocean heat transport caused by perturbations in the relative strengths of formation of North Atlantic Deep Water and Antarctic Bottom Water (Broecker, 1998). Another version of the seesaw is based on the effects of variations of Atlantic overturning circulation on the transport of near-surface ocean heat across the equator (Crowley, 1992; Stocker and Johnsen, 2003).

Assuming that the ocean/atmosphere bipolar seesaw hypothesis is correct, then a small temporal lead of Greenland climate breakpoints over their Antarctic counterparts has been interpreted as indicating a Northern Hemisphere origin for millennial-scale temperature shifts, with the North Atlantic region being the likely source (WAIS Project Members, 2015). The possibility is acknowledged that the Greenland breakpoints may have been a response to a “remote process not visible in the ice core records” (WAIS Project Members, 2015).

In contrast, the Channel River and Southern Alps records, as one comparative example of mid-latitude data, show a view of interhemispheric synchrony (within age uncertainties) of shifts to or from episodes of generally warmer summers. Examining data from the middle latitudes, where seasonality is prominent, we explore the idea that the millennial-scale stadials of the last glaciation and termination were inter-regional expressions of globally uniform climate oscillations.

Northern Hemisphere oceanic signatures

Heinrich stadial episodes encompassed distinctive signatures in Greenland ice core $\delta^{18}O$ and in peaks of North American ice-rafted debris (IRD) deposition, called Heinrich events. Increased IRD deposition was a feature of Heinrich stadials not just generally in the northern North Atlantic but also more specifically in proximity to major ice streams of the Northern Hemisphere ice sheets, including the North Pacific (Walczak et al., 2020; Figure 6a-c). These recurring episodes of ice discharge from Northern Hemisphere ice sheets into two oceans implies widespread rather than localized ice-sheet instability. In unison with increased sediment deposition during HS3, HS2 and HS1 (Figure 6c-d), relatively warmer conditions in summer offers, in our view, a likely explanation for these observations. Thus, we suggest that the progressive warming registered in isotopic records from Antarctic ice during Heinrich stadials (Figure 6e) is indicative of a widespread phenomenon, as exemplified in the comparison of the Channel River and Southern Alps records (Figure 3).

Sedimentary archives from the North Atlantic region yield elements of two millennial-scale climate signals, one similar to that in the atmosphere over Greenland and the other similar to that in the atmosphere over Antarctica as registered in ice cores. According to Rasmussen et al. (2016), the Greenland signal equates to stratification of the water column through formation of a surface layer of cold, low-salinity water, linked to an influx of meltwater and/or icebergs. The Greenland signal is prominent in records from the Nordic Seas (Rasmussen and Thomsen 2008), in the Ruddiman ice-rafting belt (Rasmussen et al., 2016), near the Bermuda Rise (Gil et al., 2009; Henry et al., 2016), in the eastern North Atlantic near the Iberian Peninsula (Sánchez Goñi et al., 2000; Shackleton et al., 2000), as well as in the western Mediterranean basin (Sánchez Goñi et al., 2002). In contrast, the Antarctic signal is evident in open marine areas which experienced only modest influxes of Heinrich stadial icebergs (Rasmussen et al. 2016), such as near the Reykjanes Ridge (Rasmussen et al., 2016) and in the southern and central North Atlantic (Ruhlemann et al., 1999; Pahnke and Zahn, 2005; Peck et al., 2008; Naafs et al., 2013; Guilderson et al., 2021), with an example illustrated in Figure 7. A common explanation for cold conditions during Heinrich stadials is that a low salinity surface layer of the North Atlantic Ocean afforded a platform for the widespread formation of sea ice (Denton et al., 2005).

Seasonality in the North Atlantic and western Europe regions

Contrasts in seasonality are suggested to have played a central role in the signatures of Greenland ice-core and moraine records from the last glaciation and termination (Denton et al., 2005). From thermally fractionated gases in the GISP2 ice core, the Younger Dryas/HS0 section shows a mean annual temperature 15°C colder than today at the Greenland summit (Severinghaus et al.,1998). In contrast, the positions of late-glacial moraines of outlet glaciers in the coastal mountains near Scoresby Sound in southeastern Greenland (Figure 8) indicate Younger Dryas summertime temperature no more than a few degrees cooler than today. In combination with the ice-core registered mean annual temperature, these relatively mild summer temperatures imply an average winter temperature 26-28°C cooler than today (Denton et al., 2005; Broecker, 2006). Such marked seasonality is best explained by an extensive Younger Dryas winter sea ice cover on the North Atlantic Ocean (Denton et al., 2005; Broecker, 2006).

A more recent chronologic study of moraines related to late-glacial ice recession in southeastern Greenland in the Scoresby Sound region suggests that summers may have become progressively warmer during the Younger Dryas (Levy et al., 2016). If so, seasonality would have been even greater than shown in Figure 8. In accord with these new chronological data from Scoresby Sound, Funder et al. (2021) and Carlson et al. (2021) documented ice retreat along Greenland's southwestern coast and noted recession from elsewhere along the ice-sheet margin during Younger Dryas time. These results from Greenland are further supported by evidence from the Scottish Highlands (Bromley et al., 2014; 2018) and from northern Norway (Wittmeier et al., 2020) for glacial recession during Younger Dryas time.

The overall result reflects Younger Dryas seasonality, with ice-sheet margin recession due to the effect of warm summers on the peripheral ablation zone, paired with exceptionally cold winters that collectively produced an overall very cold mean annual temperature registered, for example, in the GISP2 ice core from the summit of the Greenland Ice Sheet (Severinghaus et al., 1998).

Extreme seasonality is also indicated for late glacial time in northwestern Europe from subfossil remains of species of plants and beetles, together with evidence for the distributions of permafrost. The results show extremely cold winter temperature and no more than modestly cooler summers during HS1 and the Younger Dryas, thus providing further evidence of late-glacial episodes of winter-dominant extreme seasonality. A shift to substantially less cold winters heralded a return to normal seasonality with warmer mean annual temperatures that characterized the Bølling and the Holocene (Atkinson et al., 1987; Isarin, 1997; Isarin et al., 1998; Isarin and Bohncke, 1999; Renssen and Isarin, 2001; Renssen and Bogaart, 2003). The central role of North Atlantic sea ice in producing the winter-dominant cold pulses evident both in the Greenland ice-core and in the northwest European terrestrial records has been widely discussed in the literature. There is much support for the late glacial climate record of millennial change of northwestern Europe reflecting variations of the sea-ice cover on the North Atlantic Ocean (e.g., Li et al., 2005; Fluckiger et al., 2008; Sime et al., 2019).

Other biological records also highlight an association of millennial-scale climatic shifts and varying seasonality. For example, in marine sediment core MD95-2042 collected near the southwestern margin of the Iberian Peninsula, the oxygen-isotope signature from planktonic foraminifera mimics the Greenland isotopic pattern, whereas the benthic foraminifera oxygen isotope record is similar to Antarctic ice-core isotopic signals (Shackleton et al., 2000). Seasonality is also expressed in paleo-vegetation records from pollen spectra, which follow the

Greenland signal, not the Antarctic signal (Sánchez Goñi et al., 2000). Winter cold and dry intervals on the Iberian Peninsula accompanied the Heinrich and Dansgaard/Oeschger cold stadials registered in Greenland ice. Another example is provided by marine sediment core MD95-2043 from the western Mediterranean Sea (Sánchez Goñi et al., 2002), where the sea-surface temperature (SST) indicators and pollen signatures in MIS 3 co-vary together with a Greenland pattern. The pollen shows alternating steppe (stadial) and Mediterranean forest (interstadial) biomes, while the mean SST implies cold stadial winters (as does the SST record from MD95-2042).

