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Persistent millennial-scale glacier fluctuations in Ireland between 24 ka and 10 ka

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ABSTRACT

We report 80 ^{10}Be ages on 14 moraines from Irish cirques that show a previously unrecognized signal of at least eight millennial-scale fluctuations between 24.5 ± 0.7 ka and 11.0 ± 0.3 ka. Several moraine ages may be correlative with abrupt warming at the onset of the Bølling-Allerød interval (14.7 ka) and the end of the Younger Dryas interval (11.7 ka), suggesting a forced response. Our ages also identify glacier fluctuations that occurred when regional temperatures were relatively stable. This finding is consistent with modeling results showing several hundred-meter-scale glacier fluctuations in response to interannual variability. At the same time, our composite record of cirque-glacier average equilibrium line altitudes (ELAs) shows a response to warming due to increasing greenhouse gases and summer insolation modulated by abrupt climate changes. Our new ^{10}Be chronology thus records both forced and unforced millennial-scale glacier fluctuations superimposed on a lower-frequency ELA signal of forced response to climate change.

INTRODUCTION

Cosmogenic ^{10}Be chronologies of glacier fluctuations since the Last Glacial Maximum (LGM) constrain glacier fluctuations that can be associated with the well-known millennial- and orbital-scale variability of the past 20 k.y. (Shakun et al., 2015). The abrupt climate changes of the last deglaciation are thought to be linked to changes in the Atlantic meridional overturning circulation (AMOC) and associated changes in ocean heat transport, likely with a strong feedback from changes in sea ice (Liu et al., 2009). Because of their location immediately adjacent to the North Atlantic Ocean, former cirque glaciers from Ireland were strategically located to monitor the full climatic effects of AMOC changes. Many Irish cirque basins are fronted by two or more moraines (Colhoun and Synge, 1980; Harrison et al., 2010; Synge, 1968), suggesting that they preserve a record of AMOC-induced climate variability, but the lack of well-dated records prevents a clear assessment of this response. Moreover, natural variability may cause comparable glacier fluctuations (Roe and Baker, 2014), complicating the attribution of moraines to climate change.

^{10}Be DATING OF CIRQUE MORAINES

We used standard methods (Barth, 2016; Gosse and Phillips, 2001) to sample moraines in eight cirque basins that range from southern (52.0°N) to northern (54.8°N) Ireland; all but one cirque basin are on or near the west coast (Fig. 1A). Although small (~1 km^2), the cirque basins each have two to four low-relief but well-defined moraines (Fig. 1B). We used ^{10}Be to date 80 boulders from 14 moraines, with one dated moraine in each of two cirques and two dated moraines in each of the other six (Fig. 1B). Seven of the cirques also had at least one additional moraine that was not dated (Fig. 1B). Samples were processed for ^{10}Be/^{9}Be measurements following the procedures of Licciardi (2000) and Marcott (2011). ^{10}Be/^{9}Be ratios were measured by accelerator mass spectrometry (AMS) at the Purdue University PRIME Laboratory (West Lafayette, Indiana, USA).

We calculated ^{10}Be ages with the CRONUS-Earth web calculator (v. 2.0; http://cronus.cosmogenicnuclides.rocks/2.0/) (Marrero et al., 2015) using a production rate of 3.92 ± 0.31 atoms g^{-1} yr^{-1} (Phillips et al., 2016) and the nuclide- and time-dependent scaling scheme of Lifton et al. (2014) (see the GSA Data Repository[1] for details). We add the production rate uncertainty in quadrature when comparing to ages based on other dating methods; this accounts for 47% to 78% of the total uncertainty. Mean ^{10}Be ages are interpreted as reflecting the onset of glacier retreat from the moraines (Balco, 2011).

MILLENNIAL-SCALE GLACIER FLUCTUATIONS

Given the low probability of moraine preservation in any given basin (Gibbons et al., 1984), we consider our moraine ages collectively to represent a composite record of cirque-glacier variability between 24.5 ± 0.7 ka and 10.8 ± 0.5 ka. Based on stratigraphic relationships and the diversity of our moraine ages (Fig. 2A), we are able to identify eight discrete events between 24.5 ka and 11 ka (Fig. 2B; Table DR3 in the Data Repository). We constrain this millennial-scale signal by considering only the analytic uncertainty between ^{10}Be ages (Fig. 2A; Table DR3), as the reported uncertainty on the production rate used here is the same for all samples. The age of some events is represented by one moraine, while other event ages are the combination of two or three moraine ages that overlap at 1σ. We found no cirque metrics (e.g., size, orientation, latitude, elevation, slope) that would explain the regional distribution of moraine ages (Barth, 2016). We note that because moraine ages with overlapping uncertainty may differ in age, and that 13 moraines from our sampled cirques are undated (Fig. 1B), more than eight events is possible.

