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Key Points:

- $\delta^{18}O$ records from the Gulf of Mexico refine the chronology of Laurentide Ice Sheet advance and retreat through the Great Lakes
- Counterintuitively, from 17.6 to 11.3 ka, ice advanced during times of warming and retreated during times of cooling
- A feedback between meltwater, Atlantic Meridional Overturning Circulation strength, and temperature—paced by ice-sheet response time—may have set this anticorrelation

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

A. D. Wickert,
awickert@umn.edu

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Author Contributions:

Conceptualization: Andrew D. Wickert, Lauren J. Gregoire, Ruža F. Ivanović, Lael Vetter, Carrie E. Jennings
Data curation: Andrew D. Wickert, Carlie Williams
Formal analysis: Andrew D. Wickert, Kerry L. Callaghan
Funding acquisition: Andrew D. Wickert
Investigation: Andrew D. Wickert, Carlie Williams

Marine-Calibrated Chronology of Southern Laurentide Ice Sheet Advance and Retreat: ~2,000-Year Cycles Paced by Meltwater–Climate Feedback

Andrew D. Wickert[1,2,3], Carlie Williams[4], Lauren J. Gregoire[5], Kerry L. Callaghan[1,2,6,7], Ruža F. Ivanović[5], Paul J. Valdes[8], Lael Vetter[9], and Carrie E. Jennings[2,10]

[1]Saint Anthony Falls Laboratory, University of Minnesota, Minneapolis, MN, USA, [2]Department of Earth & Environmental Sciences, University of Minnesota, Minneapolis, MN, USA, [3]Deutsches GeoForschungsZentrum (GFZ): German Research Centre for Geosciences, Potsdam, Germany, [4]College of Marine Sciences, University of South Florida, St. Petersburg, FL, USA, [5]School of Earth and Environment, University of Leeds, Leeds, UK, [6]Department of Earth and Environmental Sciences, Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY, USA, [7]Now at Department of Earth and Environmental Sciences, University of Illinois, Chicago, IL, USA, [8]School of Geographical Sciences, University of Bristol, Bristol, UK, [9]Department of Geosciences, University of Arizona, Tucson, AZ, USA, [10]Freshwater Society, Saint Paul, MN, USA

Abstract Climatic warming following the Last Glacial Maximum caused the southern Laurentide Ice Sheet (LIS) to begin ~2,000-year cycles of retreat and readvance whose cause remains ambiguous. By developing a marine-calibrated chronology of southern LIS position, we counterintuitively demonstrate that between 17.6 and 11.3 ka, ice advanced during times of northern-hemisphere warming and retreated during times of northern-hemisphere cooling. Here we propose a cyclical feedback: Meltwater from ice retreat cooled the northern hemisphere by weakening the Atlantic Meridional Overturning Circulation (AMOC). This eventually lead to ice-sheet readvance, which reduced and rerouted meltwater discharge, and thereby allowed the AMOC to strengthen and the northern hemisphere to warm. Our data suggest that this antiphased ice–climate interaction, paced by ice-sheet response time, was initiated by synchronous warming and ice retreat ~18.7–17.6 ka (corresponding to the Erie "Interstade") and reached its apex during the Younger Dryas.

Plain Language Summary Twenty thousand years ago, a colder climate allowed glacial ice to flow from northern and eastern Canada into the Great Lakes region. But when climate began to warm, instead of simply melting from south to north, the margin of this ice front repeatedly retreated and re-advanced in 2,000-year cycles. First, we track these advances and retreats using records of ancient Gulf of Mexico water, stored in plankton shells retrieved from a sediment cores. Ice advance redirected water bearing "light" oxygen, with fewer neutrons, from Canada and the Great Lakes into the Mississippi River. When ice retreated, these waters found other courses to the sea, shifting Gulf of Mexico chemistry toward heavier oxygen (carrying more neutrons). Next, we ask why these ice-margin cycles occurred during a time of monotonically increasing solar radiation to the northern hemisphere. We propose that ice-sheet melt (during retreat) slowed Atlantic Ocean circulation, causing the northern hemisphere to cool and the ice sheet to gradually regrow. However, this same regrowth reduced meltwater flow to the ocean, causing the northern hemisphere to re-warm and eventually leading the ice margin to retreat once more. This cycle persisted from approximately 17,600 to 11,300 years ago, until North American ice became too small to sustain this feedback.

1. Introduction

Warming climate (Badgeley et al., 2020) associated with increasing northern-hemisphere summer insolation (Berger, 1978) triggered widespread ice retreat and the end of the global Last Glacial Maximum (LGM), approximately 19.5 ka (kiloannum: thousand calendar years before "present," BP, at 1950) (Clark et al., 2009). Laurentide Ice Sheet (LIS) meltwater produced ~63 m of global sea-level rise (Gowan et al., 2021)—approximately equal to the volume of all present-day ice masses combined—but the LIS did not smoothly retreat. Instead, the onset of deglaciation triggered repeated cycles of 150–400 km of ice retreat and readvance through the Great Lakes region (e.g., Licciardi et al., 1999; Mickelson & Colgan, 2003) (Figure 1: bases of black arrows).