If there is merit in the view that the climate variability interpreted from Greenland ice cores is heavily weighted toward the winter season (Denton et al. 2005; Broecker, 2006; Buizert et al., 2014, 2018; He et al., 2021), then the parallelism between ice-core and vegetation records suggests that the millennial variability of southern European vegetation resulted largely from wintertime forcing, with Greenland temperature and European vegetation distribution both following North Atlantic winter sea ice. We think that winter conditions severe enough to preclude some species of trees and other frost-sensitive vegetation from the European landscape would likely hamper attempts to interpret summer temperatures from vegetation records. This is apparent, for example, in paleoclimate records from Switzerland. Lake marl at Gerzensee on the northern border of the Alps yielded high-resolution stacked isotopic records showing the distinctive switch from Oldest Dryas (HS1) to Bølling climate, as well as the patterns of the Younger Dryas and minor oscillations such as the Gerzenzee and Aegelsee cool climate episodes (Siegenthaler et al., 1984; Van Raden et al., 2013). The Gerzensee pollen record has the Oldest Dryas section dominated by open herb-shrub tundra vegetation, bereft of birch and pine trees, followed by the iconic juniper peak at the boundary between the Oldest Dryas and the Bølling, approximately coeval with the isotopic switch (Ammann et al., 2013). A hallmark of the Bølling was the first appearance of late-glacial trees, with birch first, followed by pine, and within a few centuries the landscape supported birch/pine woodland. Permafrost was probably present near Gerzensee in Oldest Dryas time, but had melted out by early in the Bølling (Ammann et al., 2013). Other sites revealing characteristic Oldest Dryas steppe-tundra vegetation occur on the Swiss plateau, as well as in formerly glaciated valleys well inboard of the LGM ice limits (Eicher and Sigenthaler, 1976; Burga,1988). From these data, Burga (1988) concluded that *Artemisia* steppe-tundra dominated the Oldest Dryas vegetation prior to the onset of the Bølling, and that such sites inside the LGM ice limit demonstrate that immediately following the LGM, glaciers receded deep into the Alps, leaving only the high passes still glaciated. This was considered to reflect summer melting. During subsequent Bølling time, the vegetation records showed the spread of birch, pine, and juniper on a landscape already deglaciated. Thus, strong seasonality associated with HS1 is registered in the Swiss records.

Heinrich Summers hypothesis

Available data present two major difficulties for the bipolar seesaw concept. First is the observation of Steig and Alley (2002) that the Antarctic and Greenland ice-core proxy climate records are anti-phased for only about 50% of the time, but show closely similar signatures of change during the remaining 50%. Second, the characterization of Greenland stadials as fundamentally cold climate episodes is at odds with the concept of extreme seasonality, featuring hyper-cold winters but generally mild summers. A seesaw model thus offers at best only a partial explanation for the ice-core isotopic patterns. But it is not in accord with the comparison of summer-dominated ice melt records from northern Europe with glacier advance/retreat at an equivalent latitude in the Southern Hemisphere (Figure 3). Both records indicate glacier melt in their respective summer seasons. They show that the anti-phasing between the hemispheres seen in ice-core records disappears when specifically considering summer conditions. Here we propose an alternative explanation for the apparently anti-phased parts of the record, dubbed the Heinrich Summers hypothesis, focused on the climatic effects of abundant summer meltwater in the North Atlantic Ocean. Attention is directed here towards the Heinrich oscillations, which appear to have had stronger climatic imprints than the Dansgaard/Oeschger oscillations, although similar general principles apply to both.

A natural conditioning toward seasonality in northern latitudes exists because the two polar hemispheres have contrasting geographical configurations, with the northern featuring huge continents and the southern being ocean-dominated. In the Heinrich Summers hypothesis, the structural and temporal differences in ice-age millennial-scale climate signals between the two polar regions arises from differing amplifications of seasonality. The amplification of northern seasonality was strongly linked to the presence of substantial ice-age ice sheets on northern North America and northern Europe. Freshwater delivery into the North Atlantic Ocean, through both influent meltwater and melting icebergs, presents a mechanism for the formation of a low salinity surface water stratum in the ocean, which is then susceptible to extensive winter freezing. During the last ice age whenever the northern North Atlantic was covered with sea ice, a huge sector of the Northern Hemisphere stretching from North America to eastern Asia became essentially continental, leading to extreme seasonality marked by exceptionally cold winters (Denton et al., 2005). This raises the question of what caused the northern climate to cross this threshold into extreme seasonality. A counterintuitive answer is that the change resulted from a shift to warmer summers that stimulated increased ice melt and iceberg discharge into the North Atlantic Ocean from European and North American ice sheets, leading to exceptional winter sea ice on the summer-freshened ocean surface. By this view, the northern ice-age stadial signature is an expression of extreme seasonality (Denton et al., 2021).

The correspondence in the timing of Northern Hemisphere Heinrich episodes, related to enhanced iceberg-and-meltwater discharges, and Southern Hemisphere mountain glacier recession, points to the occurrence of episodes of warmer summers in both hemispheres. By the Heinrich Summers hypothesis, the Cordilleran, Laurentide, Greenland, Barents, Scandinavian, and British/Irish ice sheets responded to each Heinrich warming episode by net ice loss, with two examples of warmer conditions being the Channel River meltwater outflow and Hudson Strait ice discharge (Toucanne et al., 2015; Zhou et al., 2021). A likely consequence of the resulting extensively freshened sectors of the surface of the North Atlantic Ocean (Rasmussen et al., 2016) would have been a weakening of the Atlantic Meridional Overturning Circulation (AMOC) (Bohm et al., 2015; Henry et al., 2016), providing a further feedback that stimulated expansion of winter sea ice. The sea-ice lid would also have reduced heat exchange between the ocean and the atmosphere. As a result, the winter climate of the North Atlantic region during each Heinrich episode would have switched from maritime to continental, with greatly increased summer-winter seasonality over the course of each year. In sum, warm summers generated glacier melt, which then produced a derivative signal of very cold winters via the consequent rollout of sea ice and reduction of the AMOC. Because the effects were so strong in the North Atlantic region, the large winter sea-ice signal overpowered any smaller summer signature in Greenland ice cores, with the possible exception of the HS1 episode (He et al., 2021). Modelling experiments highlight a linear relationship between the extent of North Atlantic winter sea ice and the air temperature over central Greenland (Roberts and Hopcroft, 2020). By the Heinrich Summers hypothesis, the excessively cold northern stadial winters closely linked to summer melt of adjacent ice sheets create a false impression of a bipolar seesaw with Southern Hemisphere climate.

Stratification of the northern North Atlantic Ocean surface water under ice-age stadial conditions is suggested to have inhibited heat loss from subsurface water (Rasmussen et al., 2016; Su et al., 2016). This may have led to subsurface ocean warming that could have enhanced subsurface melting at ice-sheet grounding lines (Shaffer et al., 2004; Marcott et al., 2011). Recent analogs are afforded from West Greenland (Holland et al., 2008) and West Antarctica (Joughin et al., 2021), where melt-driven thinning at grounding lines is suggested to have resulted in speedup of ice streams. This mechanism may also account for the greatly enhanced iceberg production that characterized Heinrich episodes (Shaffer et al., 2004; Marcott et al., 2011). Of particular note is the finding that the increase in IRD routinely followed the onset of Heinrich climate conditions (Barker et al., 2015), suggesting that iceberg generation was a consequence, not a cause, of those conditions.

Superimposition of the Greenlandic and Antarctic isotopic records (Figure 1) highlights the strong similarity of the records, apart from the differences during Greenland stadial episodes. By the Heinrich Summers hypothesis, the Antarctic AIM episodes, which are paired with the Greenland stadials (both Heinrich and Dansgaard/Oeschger), are an expression of a foundational global signal of millennial-scale climate oscillations, in alignment with the proposition of Barker and Knorr (2007) that the Antarctic ice-age climate signal was globally pervasive. The Antarctic signature being an expression of climate shifts of global reach is consistent with the interpretation of summer warmth in melt records of the Channel River during HS1, HS2, and HS3. Moreover, there are indications of warm Younger Dryas (HS0) summers in Europe (Schenk et al., 2018), in step with the Younger Dryas ice-marginal retreat described above for Greenland. During such North Atlantic extreme-seasonality episodes, we suggest that the Greenland winter signal so dominated the mean annual temperature there that a global signature of relatively warm summers was masked. Nevertheless, western Europe records that are directly linked to summer conditions, such as the Channel River meltwater discharge, illustrate the occurrence of relatively warm summers accompanying North Atlantic winter stadials. The notion of warm summers associated with winter stadials is also exemplified by the large-scale retreat exhibited during HS1 by ice-age glaciers to positions deep within the European Alps, as shown by the occurrence of Oldest Dryas pollen signatures in post-glacial sediments.