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[1] GSA Data Repository item 2018034, methods and materials, supplemental figures and information, and 10Be analytical data from this study, is available online at http://www.geosociety.org/datarepository/2018/ or on request from editing@geosociety.org.

GEOLOGY GSA Data Repository item 2018034 | https://doi.org/10.1130/G39796.1

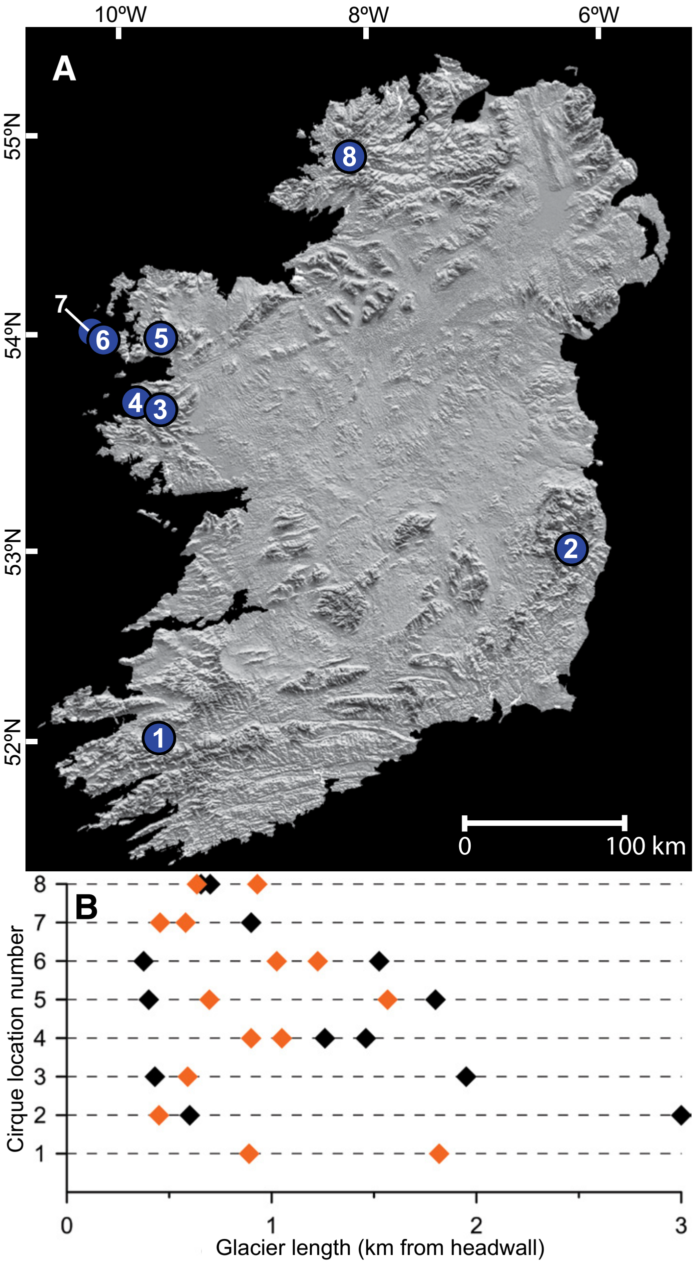

Figure 1. Cirque locations and moraine information. A: Location of Irish cirques analyzed in this study: 1—Alohart; 2—Carrawaystick; 3—Logaharry; 4—Sruhauncullinmore; 5—Corranabinna; 6—Lough Accorymore; 7—Bunnafreva; 8—Glascairns Hill. B: Glacier length as determined by distance of moraines from headwall for each respective cirque basin. Orange diamonds indicate dated moraines; black diamonds, undated moraines.

