The effects of interannual climate variability on the moraine record

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ABSTRACT

Valley glacier moraines are commonly used to infer past mean annual precipitation and mean melt-season temperature. However, recent research has demonstrated that, even in steady climates, multi-decadal, kilometer-scale fluctuations in glacier length occur in response to stochastic, year-to-year variability in mass balance. When interpreting moraine sequences it is important to include the effect of interannual weather variability on glacier length; moraines record advances that are forced either by interannual variability or by a combination of climate change and interannual variability. We address this issue for the Last Glacial Maximum (LGM) glaciers of the Colorado Front Range, United States. Using a linear glacier model that allows thorough exploration of parameter uncertainties, supplemented by a shallow-ice flowline model, our analyses suggest that (1) glacial standstills longer than 50 years were unlikely; (2) mean glacier lengths are ~10%–15% up-valley from maximum glacier lengths; and (3) individual LGM terminal moraines were formed by a combination of a climate change and interannual variability–forced advances.

INTRODUCTION

Glacial to interglacial changes in the long-term averages of annual precipitation (P) and mean melt-season temperature (T) are sufficient, in many places, to force significant changes in glacier length (tens of kilometers). But even in steady climates, year-to-year (interannual) variations in P and T have also been shown to force multi-decadal, kilometer-scale length fluctuations in valley glaciers, due solely to the random alignment of years of negative and positive mass balance (e.g., Reichert et al., 2002; Item DR8 in the GSA Data Repository[1]). A steady climate implies constant long-term averages ($\equiv \overline{P}, \overline{T}$) and, importantly, constant standard deviations ($\equiv \sigma_P, \sigma_T$). All climates, steady or transient, include interannual variability. It is often incorrectly assumed that glaciers average away all interannual climate variability, and respond only to more persistent climate fluctuations. However, glaciers act as low-pass filters, producing multi-decadal (for the glaciers discussed in this paper) length fluctuations even if the climate forcing it is not correlated from year to year (white noise), which is almost always the case (Fig. 1B; Burke and Roe, 2013). Interannual variability is a result of the stochastic fluctuations of weather (climate noise) and the internal modes of variability in the climate system, such as the North Atlantic, the Pacific–North American, and the El Niño–Southern Oscillations (see Item DR8). The amplitude of interannual variability varies with location and climate state, but it is always present. To constrain the values of past $\overline{T}$ and $\overline{P}$ using glacier moraines and to correctly interpret the moraine record, we must understand the effects of year-to-year weather variability on glacier length and moraine emplacement.

To illustrate the problem, consider two glaciers: (a) a glacier subject to constant $\overline{T}$ and $\overline{P}$ forms a steady ice-surface profile that terminates at a steady, mean length, $\overline{L}$ (Fig. 1A); and (b) a glacier subject to a climate with the same $\overline{T}$ and $\overline{P}$ that also includes interannual variability. The glacier of case (b) will produce a terminus history that will fluctuate on multi-decadal scales (red noise) around the same $\overline{L}$ as glacier (a) (Figs. 1B and 2C). However, for glacier (b) $\overline{L}$ is a theoretical position with no expression