Terrestrial records, such as pollen, might at first glance be interpreted as showing cold summers during Heinrich episodes, such as illustrated by the iconic representation of the tundra plant *Dryas octopetala*. However, an alternative possibility is that only frost-tolerant vegetation survived the severely cold stadial winters. The imprint of North Atlantic winter stadial conditions is highlighted by the extensive persistence of tundra vegetation and permafrost in mid-latitude Europe during the Oldest Dryas (Renssen and Isarin, 2001). The replacement of tundra by temperate vegetation, including forest, proceeded rapidly at the onset of the Bølling interstadial. The findings of Renssen and Isarin (2001) of a recovery of at least 15°C in winter (January) temperature across the Oldest Dryas/Bølling boundary can be interpreted as a return to normal seasonality, in the Heinrich Summers hypothesis. This importance of winter-limiting controls on vegetation is illustrated, for example, by the modern United States Department of Agriculture plant hardiness zone map of North America (Daly et al., 2012), which uses winter coldest temperatures as a major determinant of which species can survive in which winter climate zone. We suggest that warmth of summer climate is difficult to determine from vegetation records if the winter climate is too cold to allow survival of key elements of the vegetation in the first place. The example of the mismatch in the Swiss evidence from Oldest Dryas time, where glaciers receded far back into the Alps, but trees had yet to appear on the alpine foreland that remained characterized by the herbs and shrubs of Oldest Dryas tundra, is an example of a high degree of seasonality associated with winter stadial conditions in the North Atlantic region.

We postulate that North Atlantic seasonality was normal when the Greenland and Antarctic ice-core isotopic signals (Figure 1) varied in approximate unison, but the two patterns diverged when North Atlantic seasonality was exceptionally strong. The classic stadial/interstadial oscillations registered in Greenland ice cores are illustrated in relation to HS4 and HS5 in Figure 1c-d. Following an initial pronounced warming peak representing a Greenland interstadial, there ensued a parallel cooling ramp in both signals for the remainder of the interstadial. An approximately coeval change saw the onset of a rising (warming) trend in the Antarctic signal, while the Greenland signal dropped to prolonged minimal values marking the low mean annual temperatures associated with North Atlantic extreme seasonality, dominated by exceptionally cold winters. A key relationship is expressed when each Greenland stadial ended. The Greenland isotope signature abruptly rebounded to align closely with the Antarctic signature. By the Heinrich Summers hypothesis, we attribute the stadial signal to extreme northern winters, without which we suggest the Greenland and Antarctic signals would be broadly the same. In that regard, we propose that the trend of warming seen in Antarctica during northern winter-dominated climatic episodes illustrates in general terms what the character of northern summers may have been like during episodes of winter-stadial climate. We consider that the Greenland peak interstadials reveal the true nature of summer climate there, when unmasked from the overpowering signature of extremely cold winters.

We suggest that the Antarctic isotopic signature is a regional expression of climatic shifts arising elsewhere, for example in the mid-latitudes and tropics as described by the Zealandia Switch hypothesis (Denton et al., 2021). We take the subdued nature of the rising and falling ice-core isotopic trend of each AIM event to indicate that the Southern Ocean was slow to heat following a shift to warmer climate, and that the Antarctic signature is primarily associated with high-latitude Southern Ocean conditions. We view the abrupt onset of each millennial-scale climatic 'stadial' in the Greenland record as indicating a rapid shift to warmer summers that generated a prominent increase in meltwater discharge into the North Atlantic Ocean. Similarly, we envision the abrupt end to each 'stadial' as reflecting a shift in climate of global reach to cooler summer conditions that notably lessened meltwater input such that the cold and low-salinity surface layer on the North Atlantic could not be maintained. The resulting weakening of the cap of cold, low-salinity water and sea ice allowed relatively warm and saline subsurface water, which had built up at depth during the stadial, to punch through the surface stratification and release heat into the atmosphere (for discussion of various aspects of subsurface warming and/or overturning of the stratified water column see, for example, Shaffer et al., 2004; Marcott et al., 2011; Rasmussen and Thomsen, 2004; Thiagarajan et al., 2014; Guilderson et al., 2021). This caused an abrupt end to extreme seasonality, with the greatest change in winter. A repeated return of a normal seasonality condition through this mechanism could have produced the repeated iconic warm jumps seen in Greenland isotopic signatures. To explain the classic signature of the Dansgaard/Oeschger events, interpreted as comprising an abrupt warming succeeded quickly by a strong cooling trend, we posit that a shift to cooler summers reduced the meltwater flux and in turn winter sea ice extent, thus releasing the North Atlantic regional climate back to normal seasonality.

Discussion

The Heinrich Summers hypothesis has two major tenets. One is that the ice-age millennial-scale climate oscillations arose from temperature variations of global scope. By this hypothesis, the so-called Antarctic climate signal is regarded as a general representation of the character of the millennial-scale oscillations in both hemispheres. The second major tenet is that the anti-phased relations within the millennial-scale climate oscillations registered in Antarctic and Greenland ice cores is due to an exceptional rollout of sea ice in the North Atlantic that was a derivative winter response to global warming during each oscillation episode. This derivative winter response dominated Greenland isotopic signatures, giving the impression, when viewed in isolation, of a bipolar seesaw of climate change between the two polar hemispheres.

There are several lines of evidence, in addition to those described above, that reinforce the view that the Antarctic signal reflects global climate shifts. One is the meltwater signal produced by variations in the flow of the Mississippi River, when it drained the southern sector of the Laurentide Ice Sheet to the Gulf of Mexico during MIS 3. The flow variations did not follow the Greenland temperature signal but rather aligned with the Antarctic temperature signal, suggesting an ‘Antarctic’ influence on summer melting of the southern Laurentide Ice Sheet (Hill et al., 2006). Particularly important was the Gulf of Mexico freshwater event that aligned in time with the prominent Antarctic AIM warming episode during HS4. Taken together with the data relating to flow of the Channel River, this implies that notable melting episodes took place during HS1, HS2, HS3, and HS4 on the two main Northern Hemisphere mid-latitude ice sheets. At the same times, the Southern Alps moraine record indicates retracted glaciers, further highlighting the interhemispheric extent of warmer conditions during these four Heinrich stadials. A similar illustration of Heinrich stadial warmth comes from pollen analysis of a core from Lake Tulane in Florida (Grimm et al., 2006), not far from the site of the Gulf of Mexico meltwater record obtained by Hill et al. (2006). The Lake Tulane core shows a succession of peaks of *Pinus* pollen, indicating warm and wet summer climate episodes aligned with Heinrich events 1-5 in the North Atlantic Ocean.

Another reinforcing example comes from a comprehensive glacier modelling experiment that was unable to simulate the major fluctuations of the Alps icefields using forcing from the Greenland temperature record from the GRIP ice core (Seguinot et al., 2018). Instead, the requisite ice-volume fluctuations were best reproduced from a model forced by the Antarctic temperature signal from the EPICA ice cores.

In regard to the second tenet, the Northern Hemisphere winter was an important linkage between Greenland and European temperature changes during millennial-scale oscillations. The strength of the monsoon in Asia tracked Greenland temperatures, with reduced northern subtropical monsoonal circulation prevalent during Greenland stadials (Wang et al., 2001; Cheng et al., 2016; Bradley and Diaz, 2021). The importance of the northern winter stadial arose from meltwater-induced expanded sea ice on the North Atlantic Ocean that reduced the maritime influence and imparted greater continentality to a huge expanse of the Northern Hemisphere from northern North America to eastern Asia. The climate of this huge sector of the planet was close to a critical winter threshold during the last glaciation, susceptible to perturbing triggers such as episodes of warmer summers that injected glacial melt into the North Atlantic, with effects including interpreted slowing of AMOC overturning, winter expansion of sea ice, and extremely cold winters. The resulting episodes of strong seasonality required the existence of large ice sheets to supply freshwater directly into the North Atlantic Ocean, and is why the millennial-scale climate oscillations that produced winter stadial events were restricted to glacial times.

By the Heinrich Summers hypothesis, differences in the amplitude and shape of the millennial-scale climate oscillation signatures, as well as differences in the timing of climate breakpoints, in the two polar hemispheres represent different responses to a common global climate signal. The Antarctic response was a relatively smooth mean annual signal. The Greenland response included a severe winter signal leveraged by the spread of sea ice on the North Atlantic. A reason why the response may have been delayed and muted in Antarctica is that it may have depended on disruption of Southern Ocean stratification and consequent ocean warming. Therefore, the signals in the two polar regions could represent different responses to the same underlying global summer warming episodes, with the north reacting more sharply and rapidly than the south.