Methodology: Andrew D. Wickert, Carlie Williams, Lauren J. Gregoire, Ruža F. Ivanović
Resources: Andrew D. Wickert, Carlie Williams, Paul J. Valdes
Software: Andrew D. Wickert
Validation: Andrew D. Wickert
Visualization: Andrew D. Wickert
Writing – original draft: Andrew D. Wickert
Writing – review & editing: Andrew D. Wickert, Lauren J. Gregoire, Kerry L. Callaghan, Ruža F. Ivanović, Paul J. Valdes, Lael Vetter, Carrie E. Jennings

Both the driver of these cycles and their link to climate remain unclear. Chamberlin (1894) observed stacked till sequences, surmised that they resulted from repeated LIS retreat and readvance, and inferred that cooling produced advances and warming produced retreats (Flint, 1953; Taylor, 1897). However, later dating of glacial deposits (see summaries by Licciardi et al., 1999; Larson, 2011; Dalton et al., 2020), analysis of marine sediment cores (Emiliani, 1966), and applications of Milankovitch (1930) theory demonstrated that these dated glacial advances did not match periods of cooling from deep-ocean isotope records of paleoclimate. Instead, they occurred during a time of smoothly increasing northern-hemisphere summer insolation from the LGM to the end of the Pleistocene (Berger, 1978). Clark (1994) inferred that these cycles could be non-climatic in origin and instead reflect ice dynamics associated with basal-sediment deformation.

The hypothesis that the southern-LIS-margin oscillations occur independently of climate has sweeping implications for our understanding of ice-sheet response to climate change. If it is correct, little to no relationship between ice-margin position and climate could exist over thousands of years, thereby limiting our ability to predict ice-sheet behavior until we better understand subglacial sliding and till deformation (Clark, 1994; Zoet & Iverson, 2020), which are complex and can be difficult to characterize (Hansen & Zoet, 2022; Iverson & Petersen, 2011). On the other hand, if we can partially or fully disprove this hypothesis, we may gain confidence in simpler associations between climate change and ice-sheet response.

Glacial geological deposits (Licciardi et al., 1999) provide a proximal record of ice advance and retreat, but using these to develop an ice-margin chronology requires work to overcome: (a) the paucity of in situ organic material for high-precision AMS ^{14}C dating during the early stages of the last deglaciation (Dalton et al., 2020), (b) the possibility of sampling reworked organic material that predates the deposit, (c) many ages providing maximum or minimum limiting dates on peak advance or retreat rather than a continuous record (Licciardi et al., 1999), and (d) the potential for local and asynchronous ice-lobe advance and retreat (Clark, 1994). These factors hinder efforts to directly compare the near-field record of bulk ice-marginal dynamics with patterns of changing climate and ocean circulation (Leydet et al., 2018; Licciardi et al., 1999; Teller & Leverington, 2004; Wickert, 2016). This limitation inhibits more quantitative data-driven analysis of inferred climate–ice-sheet links, including the oft-cited meltwater trigger for the Younger Dryas (Broecker et al., 1989; Condron & Winsor, 2012; Flower et al., 2011; Keigwin et al., 2018; Leydet et al., 2018; Murton et al., 2010; Tarasov & Peltier, 2005) and impacts of ice-sheet melt and meltwater rerouting on the AMOC and northern-hemisphere climate earlier in the last deglaciation (Ivanović et al., 2017, 2018; Ridge, 1997).

2. Methods

To unite these terrestrial records (see Table 1) into a continuous and high-resolution chronology that describes southern-LIS-margin fluctuations in bulk, we take advantage of changes in freshwater routing produced by advance and retreat of the Great Lakes ice lobes (Figure 2). Ice advance rerouted northward and eastward flowing drainages—and their isotopically light waters (Vetter et al., 2017)—toward the Mississippi and Gulf of Mexico (GoM), whereas ice retreat reduced Mississippi River outflow by opening alternate routes for these waters to reach the ocean (Carlson et al., 2007; Larson & Kincare, 2009; Licciardi et al., 1999; Obbink et al., 2010; Wickert, 2016). The combination of drainage rerouting and ice-sheet melt temporarily increased Mississippi River outflow to two to six times its $\sim 2 \times 10^5$ m^3 s^{-1} modern value (Wickert, 2016), and therefore significantly impacted the light-isotope inventory of the GoM (e.g., Kennett & Shackleton, 1975; Leventer et al., 1982).

Foraminiferal shells continuously record oxygen-isotope ratios (δ^{18}O) in the GoM and accumulate within seafloor sediments (e.g., Flower et al., 2004). When combined with information on seawater temperature (from Mg/Ca ratios also measured in these foraminifera; see Anand et al., 2003; Khider et al., 2015) and sea level (Schrag et al., 2002; Spratt & Lisiecki, 2016), these provide a record of past seawater oxygen-isotope ratios, which we term $\delta^{18}O_{ivc\text{-}sw}$ (ice-volume-corrected seawater). Here we integrate these records with paleogeographic and paleoglaciological data from the duration of North American deglaciation to build a continuous, stratigraphically consistent, and extensively dated generalized ice-margin chronology (Table 1).