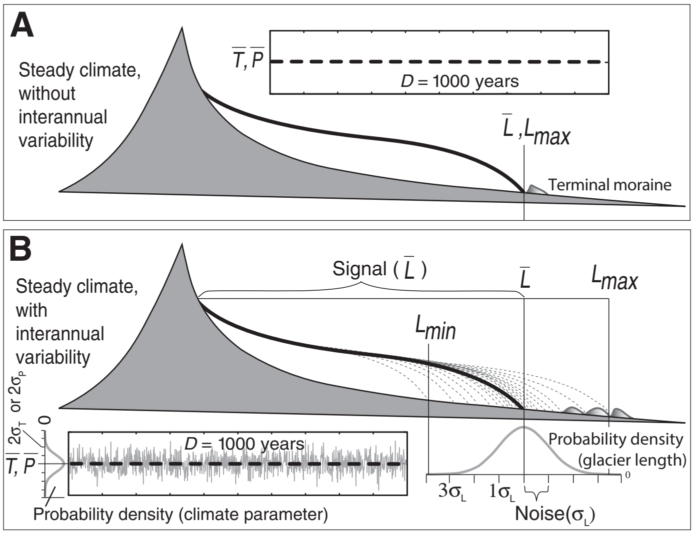

Figure 1. A: Glacier forced only by long-term average annual precipitation and mean melt-season temperature, $\overline{P}$ and $\overline{T}$ (bold dashed line), over time period, D, leads to a steady ice profile (bold black line) at mean length $\overline{L}$. Maximum terminal moraine forms at $\overline{L}$. B: Glacier forced by same $\overline{P}$ and $\overline{T}$ as in A but with interannual variability included (gray white noise in inset panel, which fills a normal distribution centered at $\overline{P}$ or $\overline{T}$) results in terminus position that fluctuates around $\overline{L}$ as shown by the gray dashed ice profiles. Given enough time, terminus position fills a normal distribution centered at $\overline{L}$ (signal; Equation 3) and is characterized by σ_L (noise; Equation 2), the standard deviation of glacier length perturbations around $\overline{L}$. A change in $\overline{L}$ would occur with a change in $\overline{P}$ or $\overline{T}$ but not a change in σ_P or σ_T.

in the landscape, and it is the location around which the terminus fluctuates. If we assume that (1) terminal moraines up to 40 m in height can be formed on time scales less than 50 yr, (2) moraines do not significantly impede subsequent advances, and (3) all moraines that are overrun by subsequent advances are removed, then the maximum excursion from $\overline{L}$ will form the furthest terminal moraines. Assumption 1 is supported by a compilation of 45 terminal moraine formation time scales and moraine heights, which shows that 25-m-tall ice contact and dump moraines, as well as 50-m-tall push and glaciotectonic moraines, form in less than 50 yr (Item DR3). Assumption 2 is primarily a concern when latero-frontal dump moraines >50 m in height are present; these are common in tectonically active regions such as the Himalaya, Andes, or Southern Alps (e.g., Benn and Evans, 1998; Item DR3). Estimates of mean climate (i.e., $\overline{P}, \overline{T}$) should be based on $\overline{L}$ rather than the maximum glacier advance, L_{max} (Fig. 1B). Thus, we face the challenge of estimating the mean length $\overline{L}$ while knowing only the glacier geometry preserved by L_{max} and recognizing the substantial uncertainties in physical parameters.

We focus on the Last Glacial Maximum (LGM) moraine record in the Colorado Front Range, United States, to establish the effect of interannual variability on the moraine record. We use a shallow-ice-approximation flowline model (using standard techniques; Item DR6) to confirm, in accordance with prior work in modern maritime, Alpine, and continental settings, that interannual variability can force significant multi-decadal length fluctuations (e.g., Oerlemans, 2001). We primarily focus on constraining the effect of parameter uncertainty on the magnitude of length

[1]GSA Data Repository item 2014014, Items DR1–DR8, is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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fluctuations forced by interannual variability using a linearized glacier model for the 11 modeled glaciers.

MODEL DESCRIPTION

Linearized Model

The linear model considers glacier length variations, L', as departures from a mean length $\bar{L}$ that are small enough that the equations are linear. Linear models use simplified glacier geometries to improve efficiency while still honoring the essence of glacier length change. They have been applied to a variety of glaciological problems (e.g., Jóhannesson et al., 1989; Oerlemans, 2001). Its use in this study is essential for efficient uncertainty analysis. Roe and O'Neal (2009) presented a complete model description. If time is discretized into increments of $\Delta t = 1$ yr, then

$$L'_{t+\Delta t} = L'_t\left(1-\frac{\Delta t}{\tau}\right)+\beta P'_t+\alpha T'_t. \quad (1)$$

The first term on the right-hand side represents the glacier's dependence on its previous state. The last two terms are the forcing due to a given year's anomaly in precipitation, P', and melt-season temperature, T', for which we use white noise with standard deviations of σ_P and σ_T. The coefficients α and β are functions of glacier geometry: $\alpha = -\mu A_{T>0}\Delta t/(wH)$, $\beta = A_{tot}\Delta t/(wH)$, $A_{T>0} = A_{abl} + Pw/(\mu\Gamma \tan\varphi)$, and τ is the characteristic time scale (also response time) over which the glacier responds to past forcing: $\tau = wH/(\mu\Gamma \tan\varphi\, A_{abl})$ (see Table 1 for definitions).