Due to the post-glacial demise of the large northern ice sheets, no modern analog exists in the North Atlantic region for a Heinrich-style influx of meltwater and icebergs leading to the formation of extensive sea ice. But there are similarities to the situation caused by recent Antarctic ice-sheet melt that has led to stratification of the adjacent parts of the Southern Ocean and a spread of sea ice, resulting in subsurface ocean warming and surface ocean cooling in a warming world (Bronselaer et al., 2018, 2020; Haumann et al., 2020).

The Heinrich Summers hypothesis is itself only a partial explanation for millennial-scale climate oscillations because it does not account for what caused these climate changes of global significance in the first place. A possible mechanism is encompassed in the Zealandia Switch hypothesis, which proposes that shifts in Southern Hemisphere atmospheric and oceanic circulation, interacting with southern continental platforms, had global climatic consequences through direct linkages into tropical circulation systems (Denton et al., 2021). The temporal commonality of glacier-related records at southern and northern mid-latitude localities of New Zealand and the Channel River in western Europe, along with melting of sectors of northern ice bodies during Heinrich episodes, could reflect changes in the latitude and strength of the austral wind system, with the far-reaching climate consequences. The overall implication is that the austral westerlies could have worked together with the planet’s heat engine in the tropical ocean to produce the global footprint necessary for the climate oscillations superimposed on the last glaciation and its termination.

Comprehensive tests of the Heinrich Summers hypothesis rely on quantifying seasonal conditions from robust paleo-proxy chronologies in both polar hemispheres. The emerging evidence from temperature-sensitive glaciers located in opposite polar hemispheres that apparently advanced and retreated in synchrony on millennial timescales during the last glaciation, along with the in-phase ice-age termination, argues for the necessity of a modified unifying theory for Quaternary glaciations and global climate change.

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Figure Captions

Figure 1. Superimposition of Greenland (blue; NGRIP; Andersen et al., 2004; Buizert et al., 2015) and Antarctic (orange, WDC; Buizert et al., 2015) ice-core $\delta^{18}O$ records. Panels show ice-core signatures spanning 22 – 68 ka (a); 10 – 26 ka, i.e., including deglacial time (b); and enlargements of the 34 – 41 ka (c) and 43 – 51 ka (d) time intervals, including the HS4 and HS5 stadials, respectively. HS: Heinrich stadial. GI: Greenland interstadials. GIs are numbered according to Rasmussen et al. (2006, 2014) and Buizert et al. (2015). Light blue/orange lines correspond to high-resolution data from the NGRIP and WDC ice cores, respectively. Thick blue/orange lines are 50-pt moving averages (from Buizert et al., 2015). Downward-pointing black arrows signify intervals of coeval Greenland and Antarctic cooling during Greenland interstadials. Vertical pink bands show Heinrich stadials. Vertical gray bands show Greenland interstadials. Figure adapted from Buizert et al. (2015).

Figure 2: Palaeogeography of western Europe at the Last Glacial Maximum. The glacial limits of the western European Ice Sheet (EIS), including the Scandinavian (SIS), British-Irish (BIIS) components, and Alpine Ice Sheet (AIS) are shown, along with the Channel and Danube river hydrographic networks (white arrows). Br.: Brandenburg-Leszno moraine (formed between 23.4 ± 0.3 and 20.3 ± 0.2 ka), Fr.: Frankfurt-Poznan moraine (from 18.7 ± 0.3 to 18.2 ± 0.2 ka), Pm.: Pomeranian moraine (from 16.7 ± 0.2 to 15.7 ± 0.3 ka) (Toucanne et al., 2015). The location of core MD95-2002 in the Bay of Biscay is also shown.

Figure 3. Comparison of a) Meltwater flux through the Channel River (Toucanne et al., 2015) with b) intervals of moraine construction in the Southern Alps of New Zealand (Denton et al., 2021, and references therein). In (a), the XRF Fe/Ca (light blue) and Ti/Ca (red) ratios from core MD95-2002 (see location in Figure 2) can be regarded as a first-order indication of relative changes in the amount of fine terrigenous components of Baltic origin from the Channel River. The latter is independently supported by the logarithmic plot of turbidite flux (dark blue) in the deep Bay of Biscay, a proxy for Channel River floods (Toucanne et al., 2015). Vertical pink bands correspond to Heinrich stadials (HS) and vertical blue bands are intervals of reduced runoff from the Channel River. LLGM refers to the local last glacial maximum. R1 – R5 refers to the Channel River meltwater (i.e., runoff) intervals identified by Toucanne et al. (2015). (b), episodes of Southern Alps moraine construction correspond with periods of reduced meltwater flux into the North Atlantic, whereas periods of Southern Alps glacier recession (such as during Heinrich Stadial 1) coincide with periods of intensified meltwater discharge into the Bay of Biscay. The moraine age versus temperature plot in Figure 3 is based on data from Table S-2 in Denton et al. (2021).

Figure 4. Oblique aerial photograph, vantage north, of the left-lateral moraine system deposited by the former Pukaki Glacier during the last glaciation, which flowed southward from the Main Divide of the Southern Alps. Exposure dates of these moraines are included in Figure 3, with details given in Kelley et al. (2014), Doughty et al. (2015), Strand et al. (2019), and Denton et al. (2021). Maps providing broader geographical context for these specific field areas are also presented in these studies.

Figure 5. Climate change either side of the Southern Ocean since 50 ka. Top: Southern Alps glacier-inferred temperature curve (see Figure 3). Bottom: South Pole Ice Core (SPICE) $\delta^{18}O$ record (Steig et al., 2021) placed on the SP19 timescale of Winski et al. (2019). Vertical pink bars represent durations of Heinrich stadials (HS). Vertical blue bars represent episodes of Southern Alps moraine construction.

Figure 6. Phasing of meltwater discharges in ice-proximal settings of the North Atlantic and North Pacific during Heinrich Stadials (HS), and their relationship with Heinrich events (HE). a), NGRIP $\delta^{18}O$ (GICC05 chronology; Svensson et al., 2008) and the North Atlantic IRD stack (Stern and Lisiecki, 2013). b) Bulk carbonate as % $CaCO_3$ (that defines the Hudson Strait source and the HE) and $\delta^{18}O$ of the planktic polar foraminifera *Neogloboquadrina pachyderma* in core Hu97048–07, Baffin slope (Rashid et al., 2012); c) total mass accumulation rates and IRD mass accumulation rates (S*x*=Siku events) at IODP Site U1419, Alaskan margin (Walczak et al., 2020); d) turbidite (i.e. flood-related deposits) flux of Baltic origin off the Channel River, (Toucanne et al., 2015); e) West Antarctic WDC $\delta^{18}O$ record (WAIS Divide Project Members, 2015) with the black arrows highlighting warming episodes. The NGRIP $\delta^{18}O$ is also shown. All data sets are shown on their original published age models. The vertical red dashed lines show the timing of HE (i.e., the deposit of Hudson Strait IRD; vertical gray bars) at each site (except in c). Vertical blue bars highlight the periods of significant meltwater releases (as suggested by sediment flux and freshwater proxies) preceding HEs (vertical gray bars in b and d). Note that (1) increased meltwater flux typically continued during and after HEs; (2) if the timing of IRD deposition at each site (i.e., HEs in the North Atlantic vs Siku events in the North Pacific; Walczak et al., 2020) shows a complex pattern (i.e., lead-lag), the Cordilleran (c), European (d), and Laurentide (b) episodes of meltwater release preceding HEs are near-synchronous (within age uncertainties).

Figure 7. Southern Hemisphere paleoclimate records (top) compared with sea-surface temperatures (SSTs) of the North Atlantic subtropical gyre since 70 ka (bottom). Top: Southern Alps glacier-inferred temperature record (see Figure 3) superimposed upon the West Antarctica WDC temperature reconstruction (Buizert et al., 2015; Cuffey et al., 2016). Bottom: Alkenone-derived SSTs from International Ocean Discovery Program (IODP) core U1313 at 41°N in the mid-latitude North Atlantic Ocean (Naafs et al., 2013). Red arrows indicate Heinrich stadial SST warming intervals.