In order to use a GoM $\delta^{18}O_{ivc\text{-}sw}$ record as an indicator of ice-margin position, we must first ensure that the oxygen-isotope inventory of the GoM can unambiguously record ice-margin oscillations. This is complicated by the fact that the isotopic record is influenced both by changes in drainage routing—our desired target—and by changes in ice-sheet melt rate, which varied in space and time. To resolve the primary driver GoM

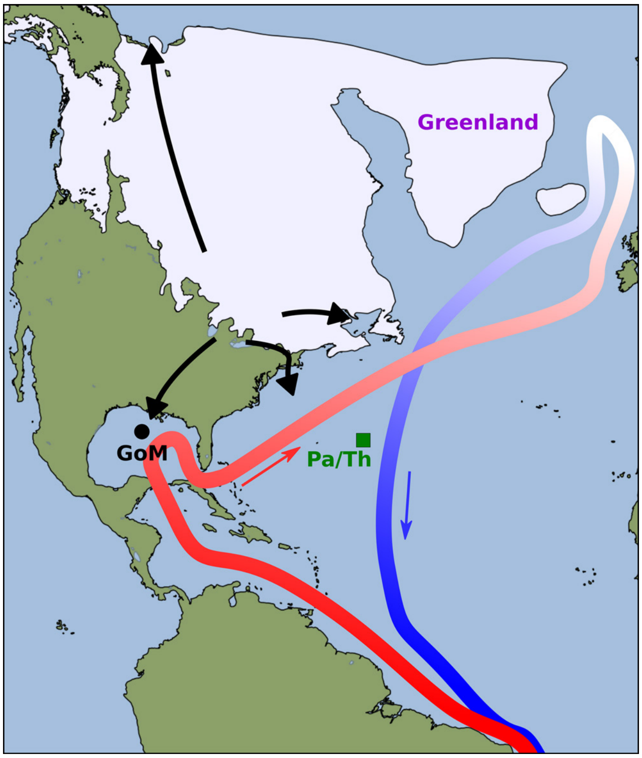

Figure 1. Deglacial North America, meltwater routing, and paleorecord locations. 15.5-ka ice extent (Dalton et al., 2020) and meltwater pathways (black arrows). Ice advance routed more water via the Mississippi toward the GoM, whereas ice retreat opened eastern outlets and/or northern meltwater outlets. Points indicate ocean core locations (LoDico et al., 2006; McManus et al., 2004; Williams, 2014; Williams et al., 2012), and Greenland is noted for its data-assimilated temperature record (Badgeley et al., 2020). The AMOC follows the red (warm) and blue (cold) arrows.

$\delta^{18}O_{ivc\text{-}sw}$, we combine reconstructed drainage-basin extents (Wickert, 2014) with information on the $\delta^{18}O$ of meteoric water (Aharon, 2006), glacial melt (Ferguson & Jasechko, 2015), and GoM seawater (Wagner & Slowey, 2011). Based on these synthetic tests (Figure S3, Text S1.4, Table S1 in Supporting Information S1), we find that ice-sheet-driven changes in drainage-basin extent should dominate the variability in low-$\delta^{18}O$ water delivery to the GoM during all times but the Bølling–Allerød warm period, associated with Meltwater Pulse 1A (Wickert et al., 2013).

Following this synthetic test, we assembled a $\delta^{18}O_{ivc\text{-}sw}$ record using *G. ruber* (white) in core MD02–2550 (Figures 1 and 3a) (LoDico et al., 2006; Wickert, 2023; Williams, 2014; Williams et al., 2012). 65 ^{14}C ages from the LGM to the early Holocene (Williams et al., 2010) underpin our age model, constructed using Bacon v2.5.1 (Blaauw & Christen, 2011) with the Marine20 radiocarbon calibration curve (Heaton et al., 2020): see Figure S1 in Supporting Information S1. This core has the most complete and well dated $\delta^{18}O$ chronology from the Gulf of Mexico across the late Pleistocene and early Holocene. Its finely laminated sediments indicate a lack of bioturbation that results from its anoxic basin origin (Meckler et al., 2008). It is located ~300 km south of the Mississippi River mouth (26.9462°N, 91.3457°W), and this distal position—seaward of the LGM shoreline—permits it to record the mixing of Mississippi-sourced waters with those from the Gulf of Mexico while decreasing its sensitivity to deltaic lobe switching by the Mississippi. We connected 487 measurements of $\delta^{18}O$ between 20.5 and 9.5 ka to this age model, alongside 295 Mg/Ca measurements as a proxy for sea-surface temperature (LoDico et al., 2006; Williams, 2014; Williams et al., 2012). Together, these provide a near-continuous record of $\delta^{18}O_{ivc\text{-}sw}$, from which we computed a 50-year moving average (using the software library by Wickert, 2019). Periods of low and high $\delta^{18}O_{ivc\text{-}sw}$ in this record closely match available terrestrial age control on the timing of ice-sheet advance and retreat, respectively (Table 1 and Text S1 in Supporting Information S1).

