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Early Younger Dryas glacier culmination in southern Alaska: Implications for North Atlantic climate change during the last deglaciation

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ABSTRACT

The transition from the glacial period to the Holocene was characterized by a dramatic reorganization of Earth's climate system linked to abrupt changes in atmospheric and oceanic circulation. In particular, considerable effort has been placed on constraining the magnitude, timing, and spatial variability of climatic changes during the Younger Dryas stadial (YD; 12.9–11.7 ka) within the North Atlantic region. Whereas the YD is clearly expressed in some climate archives, the record of mountain glacier change through the YD remains enigmatic and has elicited debate concerning the overall magnitude and seasonality associated with YD temperature change. Here, we report 19 new ^{10}Be ages from a location in the Pacific sector—the Ahklun Mountains, southern Alaska—that constrain the age of a late-glacial terminal moraine to 12.52 ± 0.24 ka, in the middle of the YD stadial. Our new ^{10}Be ages, combined with additional Northern Hemisphere records of glacier change, reveal that glacier culminations occurred in the early and/or middle YD, followed by glacier recession through the remainder of the YD. Widespread early-to-middle Younger Dryas glacier culminations imply modest summer cooling (i.e., seasonality) that briefly punctuated an overall warming trend through the YD stadial. This pattern of glacier culminations occurring in the early-to-middle YD followed by retreat through the remainder of the YD largely mimics the pattern of YD temperature change displayed in Greenland ice cores.

INTRODUCTION

Earth's climate is abruptly changing, and glaciers worldwide are in decline (Roe et al., 2017). The relatively short duration of today's ongoing climate change event, however, leaves uncertainty regarding its teleconnections around the globe and its regional manifestation in the coming decades and centuries. A longer view of Earth-system response to abrupt climate change is contained within the paleoclimate record from the last deglaciation. Often considered the quintessential example of abrupt climate change, the Younger Dryas stadial (YD; 12.9–11.7 ka) has received significant attention (Alley, 2000; Buizert al., 2014); yet the expression of the YD in records of glacier change, both throughout the North Atlantic Ocean region and beyond, remains ambiguous.

The relatively brief duration of the YD, coupled with its abrupt transitions as expressed in ice-core and marine-sediment archives, requires high-precision absolute chronological tools for dating moraines and glacial-sediment records. Many glacial chronologies lack the resolution required to attribute glacier advances to YD climate change (e.g., Gosse et al., 1995; Kelly et al., 2008), thereby inhibiting our ability to constrain the spatio-temporal climatic footprint of YD climate change. However, as newer and more precise glacier chronologies become available, there is increasing evidence that some glacier advances in the Northern Hemisphere, including Norway (Andersen et al., 1995), Scotland (Bromley et al., 2018), and Greenland (Jennings et al., 2014), culminated during the early or middle YD rather than at the abrupt termination of the cold event. Moreover, the apparently limited response of Greenland mountain glaciers, which were located directly adjacent to the canonical record of extreme YD temperature change (i.e., Greenland ice cores), highlights the likely role of seasonality in YD climate change (Denton et al., 2005). There also remains uncertainty regarding the global versus hemispheric climate forcing of glacier change during the last deglaciation (Clark et al., 2012; Shakun et al., 2012; Bereiter et al., 2018).

Methodological advances in cosmogenic-nuclide exposure dating over the past 15+ yr now provide an opportunity to determine the finer structure of Arctic climate change displayed within moraine records, and in particular glacier response to the YD stadial. Here, we use 19 new high-precision cosmogenic ^{10}Be exposure ages to report an updated chronology of moraines deposited during the Mount Waskey (Alaska) advance, which broadly dates to around the time of the YD, as originally reported by Briner et al. (2002).

SETTING

In the Mount Waskey region (Fig. 1B), prominent, well-preserved moraines are located ~4 km down-valley of the local cirque glacier complex and mark what is likely a readvance of the valley glacier during overall retreat, as marked by the crosscutting relationship between the Mount Waskey moraines and ice-flow features in the main east-west–trending trunk valley (Briner et al., 2002). The Mount Waskey moraines are, notably, clast-supported features, and they impound a lake; a macrofossil-based radiocarbon age from basal lake sediments constrains the age of the Mount Waskey moraines to >11,010 ± 250 cal yr B.P. (Levy et al., 2004). Briner et al. (2002) originally presented seven ^{10}Be ages from Mount Waskey moraine boulders and a neighboring equivalent moraine with a mean age of 11.31 ± 0.71 ka, after excluding two older outliers (*n* = 5; see the GSA Data Repository[1]).