Figure 8. An interpretation of Younger Dryas climatic conditions in the Greenland region, used with permission and modified slightly from Broecker (2006), in turn following Denton et al. (2005). Red dots indicate the locations of the ice cores discussed in Denton et al. (2005). The mean annual temperature relative to modern is derived from the measurements of argon and nitrogen trapped in the GISP2 ice core on Summit, Greenland (Severinghaus et al., 1998). The summer temperature is from estimated snowline elevations associated with moraine belts of glaciers draining the mountains alongside Scoresby Sound (Denton et al. 2005). The winter temperature estimate represents the conditions necessary, in combination with the summer temperature estimate, to produce the mean annual temperature calculated by Severinghaus et al., 1998). Such extreme winter cold is interpreted as a consequence of the North Atlantic being extensively frozen during Younger Dryas winters.

Figure 1

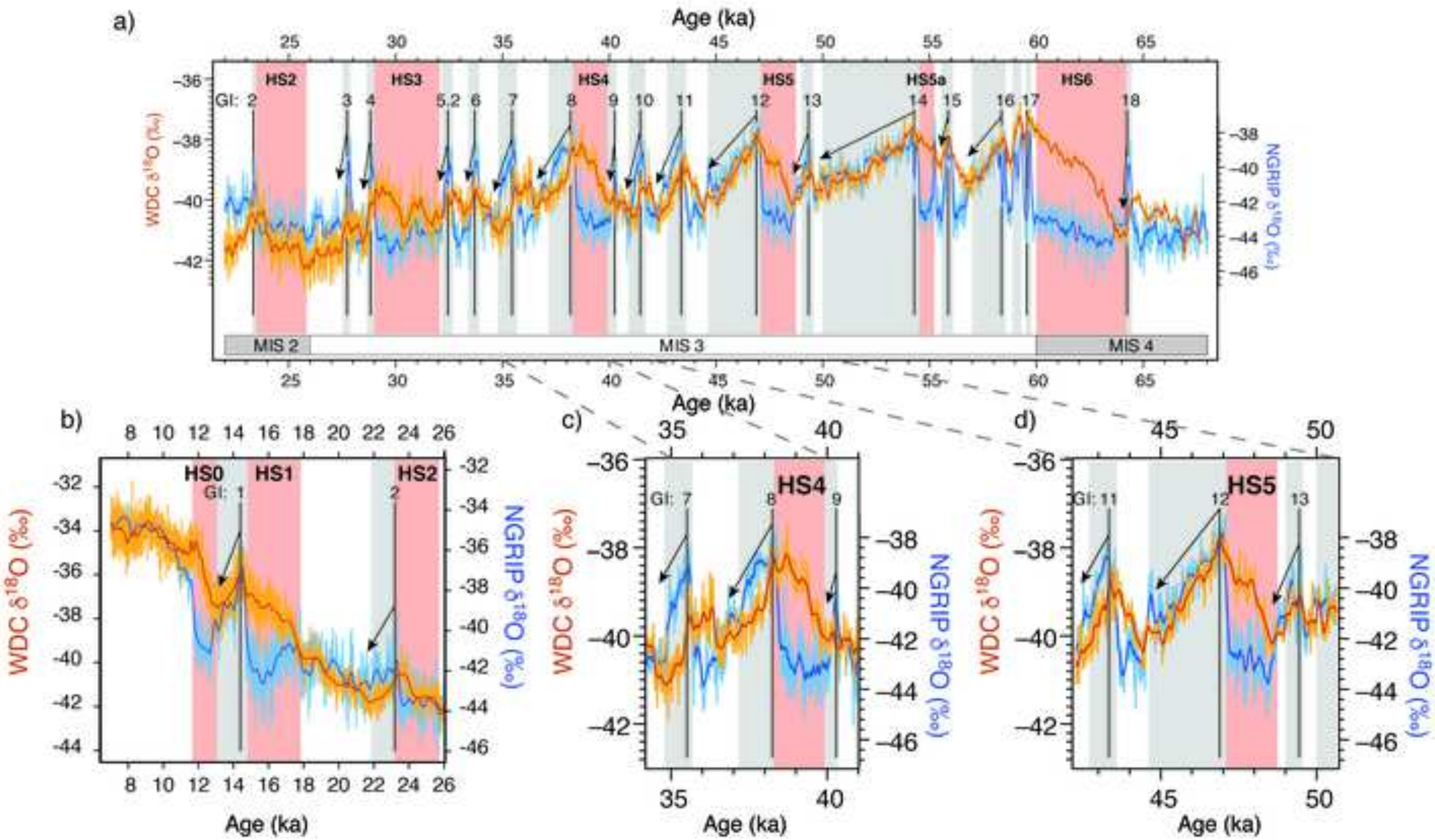
a)
Age (ka)
HS2
HS3
HS4
HS5
HS5a
HS6
GI: 2
MIS 2
MIS 3
MIS 4
WDC δ18O (‰)
NGRIP δ18O (‰)
b)
HS0
HS1
HS2
GI: 1
c)
HS4
GI: 7
d)
HS5
GI: 11

Figure 2

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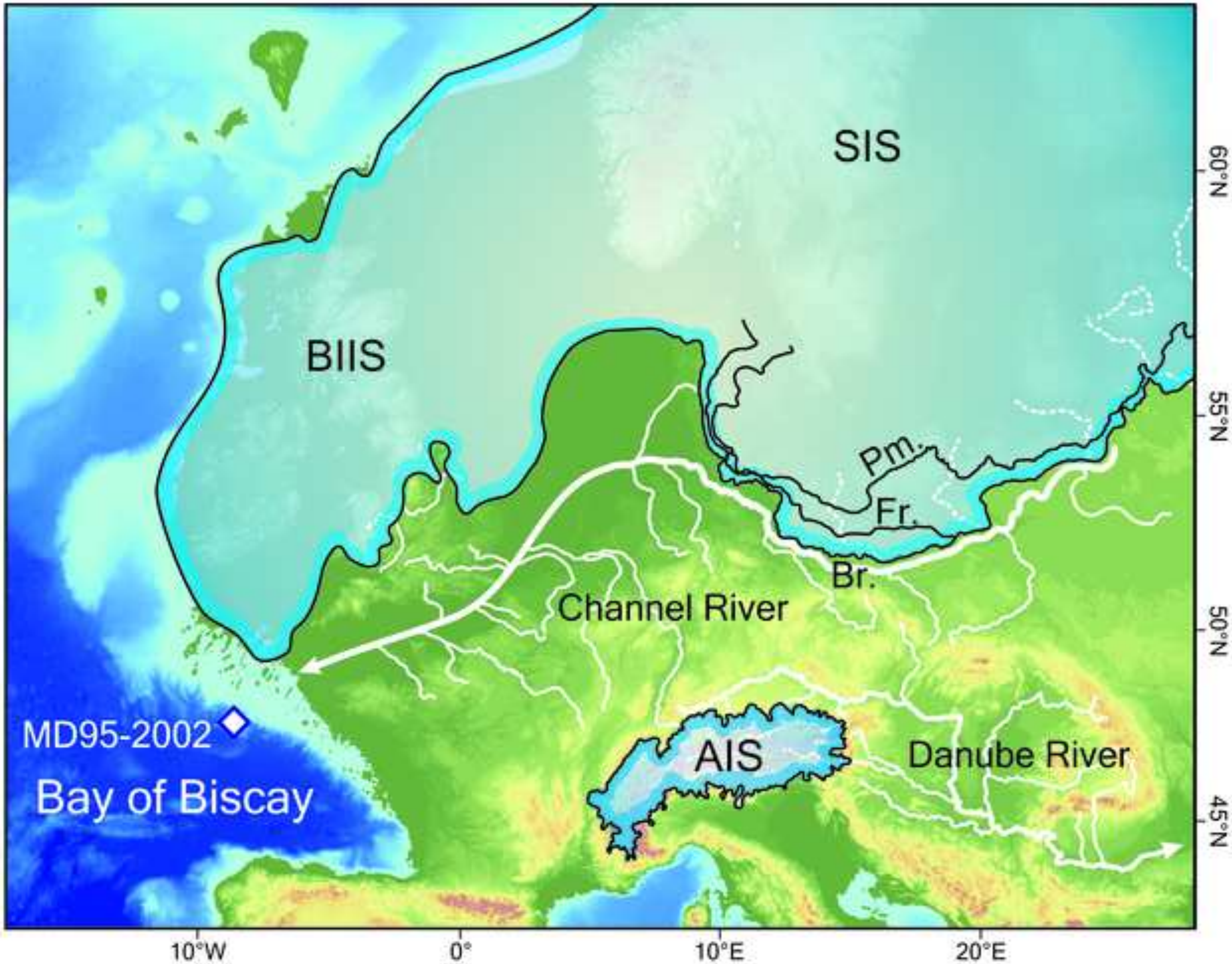