3. Results

Multiple methods converge on a ~2,000-year period of ice-margin fluctuations. Manually picking peaks in the GoM $\delta^{18}O_{ivc\text{-}sw}$ record (Figure 3a) yields a 2.1 ± 0.6 kyr oscillation period. The Lomb–Scargle periodogram (Lomb, 1976; Scargle, 1982; VanderPlas, 2018) of these data displays a 1.63 kyr peak (Figure S2 in Supporting Information S1). Terrestrial data from glacial deposits constrain a 2.2 ± 0.7 kyr ice advance–retreat period (see references in Table 1 as well as Willman & Frye, 1970; Dreimanis & Karrow, 1972; Johnson et al., 1997; Karrow et al., 2000; Larson & Kincare, 2009; Larson, 2011).

We then binned the $\delta^{18}O_{ivc\text{-}sw}$ proxy southern LIS chronology into 50-year intervals, and correlated this against 50-year-mean spatially averaged temperatures from Greenland (Badgeley et al., 2020). At 100-year increments aligned with the start of each century BP, we computed correlation coefficients across a 950-year moving window (Figure 3c; Text S1.5 in Supporting Information S1), just approaching the half-period of the 2-kyr advance–retreat cycles and therefore approximately maximizing the number of data points that can be meaningfully correlated.

Prior to 17.6 ka, these data generally indicate a slight positive correlation between (approximately constant) Greenland temperature (Badgeley et al., 2020) and ice-margin change. After 11.3 ka, ice retreat and temperature increase more strongly align, consistent with modeling work demonstrating that Holocene-age LIS mass loss occurred dominantly due to surface ablation (Carlson et al., 2009). Between these times and during the main period of ice-margin oscillations, 17.6–11.3 ka, these data agree with neither the early-hypothesized direct correlation between temperature and ice-sheet extent (Flint, 1953; Taylor, 1897) nor the later-hypothesized

Table 1
Terrestrial and Marine Chronologies of Southern LIS Advance and Retreat

Event	Start date ($\delta^{18}O$, GoM) [ka]	Start date (terrestrial) [ka]	Terrestrial age source
Last Glacial Maximum (Nissouri Advance)	–	26.0	Muller and Calkin (1993); Clark et al. (2009)
Erie Retreat	18.7	~19.2	Mörner and Dreimanis (1973); Monaghan (1990); Muller and Calkin (1993); Ridge (1997)
Port Bruce Advance	17.6	~18.2	Fullerton (1980); Mickelson et al. (1983); Hansel and Johnson (1992); Licciardi et al. (1999); Dyke (2004)
Mackinaw Retreat	16.2	~16.1	C. F. M. Lewis et al. (1994); Karrow et al. (2000)
Port Huron Advance	15.2	15.6	Maher and Mickelson (1996)
Two Creeks Retreat	14.0	14.1	Kaiser (1994); Larson et al. (1994)
Onaway (or Greatlakean or Two Rivers) Advance	13.7	13.5	Broecker and Farrand (1963); Hansel and Mickelson (1988); Ridge (1997); Karrow et al. (2000); Rech et al. (2012)
Younger Dryas (Gribben) Retreat	12.8	12.9	Karrow et al. (2000); Toney et al. (2003); Richard and Occhietti (2005); Stanford (2010); Leydet et al. (2018)
Marquette Advance	11.7	11.6	Lowell et al. (1999)
Abitibi Retreat	10.5	10.6	Karrow et al. (2000); Fisher (2003); Breckenridge (2007); Derouin et al. (2007)

Note. The ~ symbol indicates poor age control: The Erie Retreat and Port Bruce Advance are constrained by maximum and minimum limiting dates, and direct dates of the Mackinaw Retreat are from a radiocarbon calibration-curve plateau (Heaton et al., 2020). Terrestrial dates are from deposits associated with the southern LIS. Marine dates are interpreted from the rise and fall of $\delta^{18}O_{ivc\text{-}sw}$ from the Gulf of Mexico record from core MD02–2550 (Brown, 2011; LoDico et al., 2006; Meckler et al., 2008; Williams, 2014; Williams et al., 2010, 2012).

non-correlation (Clark, 1994). Rather, the bulk of the data indicate a dominant anticorrelation: the southern LIS counterintuitively advanced during times of warming and retreated during times of cooling.

One mechanism by which LIS retreat and associated melt and northerly drainage rerouting could correlate with a cooling climate is through meltwater delivery to the North Atlantic and/or Arctic Oceans, ≳50°N (Smith & Gregory, 2009): see Text S2 in Supporting Information S1. This meltwater can form a low-salinity cap atop the seawater, increasing its density stratification and either inhibiting the AMOC directly or preconditioning the North Atlantic to switch AMOC modes. Weakening the AMOC decreases heat transport from the equator to higher latitudes (Ivanović et al., 2017, 2018).