The clast-supported structure of the Mount Waskey moraines encourages exceptional moraine stability and largely circumvents issues

[1]GSA Data Repository item 2019204, materials, methods, and ^{10}Be age calculations, is available online at http://www.geosociety.org/datarepository/2019/, or on request from editing@geosociety.org.

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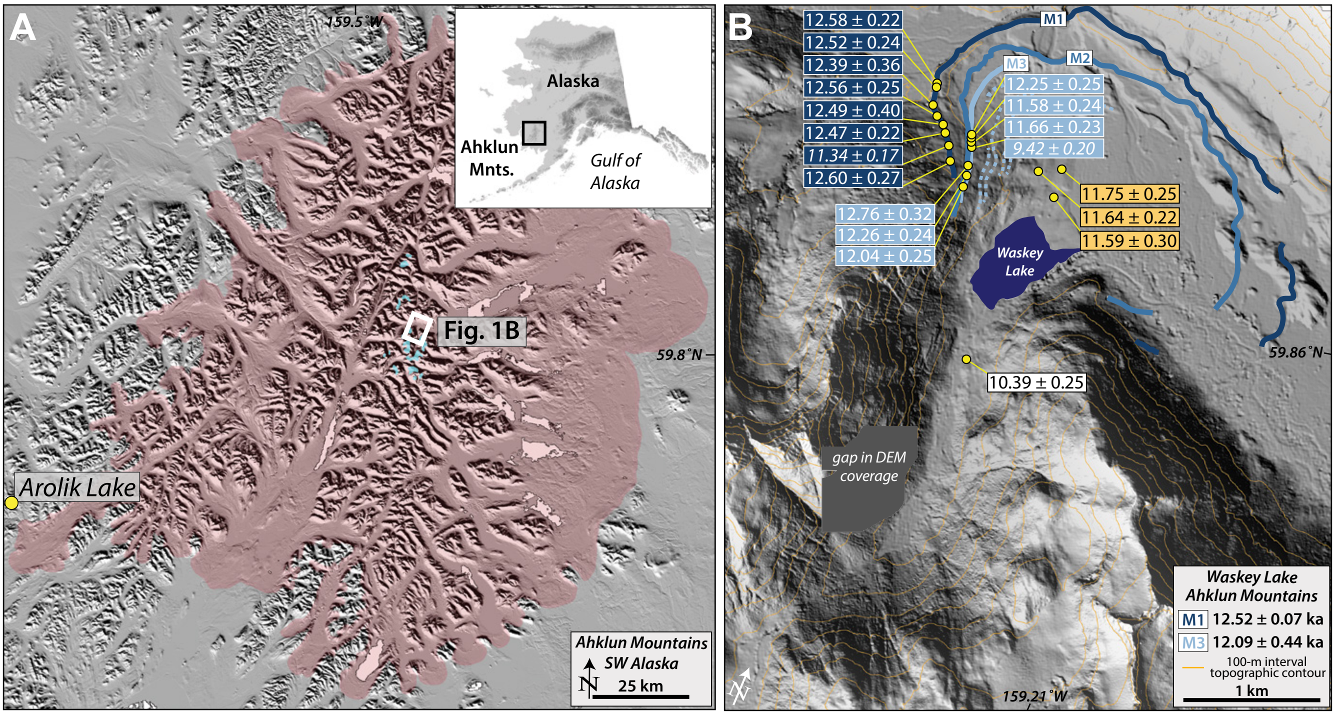

Figure 1. During the Last Glacial Maximum (LGM), the Ahklun Mountains (southern Alaska) hosted an ice cap with outlet glaciers filling major valleys and spreading out onto adjacent lowlands; deglaciation from maximum LGM ice limit was under way by ca. 22 ka (Kaufman et al., 2011, 2012; Briner et al., 2017). A: Late Wisconsin maximum ice extent in Ahklun Mountains (red shading), with locations of Mount Waskey field area and Arolik Lake. B: Waskey Lake field area with mapped moraines (M) and individual ^{10}Be ages (ka; 1σ analytical uncertainty only; Table DR1 [see text footnote 1]). DEM—digital elevation model.

that have plagued ^{10}Be chronologies in geomorphically unstable environments, such as Alaska (Briner et al., 2005). Moreover, since the initial ^{10}Be measurements of Briner et al. (2002), the cosmogenic isotope community has made remarkable improvements in: (1) isolating ^{10}Be from quartz, (2) accelerator mass spectrometric measurement of the ^{10}Be/^{9}Be ratio (Rood et al., 2013), and (3) precisely constraining ^{10}Be reference production rates (e.g., Balco et al., 2009; Young et al., 2013; Putnam et al., 2019). Combined, the Mount Waskey moraines provide an opportunity to develop a rare, and precise, centennial- to millennial-scale record of late-glacial ice extent in Alaska using ^{10}Be.