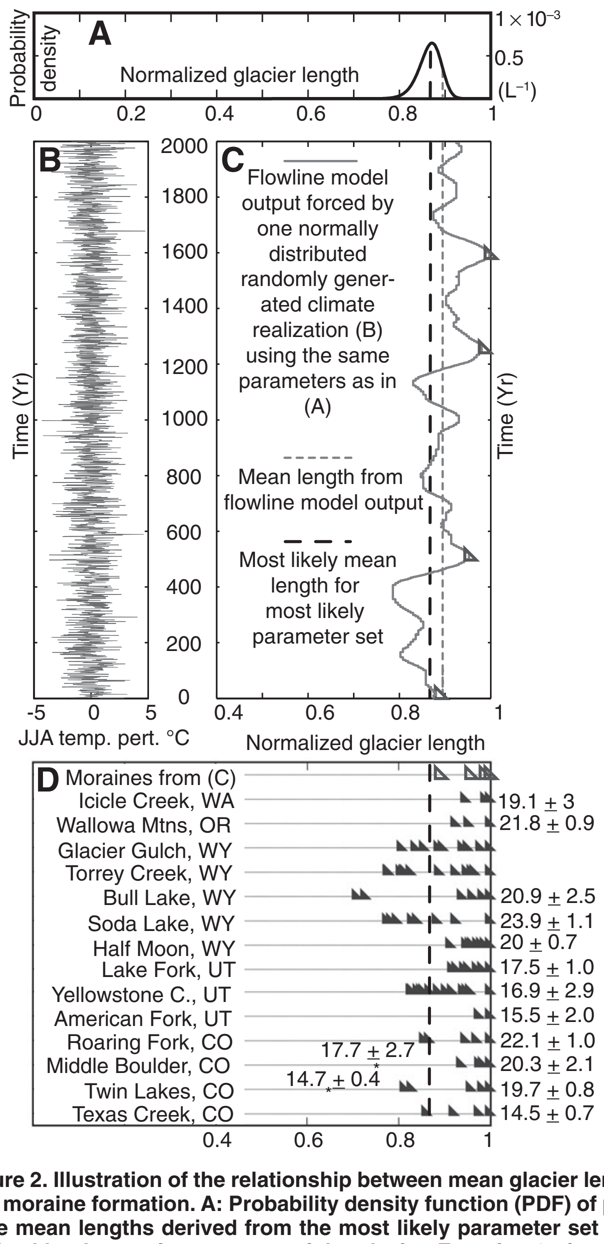


Figure 2. Illustration of the relationship between mean glacier length and moraine formation. A: Probability density function (PDF) of possible mean lengths derived from the most likely parameter set normalized by the maximum extent of the glacier. Equation 3 gives the most likely mean length $\bar{L}$ from this PDF. B: Example melt-season white-noise climatology, which is used to produce example glacier terminus history in shown in C (JJA temp. pert.—June, July, August temperature perturbation). C: Example terminus history with potential moraine-forming locations indicated by triangles. D: Glacier length normalized to Last Glacial Maximum (LGM) maximum terminal moraine with terminal moraines in-board from maximum extent shown as triangles for western United States LGM valleys (WA—Washington; OR—Oregon; WY—Wyoming; UT—Utah; CO—Colorado). Note scatter in LGM maximum terminal moraine ages (ka) shown on right (see Data Repository [see footnote 1] for citations).

Climate Data and Parameter Selection

Meteorological data were extracted from the longest-running high-elevation weather station in North America on Niwot Ridge, Colorado (Fig. 3B; station D1, 1952–2010, 3743 m above sea level). Assuming that the melt season runs from June to September, we determined that melt-season temperature ($\bar{T}$, σ_T) is (6.3, 1.3) °C and annual precipitation ($\bar{P}$, σ_P) is (1.2, 0.22) m yr^{-1}. Data were linearly detrended. We consider a range of near-surface lapse rates based on a global compilation of summer on-ice, near-surface lapse rates which for valley glaciers has a mean of 4.0 ± 2.1 °C km^{-1} (1σ) (Table 1; Item DR1). We constrain the melt-factor, μ (i.e., ablation rate per 1 °C change in T), based on a global compilation of μ for snow (4.5 ± 1.7 mm day^{-1} °C^{-1}) and ice (7.7 ± 3.2 mm day^{-1} °C^{-1}; Item DR2). We also consider a relatively broad range of accumulation-area ratios (*AAR*), the ratio of the accumulation area to the total glacier area, from 0.5 to 0.8 (Meier and Post, 1962).