To test an AMOC-driven relationship between LIS retreat and temperature, we correlatd Pa/Th ratios from deep-sea sediment (McManus et al., 2004; Ng et al., 2018)—as a residence-time-based proxy for AMOC strength—against $\delta^{18}O_{ivc\text{-}sw}$. Because of the lower Pa/Th data density (one point per 86 ± 77 years) than the 50-year-increment temperature reanalysis product (Badgeley et al., 2020), we calculated 100-year moving averages of Pa/Th. We sampled this 100-year moving-average time series at the same 50-year increments as the temperature reanalysis and 50-year moving-average $\delta^{18}O_{ivc\text{-}sw}$ data, and then correlated Pa/Th ratios against $\delta^{18}O_{ivc\text{-}sw}$. Between 17.6 and 11.3 ka, AMOC strength generally anticorrelates with ice retreat, in line with the temperature records (Figure 3c). However, during the Bølling–Allerød (14.6–12.9 ka), positive correlations between AMOC strength and $\delta^{18}O_{ivc\text{-}sw}$ result from significant direct ice-sheet melt of low $\delta^{18}O$ waters (Vetter et al., 2017). These add a directly climate-driven signal to the Gulf of Mexico $\delta^{18}O_{ivc\text{-}sw}$ record that can counteract or overwhelm the influence of ice-sheet-extent (Figure S3 in Supporting Information S1). Prior to 17.6 ka, air temperature in Greenland remained approximately constant (Figure 3b), consistent with records from the Bahamas (Arienzo et al., 2015). In contrast, the 18.7 ka onset of the Erie Retreat corresponds to the beginning of AMOC fluctuations and weakening (Figure 3b) as well as to a drop in sea-surface temperature near Iberia (Naughton et al., 2016).

4. Discussion

Assuming that the Greenland temperature record is correlative with that of the Laurentide, as they lay adjacent to one another and no similar Laurentide temperature record exists, we propose the following sequence of