Figure 3 Click here to access/download;Figure;Fig_3_ST.tif

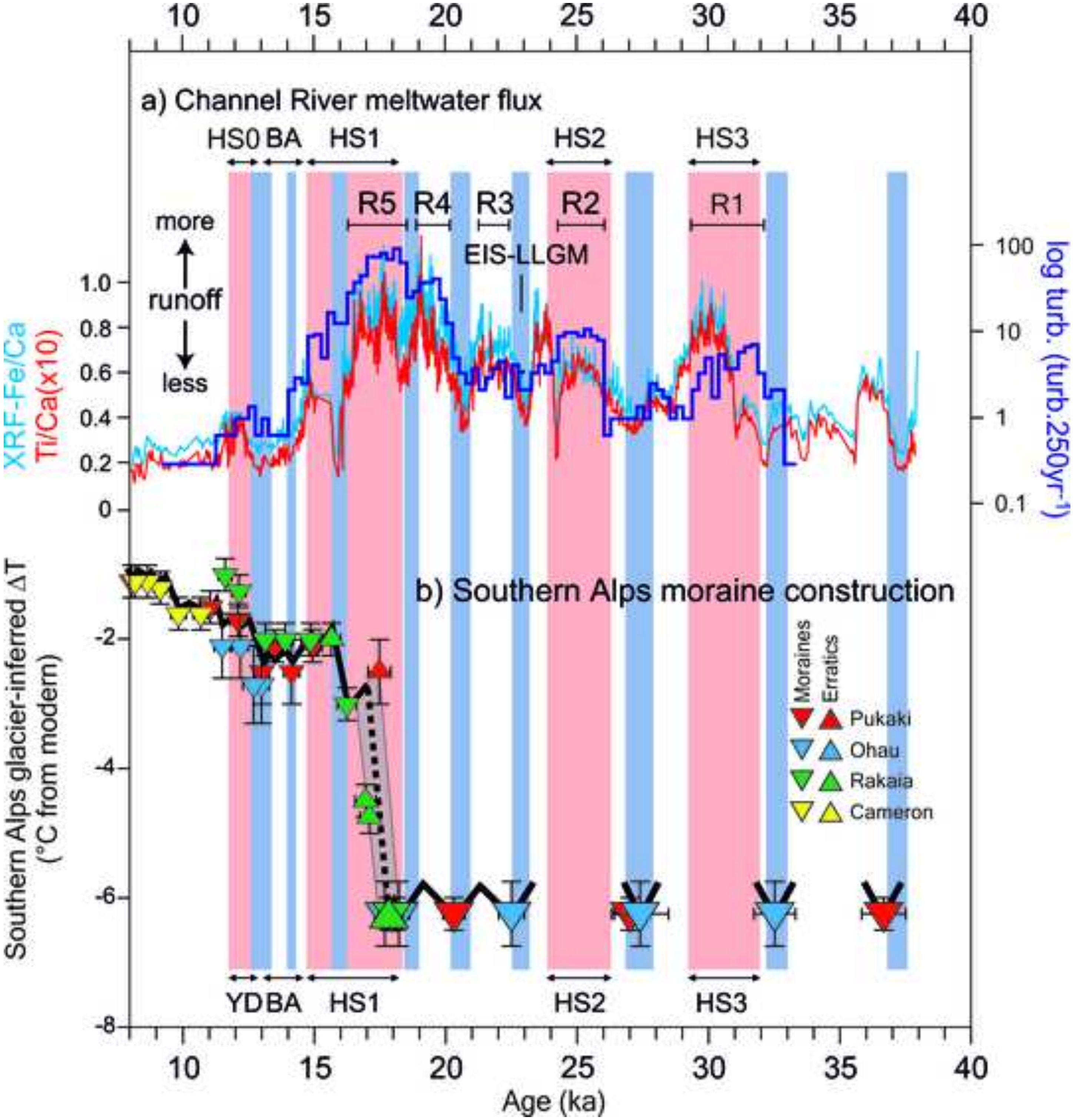

Figure 4

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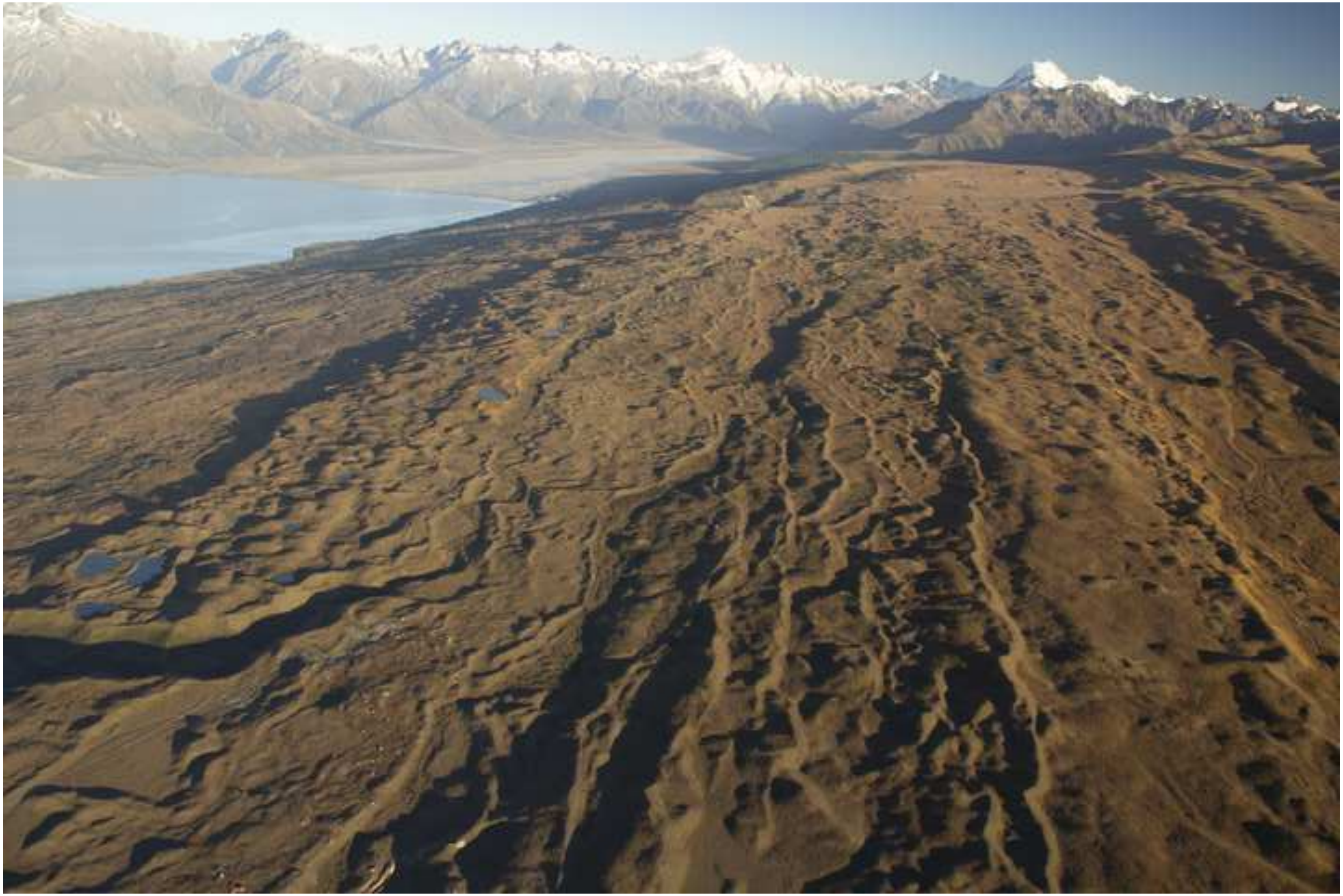