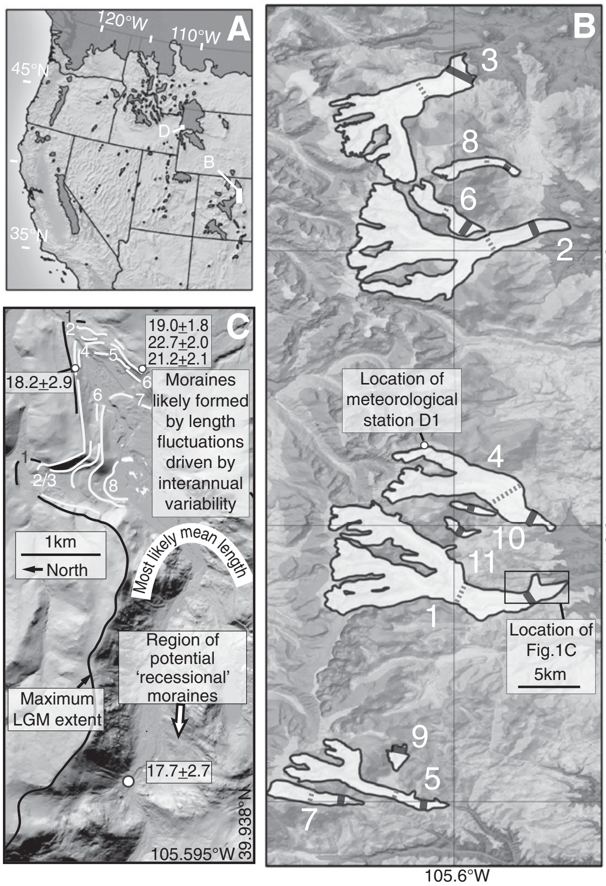
IMPACT OF INTERANNUAL VARIABILITY ON MEAN GLACIER LENGTH

The flowline model (Item DR6) was integrated with mid-range parameters (Table 1) for the basal slope and length of a mid-sized LGM Front Range glacier (Fall Creek glacier; Table 2; Fig. 2C). The most likely parameter set generated a standard deviation of length fluctuations (σ_L) of 370 m. For the linear model σ_L can be solved exactly:

$$\sigma_L = \sqrt{\frac{\tau\Delta t}{2}}\sqrt{\alpha^2\sigma_T^2+\beta^2\sigma_P^2}\ . \quad (2)$$

TABLE 1. LINEAR MODEL PARAMETERS AND GEOMETRY INPUTS

Name	Units	Description	Minimum	Mean	Maximum
μ	(m °C^{-1} yr^{-1})	Melt factor	0.5	0.7	0.9
Γ	(°C km^{-1})	On-ice near-surface lapse rate	3.5	5	6.5
AAR		Accumulation-area ratio	0.5	0.65	0.8
$\bar{P}$	(m)	Mean annual precipitation	0.6	1.2	2.4
σ_T	(°C)	Standard deviation of summertime temperature	1	1.3	1.6
σ_P	(m yr^{-1})	Standard deviation of annual precipitation	0.11	0.22	0.44
D	(yr)	Duration of climate change	500	4000	7500
Geometry inputs					
A_{tot}		Total area of the glacier			
A_{abl}		Ablation area of the glacier			
tan ϕ		Slope of the glacier bed			
w		Width of the ablation zone			
H		Thickness of the glacier			



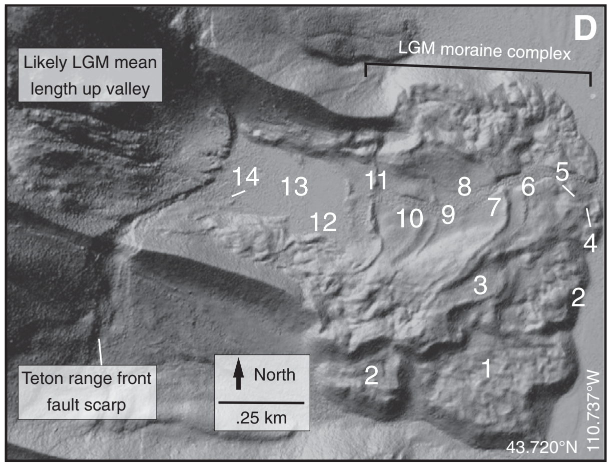


Figure 3. A: Map of western U.S. glaciers during Last Glacial Maximum (LGM) with generalized glacier outlines, after Young et al. (2011). B: Shaded relief map showing areal extent of 11 modeled glaciers (Table 2) and location of weather station used in this study. $\bar{L}_{mean}$, most likely estimate of mean length (solid line), and $\bar{L}_{min}$, minimum possible mean length (dashed line), are shown for each modeled glacier. C: Lidar-derived hillshade of terminal region of LGM Middle Boulder Creek (Colorado) glacier. Cosmogenic radionuclide dates are in ka (see Data Repository [see footnote 1] for citations). Note that two distinct LGM advances could have been dated leading to spread of cosmogenic radionuclide exposure ages. Numbers near moraines denote number of distinct ice advances recorded in pro-$\bar{L}$ area. D: Lidar hillshade of Glacier Gulch, Wyoming, LGM terminal moraine complex. Fourteen ice-marginal features preserved support mobile termini of western U.S. LGM glaciers. Note that ice-marginal feature 4 was formed by a re-advance that crosscut advances 1–3.