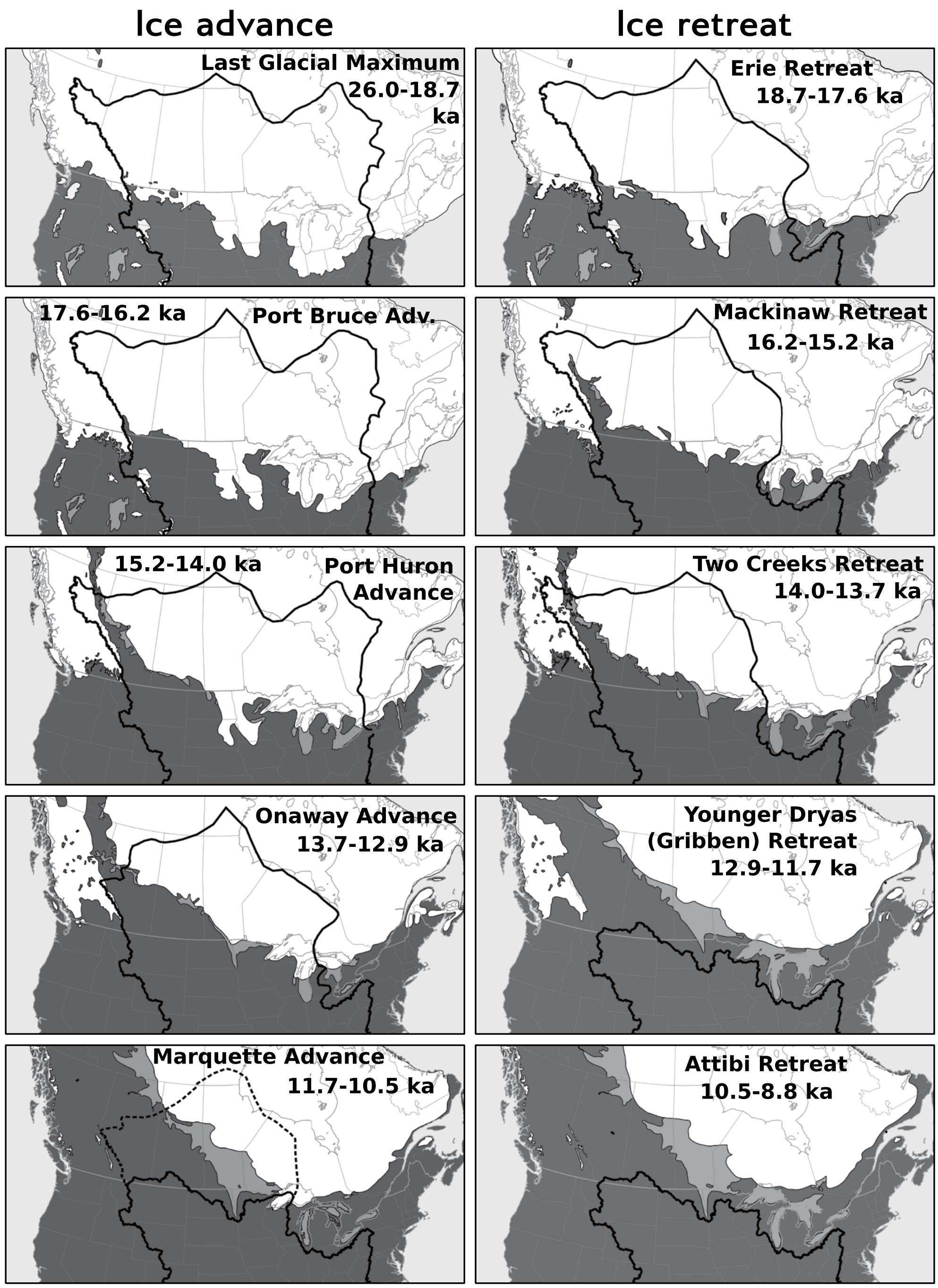

Figure 2. Southern LIS (white area) chronology and associated Mississippi River drainage-basin extent (heavy black line). Lakes are medium gray, land is dark gray, and oceans are light gray. Medium-gray lines indicate current (2022) political boundaries. Ice-sheet extents are modified slightly from their published dates (Dyke, 2004; Dyke et al., 2003) to fit the new marine chronology, for which ages on each panel are provided. Mississippi drainage-basin extents follow Wickert (2014), who used contours of ice-sheet extent through time (Dyke, 2004; Dyke et al., 2003) as approximate contours of ice-sheet thickness. The dashed line for the Marquette Advance indicates that Lake Agassiz drained into the Mississippi for at least some of this time (Fisher, 2003), though the exact dates remain unclear (Fisher & Breckenridge, 2022). The 8.8-ka age for the end of the Abitibi Retreat, marked by the Cochrane Advance, has an estimated error of ±0.2 kyr (Breckenridge et al., 2012).

events (Figure 4): First, warming temperatures and increasing northern-hemisphere summer insolation (Ullman et al., 2015) caused the LIS to melt during the end of the LGM, resulting in the Erie Retreat ("Erie Interstade": Mörner & Dreimanis, 1973; Monaghan, 1990; Muller & Calkin, 1993; Ridge, 1997). This, combined

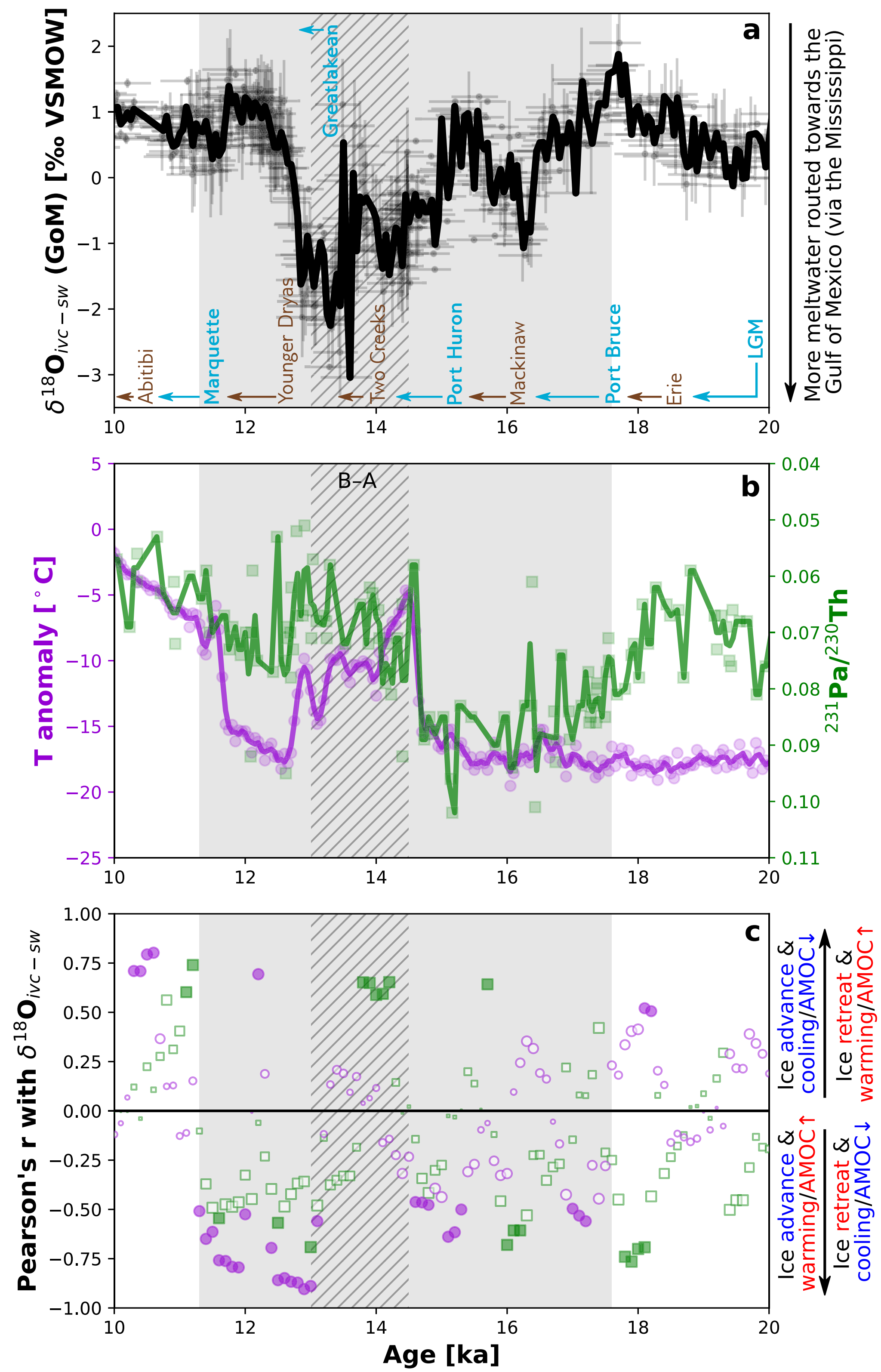
a
b
c
B–A
Abitibi
Marquette
Younger Dryas
Greatlakean
Two Creeks
Port Huron
Mackinaw
Port Bruce
Erie
LGM
More meltwater routed towards the Gulf of Mexico (via the Mississippi)
$\delta^{18}O_{ivc-sw}$ (GoM) [‰ VSMOW]
T anomaly [°C]
$^{231}Pa/^{230}Th$
Pearson's r with $\delta^{18}O_{ivc-sw}$
Ice advance & cooling/AMOC↓
Ice retreat & warming/AMOC↑
Ice advance & warming/AMOC↑
Ice retreat & cooling/AMOC↓
Age [ka]