Figure 5

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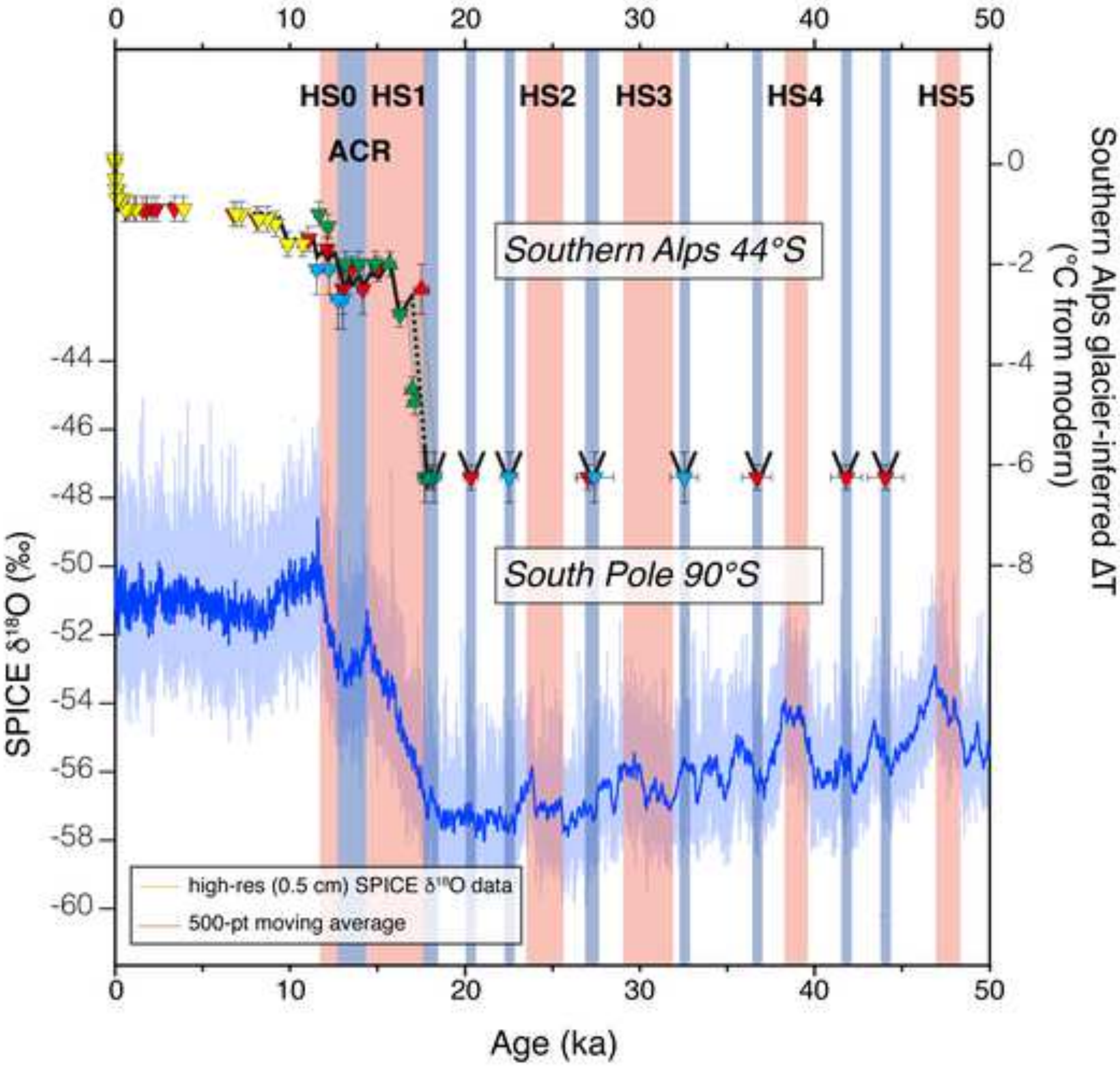
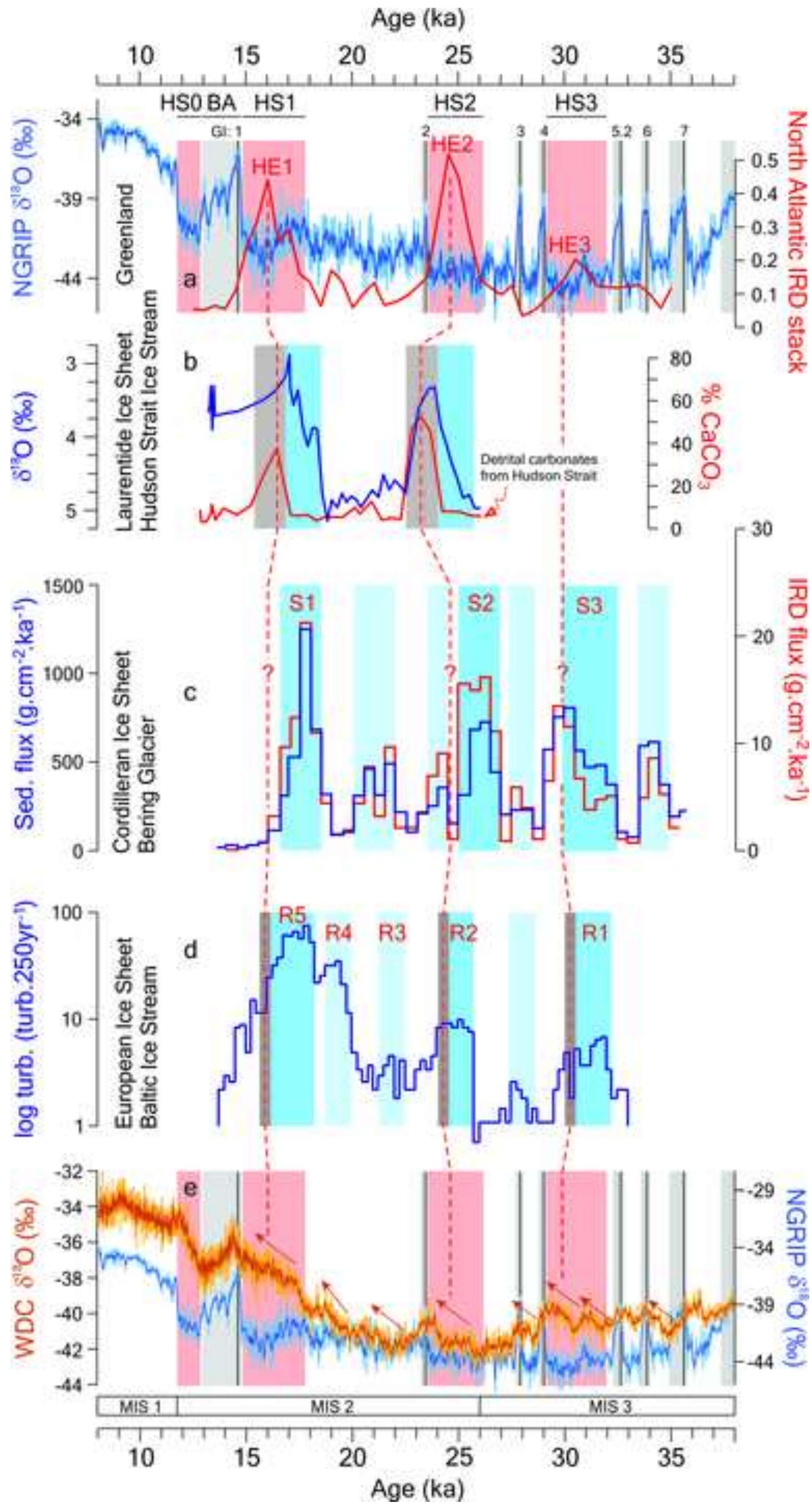


Figure 6



Age (ka)
10
15
20
25
30
35
HS0
BA
HS1
HS2
HS3
GI: 1
2
3
4
5.2
6
7
HE1
HE2
HE3
NGRIP δ18O (‰)
Greenland
a
North Atlantic IRD stack
b
δ18O (‰)
Laurentide Ice Sheet
Hudson Strait Ice Stream
Detrital carbonates from Hudson Strait
% CaCO3
c
Sed. flux (g.cm-2.ka-1)
Cordilleran Ice Sheet
Bering Glacier
IRD flux (g.cm-2.ka-1)
S1
S2
S3
?
d
log turb. (turb.250yr-1)
European Ice Sheet
Baltic Ice Stream
R5
R4
R3
R2
R1
e
WDC δ18O (‰)
NGRIP δ18O (‰)
MIS 1
MIS 2
MIS 3
Age (ka)