MOUNT WASKEY ^{10}Be MORAINE CHRONOLOGY

We present eight ^{10}Be ages from the outer moraine crest (M1), seven ^{10}Be ages from an inner moraine (M3), three ^{10}Be ages from erratic boulders located immediately inboard of the Mount Waskey moraines, and a single ^{10}Be age from a boulder perched on bedrock up-valley of Waskey Lake (Fig. 1B; using Baffin Bay production rate and Lm scaling; Young et al., 2013; see the Data Repository for ^{10}Be details). The ^{10}Be ages from the outer moraine range from 12.60 ± 0.27 ka to 12.39 ± 0.36 ka and have a mean age of 12.52 ± 0.07 ka (n = 7) after excluding one younger outlier (11.34 ± 0.17 ka; >2σ younger than population mean; Table DR1 in the Data Repository). The ^{10}Be ages from the inner moraine range from 12.76 ± 0.32 ka to 11.58 ± 0.24 ka and have a mean age of 12.09 ± 0.44 ka (n = 6) after excluding one younger outlier (9.42 ± 0.20 ka). Three ^{10}Be ages from boulders inboard of the innermost recessional moraine are 11.75 ± 0.25 ka, 11.64 ± 0.22 ka, and 11.59 ± 0.30 ka (mean = 11.66 ± 0.08), and one erratic boulder up-valley of Waskey Lake has a ^{10}Be age of 10.39 ± 0.25 ka (Fig. 1B).

DISCUSSION

Including the production-rate uncertainty (1.8%; Young et al., 2013), our ^{10}Be ages reveal that the culmination of the Mount Waskey phase occurred at 12.52 ± 0.24 ka—early within the YD stadial (Fig. 2). Following this culmination, the Mount Waskey glacier retreated 1 km through the YD, yet it remained relatively near its YD maximum extent until 11.66 ± 0.23 ka, as constrained by ^{10}Be ages from inside the Mount Waskey moraine complex before retreating up valley (Figs. 1B and 2). Indeed, the Mount Waskey moraine complex appears to represent a response of the Mount Waskey glacier to YD cooling. Records of climate variability in southern Alaska also point to pronounced climate changes through the YD interval. At Arolik Lake (Fig. 1A), a record of biogenic silica—considered a proxy for changes in summertime temperature—clearly captures YD cooling (Fig. 3; Hu et al., 2003). In a review of qualitative lacustrine summer-temperature–sensitive proxy data, Kaufman et al. (2010) provided evidence from several additional sites in southern Alaska showing early YD cooling. Offshore, Gulf of Alaska (GOA) planktonic δ^{18}O values also capture a YD signal (Praetorius and Mix, 2014), and a complementary record of GOA alkenone-based ocean temperatures also reveals pronounced YD cooling, with lowest temperature occurring in the middle YD (Fig. 3; Praetorius et al., 2015). We cannot rule out that changes in winter snowfall contributed to the oscillation of the Mount Waskey glacier. However, pollen records indicate that southern Alaska, including the Ahklun Mountains, remained relatively dry during the YD (Peteet and Mann, 1994; Hu et al., 2002), suggesting that oscillations of the Mount Waskey glacier during late-glacial times were likely driven by summer temperature versus a marked increase in winter snowfall.

Although several independent proxy records point to YD-related temperature variability in the southern Alaska–GOA region, the exact nature of this temperature variability is less clear. The mean-annual temperature depression during the YD displayed in Greenland ice cores is thought to be heavily biased by an extreme wintertime temperature anomaly, with minimal summertime temperature change (Denton et al., 2005; Buizert et al., 2014). Whereas the Mount Waskey moraines mark a response to YD cooling, their down-valley position equates to