Figure 3.

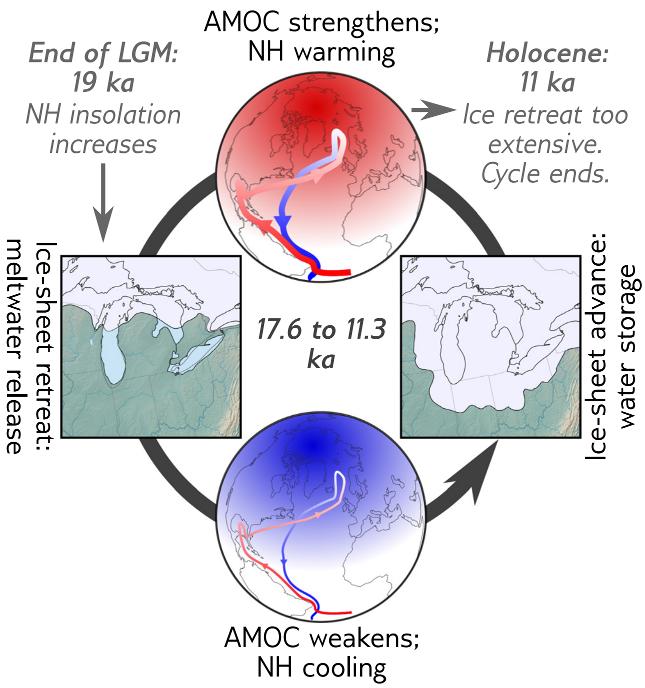

Figure 4. LIS–AMOC feedback loop. Ice-sheet retreat sends meltwater to the North Atlantic and/or Arctic Oceans, weakening the AMOC and causing northern-hemisphere cooling. This eventually leads to ice-sheet readvance, reducing meltwater discharge and allowing the AMOC to recover. This restores heat transport to the North Atlantic, leading to renewed ice-sheet retreat. This cycle was initiated by increased solar radiation at the end of the LGM and terminated in the early Holocene following significant ice-sheet mass loss and retreat.

with the opening of more northerly meltwater outlets (capable of weakening the AMOC: Smith & Gregory, 2009), initiated a cycle in which (a) the LIS retreated and sent meltwater to the North Atlantic and/or Arctic Oceans; (b) this meltwater capped the North Atlantic, slowing the AMOC and reducing northern-hemisphere temperatures; (c) this cooling induced southern LIS readvance and associated water storage in newly-produced glacial ice; and (d) as freshwater delivery to the oceans decreased, the AMOC recovered and northern-hemisphere temperatures rose. This then induced renewed ice-sheet retreat, continuing the cycle. Final termination of this cycle occurred in the early Holocene when peak northern-hemisphere summer insolation (Berger, 1978; Carlson et al., 2008), an ice-free Hudson Bay (Ullman et al., 2016), and a diminished Laurentide Ice Sheet tipped the scales toward a dominance of climatic forcing over ice-sheet response.

To produce the observed anticorrelation between ice-margin migration and both temperature and AMOC strength, AMOC response to meltwater input must be fast, whereas the time for ice-sheet response to changing temperature must be approximately half of the measured ∼2 kyr advance–retreat cycle. Ocean-circulation modeling indicates that the AMOC responds to meltwater inputs within a decade (Condron & Winsor, 2012; Ivanović et al., 2017, 2018). A characteristic response time (Johannesson et al., 1989) of the southern LIS to a mass-balance perturbation is roughly 500–2000 years, based on the thickness of the ice lobes and their proximal up-ice contributing areas (1–2 km: Margold et al., 2015; Margold et al., 2015; Gowan et al., 2021) and characteristic southern LIS ablation rates (1–2 m yr^{-1}: Peltier et al., 2015; Ivanović et al., 2017; Ivanović et al., 2018). The large scale gap between these response times supports the hypothesized close link between ocean circulation and temperature, with ∼2,000-year cycles paced by a ∼1000-year ice-sheet response time (Figure 4).