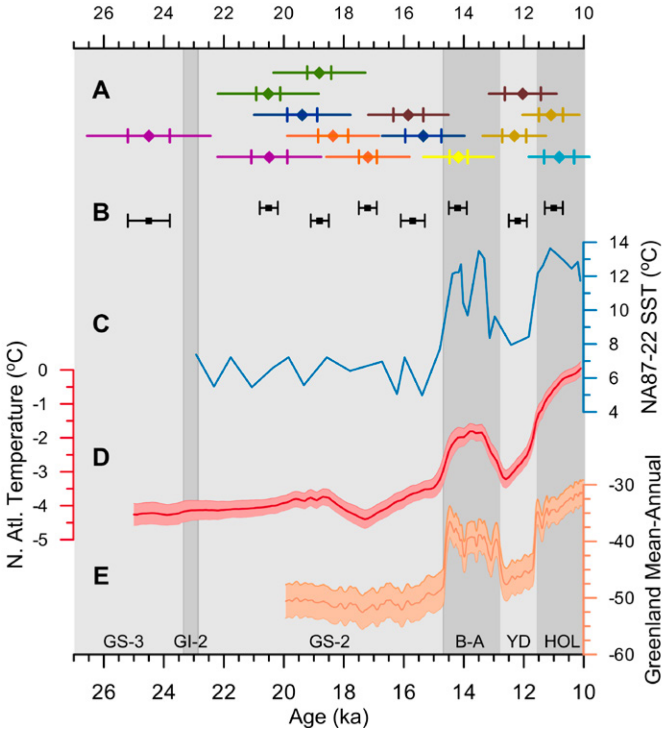

Figure 2. ^{10}Be moraine chronology and North Atlantic climate. A: ^{10}Be ages for each of the 14 moraines dated in this study (in Ireland) separated by cirque basin: Alohart (purple), Carrawaystick (light blue), Logaharry (yellow), Sruhauncullinmore (gold), Corranabinna (dark blue), Lough Accorymore (orange), Bunnafreva (green), and Glascairns Hill (brown). Horizontal line indicates uncertainty, with hatch marks showing analytic uncertainty and full line including production rate uncertainty. B: Minimum number of deglacial events (black squares) determined through combining overlapping moraine ages while preserving cirque-moraine stratigraphy. C: Sea-surface temperature (SST) from marine sediment core NA22-87 (blue) located just west of Ireland (55.5°N, 14.7°W; Waelbroeck et al., 2001). D: North Atlantic (N. Atl.) SST stack (red) as deviation from early Holocene (11.5–6.5 ka) SST, with 1σ uncertainty band (Shakun et al., 2012). E: Greenland mean-annual temperature reconstruction (orange) with 1σ uncertainty band (Buizert et al., 2014). Gray boxes correspond to well-defined interstadials and stadials and Holocene interglaciation (GS-3, GS-2, and GI-2 correspond to Greenland stadials 3 and 2 and Greenland interstadial 2, respectively; B-A corresponds to Bølling-Allerød warm interval; YD corresponds to Younger Dryas cold interval; HOL corresponds to Holocene).

CLIMATIC INTERPRETATION OF IRISH CIRQUE GLACIATION

Our initial hypothesis had been that Irish cirque-glacier moraines would record the large and abrupt warming events during the latter part of the deglaciation (Fig. 2). Such a forced response to the onset of the Bølling-Allerød interval (14.7 ka) may be supported by a moraine dated to 14.2 ± 1.2 ka, while the moraines dated at 12.3 ± 1.1 ka and 12.0 ± 1.1 ka may represent a response to the end of the Younger Dryas interval (11.7 ka). In these cases, however, the total age uncertainties on the moraines preclude a robust correlation to these events.

The remainder of our moraine ages identify a persistent millennial-scale signal when northern North Atlantic climate was relatively stable. In particular, the oldest event at 24.5 ± 0.7 ka and the four events between 21 ka to 15 ka (Fig. 2B) occurred during intervals of relatively stable and cold surface air temperatures in the North Atlantic region (Figs. 2C–2E), which correspond to Greenland stadials (GS) 3 and 2, respectively (Rasmussen et al., 2014). Such sustained periods of stable climate should have favored a positive surface mass balance for Irish glaciers (Liu et al., 2009) that would have maintained them at their extended moraine positions, rather than caused multiple episodes of retreat and readvance. We note that there is evidence of millennial-scale change during the GS-2 interval elsewhere (Barker et al., 2009; Clark et al., 2012; Toucanne et al., 2015), but this variability is too infrequent, too long, and/or too different in age to explain our cirque-glacier record and, more importantly, is not expressed in the northern North Atlantic region (Fig. 2; Fig. DR2 in the Data Repository).