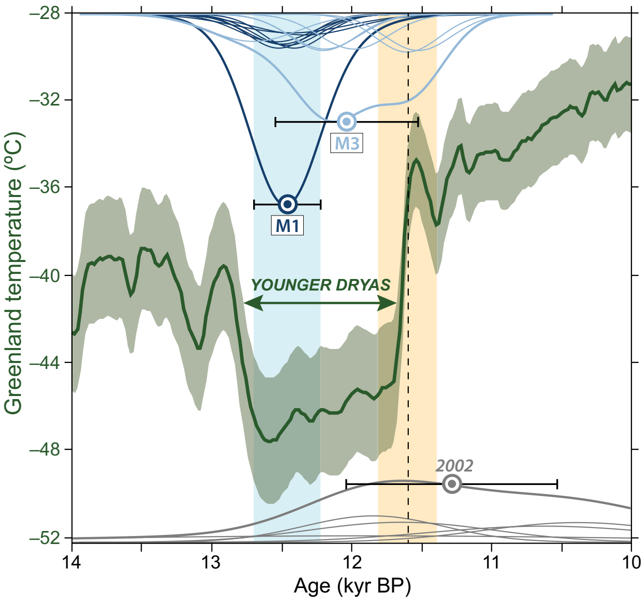

Figure 2. Two generations of ^{10}Be measurements at Waskey Lake (Ahklun Mountains) vs. gas-phase Greenland temperature (Buizert et al., 2014). Shown are original ^{10}Be measurements from 2002 (gray; Briner et al., 2002) compared to our new ^{10}Be ages from outer (M1) and inner (M3) Mount Waskey moraines, and ^{10}Be ages from erratics located immediately inboard of Mount Waskey moraines (orange shading; Fig. 1B). Production-rate uncertainty was propagated in quadrature (1.8%; Young et al., 2013); Mount Waskey moraines are dated to 12.52 ± 0.24 ka (M1) and 12.09 ± 0.49 ka (M3), and erratics provide a minimum limiting age of 11.66 ± 0.23 ka. Our ^{10}Be ages are in stratigraphic order; therefore, undated middle moraine (M2) must have been deposited between 12.52 ± 0.24 ka and 12.09 ± 0.49 ka (Fig. 1B). Also note that inner moraine (M3) must be older than 11.66 ± 0.23 ka, as constrained by ^{10}Be ages immediately inside Mount Waskey moraines (Fig. 1B; Table DR1 [see text footnote 1]), and must also be younger than 12.52 ± 0.24 ka, as constrained by stratigraphically older M1 moraine. Using the original ^{10}Be measurements from 2002, the Mount Waskey moraines are dated to 11.31 ± 0.74 ka. To plot ^{10}Be ages on the B.P. time scale and make them comparable to Greenland temperature time scale and time scale used in Figure 3, 64 yr and 50 yr were subtracted from new and A.D. 2002 data sets, respectively (year of sample collection minus CE 1950): 12.46 ± 0.24 kyr B.P. (M1; blue vertical bar), 12.03 ± 0.49 kyr B.P. (M3), 11.60 ± 0.24 kyr B.P. (inboard erratics; orange vertical bar), and 11.26 ± 0.74 kyr B.P. (Briner et al., 2002).

an equilibrium line altitude of only 80 ± 30 m lower than present (Briner et al., 2002), suggestive of very modest YD summertime cooling and consistent with the seasonality hypothesis (Denton et al., 2005). Although several proxy records in southern Alaska capture a YD signal, including GOA planktonic $\delta^{18}O$ values that correspond tightly with summit Greenland $\delta^{18}O$ values through the YD (Fig. 3), the summertime component of this temperature change is likely minimal. Nonetheless, our data suggest that the positive glacier mass balance in southern Alaska that occurred in the early YD became negative, forcing glacier retreat, during the switch to modest summer warming in the early-to-middle YD (Fig. 3).

In contrast to the late-glacial temperature pattern displayed in Greenland ice cores, globally integrated records of temperature change depict alternative temperature profiles (Fig. 3). A synthesis of terrestrial and marine temperature proxy records reveals cooling before the YD onset with minimum temperatures achieved at ca. 12.7 ka, followed by continuous warming through the YD (Fig. 3; Shakun et al., 2012). This temperature pattern is largely mimicked in an estimate of mean global ocean temperature, which records the lowest ocean temperature of the late-glacial period occurring at ca. 12.8–12.7 ka, near the onset of the YD, and similarly shows steady warming until 11.9 ka (Fig. 3; Bereiter et al., 2018). The Southern Hemisphere glacial record is compatible with these climate trends. Highly resolved mountain glacier chronologies reveal that glacial culminations occurred just prior to the YD followed by net glacier recession through the YD (Kaplan et al., 2010, 2011; Putnam et al., 2010; García et al., 2012; Sagredo et al., 2018). It has recently been hypothesized that even in the North Atlantic region, glacier behavior may follow trends expressed in globally integrated temperature records, rather than temperature change trends influenced by Atlantic meridional overturning circulation (AMOC; i.e., Greenland ice cores; Bromley et al., 2018).