The proposed feedback may explain periods of rapid climate and ice-sheet change and provide targets for improved models of climate dynamics. Persistent ice retreat and northerly routed melt during the Younger Dryas correlates strongly with northern-hemisphere cooling (Condron & Winsor, 2012; Ivanović et al., 2017; Keigwin et al., 2018; Meissner & Clark, 2006; Murton et al., 2010; Smith & Gregory, 2009). Likewise, southward meltwater rerouting and ice-sheet storage during the Port Huron Advance (15.4–14.0 ka) could strengthen the AMOC (Smith & Gregory, 2009) during the Břlling warming, though the plausibility of this mechanism modifying ocean-scale climate also depends on the magnitude of Arctic-directed melt, for example, from the Cordilleran–Laurentide ice-saddle collapse (Gregoire et al., 2012; Ivanović et al., 2017), which would weaken the AMOC (Smith & Gregory, 2009). Importantly, climate-model response to freshwater forcing varies based on model structure and boundary conditions (e.g., comparing Ivanović et al., 2018; Obase et al., 2021; Romé et al., 2022; Sun et al., 2022), and models may be over-sensitive (as suggested by He & Clark, 2022) or under-sensitive (Valdes, 2011) to freshwater forcing. By presenting time-series data on freshwater routing to the oceans and their correlations with atmospheric temperature and ocean circulation, we provide ingredients to test and help improve such dynamical models.

Although the LIS was the largest northern-hemisphere ice sheet, the Greenland and Fennoscandian ice sheets may also have influenced—and been influenced by—ocean circulation. The Greenland Ice Sheet has a response time similar to that of the southern LIS (Cuffey & Marshall, 2000), and it also retreated and

Figure 3. Paleorecords and correlations. The gray field highlights the time of anticorrelation between temperature and ice extent, and the diagonally hatched region denotes the Bølling–Allerød, during which we expect $\delta^{18}O_{ivc\text{-}sw}$ to be significantly influenced by transient ice melt and therefore no longer be a good indicator of ice-sheet extent. Lines provide 100-year moving averages. (a) $\delta^{18}O_{ivc\text{-}sw}$ record from core MD02–2550 in the Gulf of Mexico (LoDico et al., 2006; Williams, 2014; Williams et al., 2012). Error bars indicate 2-σ uncertainties in both age and $\delta^{18}O_{ivc\text{-}sw}$. Aside from the LGM, labeled periods of advance (bold blue-gray) and retreat (roman brown) denote their start times, with arrows indicating durations (Table 1). (b) Greenland temperature anomalies from present (Badgeley et al., 2020) and Atlantic Pa/Th ratios as a proxy for AMOC strength (higher Pa/Th: weaker AMOC). (c) Correlations between $\delta^{18}O_{ivc\text{-}sw}$, indicating ice-sheet extent, and both Greenland temperature and North Atlantic Pa/Th ratios. Markers are plotted for correlations within each 950-year window. Marker sizes are proportional to one minus Pearson's p (with no correlation as the null hypothesis), and filled markers indicate that the correlations are statistically significant to the $p < 0.05$ level.

thinned during the Younger Dryas (Carlson et al., 2021; Rainsley et al., 2018). Geological evidence (Boswell et al., 2019; Toucanne et al., 2009, 2015) alongside model results (Ivanović et al., 2018) from both the most recent and prior glacial periods indicate that Fennoscandian Ice Sheet melt likewise corresponds to periods of northern-hemisphere cooling and AMOC slowdown. Moving beyond our LIS focus—itself a product of the utility of the GoM records—and considering northern-hemisphere ice-margin fluctuations in sum could improve our understanding of climate–meltwater interactions and plausibly bolster our observed climate–ice-margin anticorrelation.

5. Conclusions

The proposed ice–ocean coupling presents a mechanism for an ice sheet to temporarily prolong glacial-stage climatic conditions by creating a protective barrier of freshwater that inhibits heat transport from the tropics. It explains the enigmatic observation that the southern LIS retreated during the Younger Dryas cold period (Dalton et al., 2020) and extends this interpretation of antiphased climate change and ice-sheet response back to 17.6 ka, though with a weaker feedback prior to the opening of major northerly meltwater outlets (Carlson et al., 2007; Condron & Winsor, 2012; Keigwin et al., 2018; Murton et al., 2010; Smith & Gregory, 2009). Together, these data indicate that the LIS may have controlled North Atlantic climate cyclicity across the majority of the Late Pleistocene deglaciation. Over the coming century, we may observe whether retreat of the much-smaller Greenland Ice Sheet produces a similar AMOC feedback (Bakker et al., 2016; Ivanović et al., 2018) and/or whether Antarctic Ice Sheet meltwater and its dynamics follow modeled predictions to a different end (Bronselaer et al., 2018; Fogwill et al., 2015) by enhancing deepwater temperatures, thermally eroding the ice-sheet base, and enabling a destabilizing positive feedback toward further mass loss.

Data Availability Statement

Both raw and processed data are available from Wickert (2023). In addition, these analyses are based on the "d18O-ivc-sw" library, available on GitHub (https://github.com/awickert/d18O-ivc-sw) and archived on Zenodo (Wickert, 2019).

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