Although regional temperature reconstructions do not identify large abrupt changes in northern North Atlantic climate during the 21–15 ka interval, all high-resolution Greenland ice-core δ^{18}O records show rapid climate fluctuations on the shortest resolved (decadal) time scales (Rasmussen et al., 2014). Similarly, a transient simulation of the last deglaciation with a climate model (TraCE, http://www.cgd.ucar.edu/ccr/TraCE/)

shows interannual variability in summer temperature and winter precipitation over Ireland (Figs. 3A and 3B) (He, 2011). Interannual climate variability comprises the year-to-year fluctuations that occur due to the vagaries of weather even in a constant climate, and is defined by the statistics of such fluctuations during some period of interest (here, centuries to millennia). Such variability is characterized by a white or weakly red power spectrum (e.g., Roe and Baker, 2016, and references therein). Glaciers act as low-pass filters of this variability, leading to substantial length fluctuations (hundreds of meters to kilometers, depending on glacier geometry and climatic setting) (Oerlemans, 2000; Roe et al., 2017), suggesting that moraines formed during this period of stable climate from 21 to 15 ka may represent an unforced response to this variability. Behavior of this sort leads to the greatest preservation potential of moraines recording the largest glacier readvances (Gibbons et al., 1984; Roe and O'Neal, 2009).

We use two glacier models to characterize glacier fluctuations in response to natural climate variability (see the Methods section of the Data Repository). The first is a numerical model of ice flow using the shallow-ice approximation for ice dynamics, including Weertman-style sliding (Roe and Baker, 2016). Our second model is based on recent work that has shown that glacier dynamics can be accurately emulated by a linear, third-order differential equation (Roe and Baker, 2014). We drive the numerical glacier model with interannual variability from the TraCE simulation (Fig. 3A and 3B). Melt-season (June to August) temperature variability is taken directly from the detrended TraCE output, and related to summer mass balance via a melt factor of 0.65 m yr^{-1} K^{-1} (Anderson et al., 2014). Winter half-year variability is scaled to a standard deviation of 0.4 m yr^{-1} to account for orographic enhancement of the coarse TraCE model grid resolution (see the Methods section of the Data Repository). The winter half-year precipitation is consistent with normally distributed white noise, while melt-season temperature exhibits a small degree of interannual persistence (see the Methods section of the Data Repository; Fig. DR1; Table DR4), which acts to enhance glacier variability (Roe and Baker, 2016). Temperature variability increases slightly toward the end of the interval (Fig. 3A), while precipitation variability decreases a little (Fig. 3B).

For our central estimate of parameters, the glacier length fluctuations have a standard deviation of $\sigma_L = 160$ m (Fig. 3C; see Video DR1 in the Data Repository). Because of the small size of these glaciers, extreme excursions are up to 50% of maximum glacier length. This σ_L is smaller than reported for some larger glaciers (Oerlemans, 2000; Roe and O'Neal, 2009), but is consistent with smaller glaciers in more arid climates (Malone et al., 2015; Roe et al., 2017). For the three cirques considered, and for the uncertainty in mass balance variability, we find a range of σ_L between 110 and 200 m (Table DR5). The number of predicted moraines is in good agreement with the number of mapped moraines in the cirques (Fig. 1B). From the three-stage model equations, the average return time of a given advance of distance ΔL is given by $R(\Delta L) = 2\pi\tau \times \exp[\Delta L^2/(2\sigma_L^2)]$, where τ is the time scale over which glaciers integrate mass balance anomalies (Roe and Baker, 2014). Thus for these glaciers, advances of several hundred meters can be expected on millennial time scales. We emphasize that the goal of our model integrations is not to reproduce the exact observed moraine record of these Irish cirques, but instead illustrate that fluctuations on a similar time scale can be driven by interannual climate variability.

We next evaluate whether there is a climate signal in our composite moraine record as inferred from the long-term (centennial-scale) cirque-glacier equilibrium line altitudes (ELAs). We reconstructed ELAs for each glacier that deposited one of the 14 dated moraines using an area-accumulation ratio for steady-state glaciers of 0.60 ± 0.05 (Porter, 1975, 1977) (Fig. 4). The ELAs capture the mean state of the glaciers that were otherwise fluctuating in response to interannual variability or retreating due to climate change to produce the moraine records. Figure 4 compares our composite ELA record from 22 to 10 ka to the mean-annual temperature records from Greenland ice cores (Buizert et al., 2014) and a stack of North Atlantic sea-surface temperatures (Shakun et al., 2012). Warming through this interval occurred in response to increasing insolation and greenhouse-gas concentrations that was modulated by abrupt changes in the AMOC (He, 2011). Within the age uncertainties of our moraines used to constrain the ELAs, the ELA signal generally tracks changes in regional climate, with ELAs averaging 315 ± 50 m above sea level (a.s.l.) ($n = 10$) associated with the cold LGM, Oldest Dryas, and Younger Dryas, and 500 ± 105 m a.s.l. ($n = 3$) during the warm Bølling-Allerød and early Holocene.