Because many glacial chronologies often are not resolved at the centennial scale, it remains unclear whether the climatic forcing mechanisms expressed in globally integrated proxy records were most important for forcing Northern Hemisphere glacier change during the late-glacial period. Nonetheless, our data set suggests that North Atlantic–centric climate variability affected glacier behavior in the North Pacific sector of the Northern Hemisphere. The YD terminated with abrupt mean-annual warming at ca. 11.7 ka as recorded in Greenland ice cores, and one could expect moraine abandonment at this time (Fig. 2), yet close scrutiny of Greenland temperature records reveals that maximum YD cooling occurred early in the stadial (ca. 12.7–12.4 ka; Buizert et al., 2014), followed by relatively modest warming until abrupt warming at ca. 11.7 ka (Fig. 2). Therefore, the culmination of maximum YD glacier limits might be expected to occur during the early YD (Fig. 2; Vacco et al., 2009). Here, the Waskey phase culminated at 12.51 ± 0.24 ka, followed by glacier recession, yet ice remained within ~1 km from its maximum YD position until 11.66 ± 0.23 ka, i.e., the end of the YD (Figs. 1B and 2). In addition, many records of glacier and ice-sheet change from the North Atlantic region also reveal that glacial culminations occurred during the early-to-middle YD (Andersen et al., 1995; Briner et al., 2014; Jennings et al., 2014). Interestingly, some records from elsewhere around the globe do as well; an exceptionally well-dated glacier advance with bracketing radiocarbon ages reveals the culmination of a Quelccaya ice cap advance at ca. 12.5–12.4 ka, followed by glacier recession through the remainder on the YD (Kelly et al., 2012).

Over millennial time scales, glacier chronologies in both hemispheres appear to be characterized by net glacier recession during the YD, suggestive of a global pacemaker through the late-glacial period (i.e., CO_2; Shakun et al., 2012). However, at least in Northern Hemisphere, it appears that overall glacier recession during the late-glacial period was briefly interrupted by YD cooling, with glacier culminations occurring in the early-to-middle YD; this pattern of glaciation is consistent with records of climate variability from the North Atlantic and the North Pacific. Overall YD temperature change was dominated by a severe wintertime temperature anomaly (Denton et al., 2005), but YD glacial culminations suggest some degree of summer temperature change (Fig. 3). Wintertime sea ice in the North Atlantic region likely drives the extreme wintertime cooling associated with abrupt climate events (Denton et al., 2005; Brauer et al., 2008), but we suggest the impacts of expanded sea ice extend into the summer season via direct cooling or a shortened melt season—both a result of lingering sea ice. For example, modeling exercises suggest that while wintertime sea ice clearly dictates North Atlantic climate, these climate anomalies tend to be weaker beyond the North Atlantic and also may extend into the summer season (Alley, 2007). Regardless, changes in AMOC, likely exacerbated by changes in sea-ice cover, led to Northern Hemisphere glacier behavior that had a strong regional expression, superimposed on the global temperature pattern driven primarily by changes in CO_2.

CONCLUSIONS

Redating of the Mount Waskey moraines indicates that the Mount Waskey glacier advance culminated in the early YD, followed by modest glacier recession through the remainder