Figure 7

Click here to access/download;Figure;Fig_7_NZ_WAIS_North_Atlantic_v2-01.tif

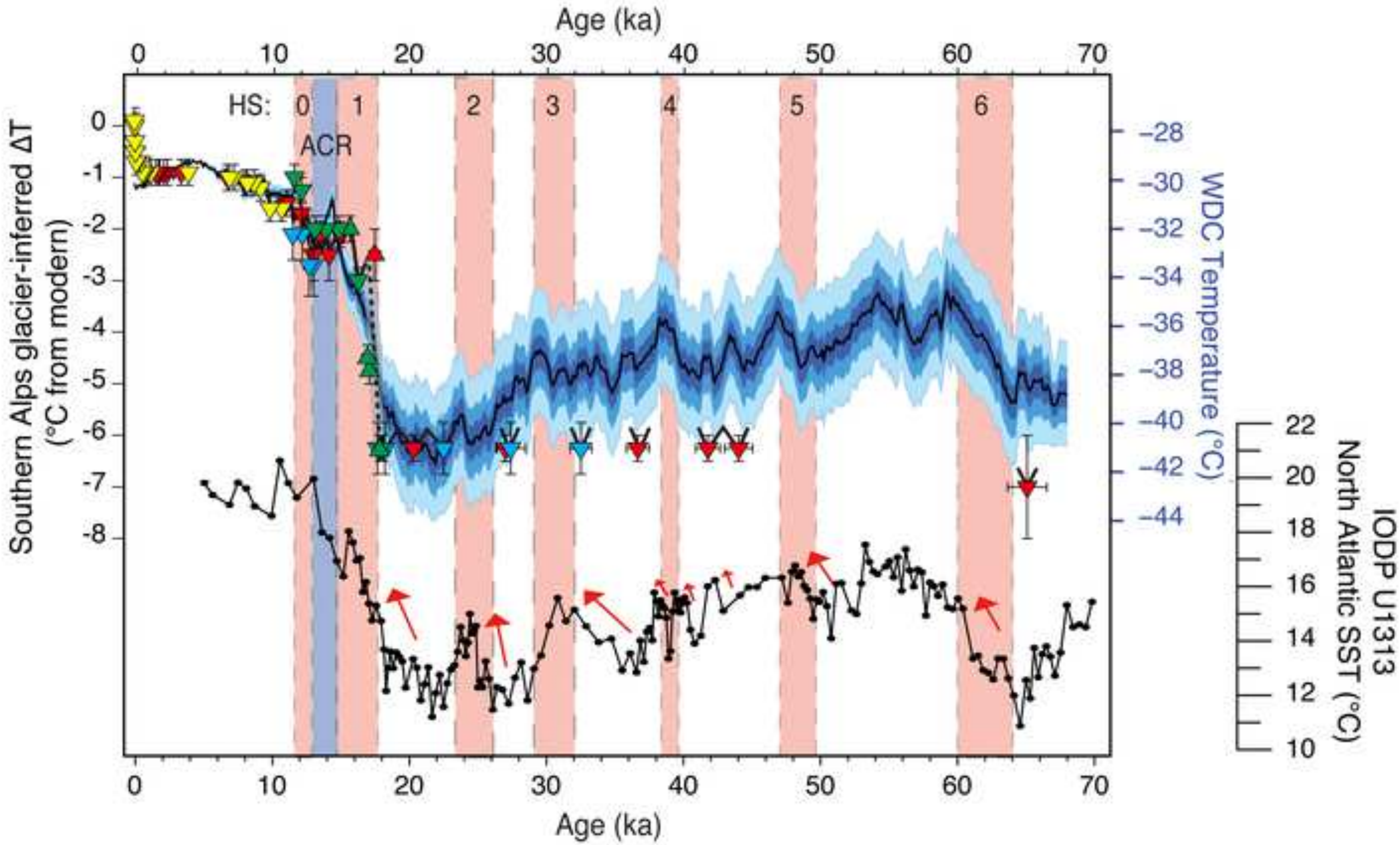
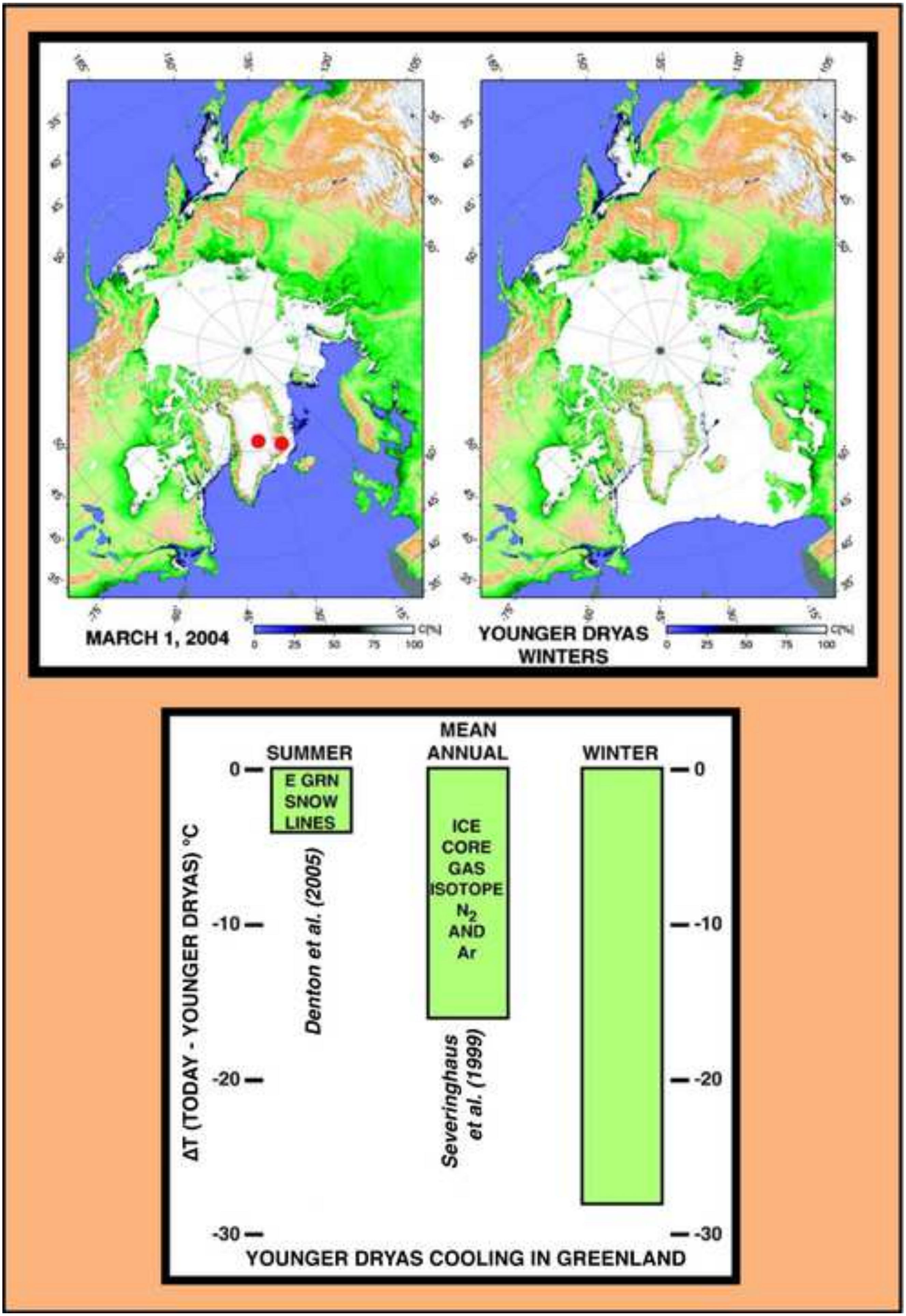


Figure 8

Click here to access/download;Figure;Fig_8_Broecker_seasonality-01.tif



Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Author Contributions

George Denton: Conceptualization; Methodology; Validation; Investigation; Writing – Original Draft; Writing – Review & Editing; Supervision; Project Administration; Funding Acquisition. **Aaron Putnam:** Conceptualization; Methodology; Validation; Investigation; Writing – Original Draft; Writing – Review & Editing; Visualization; Project Administration; Funding Acquisition. **Samuel Toucanne:** Conceptualization; Methodology; Validation; Investigation; Writing – Original Draft; Writing – Review & Editing; Visualization. **David Barrell:** Conceptualization; Methodology; Validation; Investigation; Writing – Original Draft; Writing – Review & Editing; Visualization. **Joellen Russell:** Conceptualization; Investigation; Writing – Original Draft; Writing – Review & Editing.