We thus conclude that our new Irish cirque-glacier chronology sheds light on several important features of the North Atlantic climate in the interval 22–10 ka. There is a persistent millennial-scale signal, some

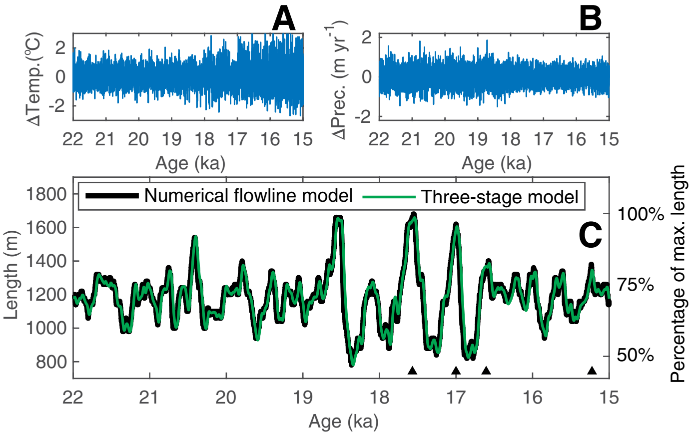

Figure 3. Cirque glacier response to interannual climate variability. A: Detrended melt-season temperature (June to August) from TraCE climate model simulation for 22–15 ka (see the Methods section of the Data Repository [see footnote 1]). B: As in A, but for winter half-year (September to February) precipitation. C: Glacier-length fluctuations for characteristic geometry of Irish cirque glaciers (Lough Accorymore in this study), demonstrating close agreement between numerical flowline model (black) and linear three-stage model (green). Right-hand scale shows percentage of maximum extent. Triangles at bottom identify moraines that would be preserved from ice-margin fluctuations.

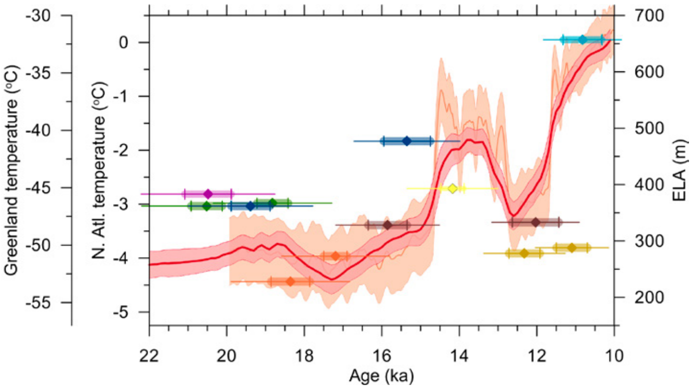

Figure 4. Comparison of reconstructed Ireland cirque equilibrium-line altitudes (ELAs) and regional temperature. Orange line shows Greenland mean-annual air temperature with 1σ uncertainty indicated by shaded area (Buizert et al., 2014). Red line shows North Atlantic (N. Atl.) sea-surface temperature stack as deviation from early Holocene (11.5–6.5 ka), with 1σ uncertainty indicated by shaded area (Shakun et al., 2012). Diamonds show reconstructed ELA for each dated moraine with its assigned age uncertainty, with uncertainty in ELAs shown by thickness of horizontal bars: Alohart (purple), Carrawaystick (light blue), Logaharry (yellow), Sruhauncullinmore (gold), Corranabinna (dark blue), Lough Accorymore (orange), Bunnafreva (green), and Glascairns Hill (brown). The three records were scaled so that maxima and minima of each record are in general agreement.

of which is attributable to changes in the AMOC and associated abrupt climate changes. However, many of our moraine ages record glacier fluctuations during periods of relatively stable climate and are best explained as a response to stochastic forcing from interannual variability. Finally, as shown in our composite ELA record, this millennial-scale signal is superimposed on the longer-term climate changes associated with insolation, greenhouse gases, and the AMOC during the last deglaciation.

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