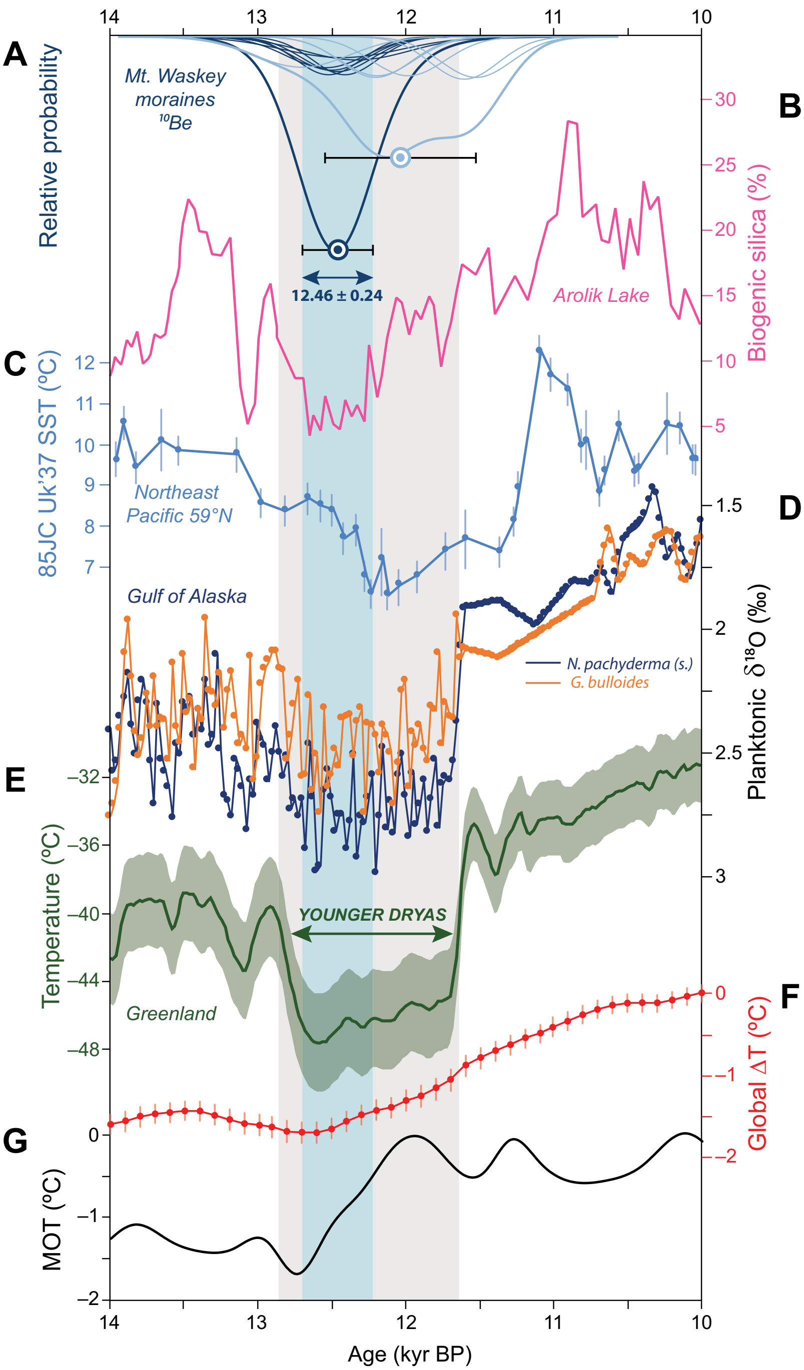

Figure 3. A: ¹⁰Be ages from Waskey Lake (Ahklun Mountains) in context of regional to global records of climate variability. B–G: Waskey ¹⁰Be ages are compared to records of: (B) biogenic silica from Arolik Lake (Hu et al., 2003; Fig. 1A), (C) alkenone-based sea-surface temperature (Uk'$_{37}$ SST) from Gulf of Alaska (Praetorius et al., 2015), (D) Gulf of Alaska planktonic ¹⁸O values (*Neogloboquadrina pachyderma*, *Globigerina bulloides*; Praetorius and Mix, 2014), (E) Greenland temperature (Buizert et al., 2014), (F) global temperature change relative to early Holocene mean (11.5–6.5 ka; Shakun et al., 2012), and (G) mean ocean temperature relative to modern (MOT; Bereiter et al., 2018). Blue vertical bar marks culmination of Waskey phase as defined by ¹⁰Be ages on the outer moraine (12.46 ± 0.24 kyr B.P. or 12.52 ± 0.24 ka).

of the YD. Our reconstructed patterns of glacier change, combined with regional records of climate variability, support modest summertime cooling that drove YD glacier change in the GOA region. Moreover, our record of YD-related glaciation is consistent with the overall pattern of Northern Hemisphere glaciation during the YD, where glacier culminations occurred in the early or middle of the YD, followed by net glacier recession. Whereas YD cooling in the Northern Hemisphere was almost certainly biased toward the wintertime, widespread early to mid-YD glacier culminations in the Northern Hemisphere likely required a component of modest summertime cooling, consistent with the seasonality hypothesis. Despite a recent challenge to a classical Younger Dryas signature in records of Northern Hemisphere glaciation (i.e., Bromley et al., 2018), it seems that there was indeed a glacier response to AMOC-modulated climate change during the YD, yet this response was likely a brief interruption of overall glacier recession. Many glacier culminations seem to have occurred during the early-to-middle YD as opposed to at the YD termination.

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