TABLE 2. GLACIER GEOMETRY INPUTS, MEAN LENGTHS, AND SIGNAL-TO-NOISE RATIOS

Glacier name	Area (km^2)	Slope	Width (km)	Height (km)	L_{max} (km)	$\bar{L}_{max}$ % to L_{max}	$\bar{L}_{mean}$ % to L_{max}	$\bar{L}_{min}$ % to L_{max}	Mean signal-to-noise ratio	Response time (τ) (yr)
1. Middle Boulder	56.62	0.031	1.30	0.22	18.55	97	86	62	16.68	133.44
2. North Saint Vrain	45.89	0.050	1.16	0.19	15.25	97	88	68	19.63	77.95
3. Bear Lake	31.19	0.055	1.56	0.16	12.61	97	87	63	17.70	118.99
4. North Boulder	26.00	0.091	1.32	0.11	12.47	97	89	71	22.94	50.10
5. Fall Creek	14.57	0.078	0.58	0.14	10.55	96	86	65	17.86	57.75
6. Hunter's Creek	6.25	0.138	0.81	0.09	6.19	96	85	59	16.12	69.00
7. Mill Creek	5.80	0.089	0.52	0.11	5.94	95	79	41	10.27	91.33
8. Roaring Fork	4.11	0.178	0.51	0.08	5.72	96	86	63	17.69	45.59
9. Silver Creek	1.67	0.131	0.45	0.04	2.07	83	28	–119	1.11	67.22
10. Rainbow Creek	1.42	0.120	0.44	0.04	2.92	87	43	–77	2.11	83.50
11. Horseshoe Creek	1.41	0.137	0.35	0.05	2.86	90	57	–30	3.64	73.85

Note: L_{max} = maximum glacier length; $\bar{L}$ = mean glacier length; $\bar{L}_{min}$ = minimum estimate of $\bar{L}$; $\bar{L}_{mean}$ = most likely $\bar{L}$; $\bar{L}_{max}$ = maximum estimate of $\bar{L}$; $\bar{L}$% to L_{max} = 100 $\bar{L}/L_{max}$; signal-to-noise ratio = $\bar{L}/\sigma_L$.

For the same parameters as the flowline model, the linear model suggests σ_L = 415 m, consistent with the ~15% overestimate of the flowline model results described by Roe (2011). This inter-model difference is much smaller than the parameter uncertainty (Table 1). The outer bounds of the linear model σ_L are 180 and 800 m. A high sensitivity to T or P (i.e., large α or β) or a long response time leads to a large σ_L.

We use excursion statistics for glaciers driven by climate variability (after Roe, 2011; Reichert et al., 2002). In any given time interval, D, the mean glacier length, $\bar{L}$, cannot be known exactly, but it is described by a probability distribution (Fig. 2A). Roe (2011) showed that the most likely $\bar{L}$ can be related to the maximum glacial length, L_{max}, by

$$\bar{L} = L_{max} - \sigma_L \sqrt{2ln\left(\frac{D\dot{\sigma}_L}{2\pi\sigma_L \ln(2)}\right)}, \quad (3)$$

where $\dot{\sigma}_L$ is the standard deviation of the time rate of change of glacier length (see Roe, 2011, his equations 9 and A8) with p = 0.5. Equation 3 is quite general, and holds provided the probability distribution of glacier fluctuations is normally distributed (Fig. 1B). It has been shown to govern the variability of terminus position in flowline glacier models (Reichert et al., 2002; Item DR7). Roe (2011) further demonstrated that setting $\dot{\sigma}_L = \sigma_L\sqrt{2/\psi\tau\Delta t}$ emulated the behavior of a standard numerical flowline model, where ψ ($\approx$ 10) is a factor introduced because high frequencies are damped more strongly in a numerical flowline model than is predicted by the linear model. The effect of varying ψ is minimal: doubling or halving of ψ results in a ±0.6% change in $\bar{L}$ when D is larger than the glacier response time, τ. We consider a broad range of D (the duration of the climate of interest) values between 500 and 7500 yr, the upper limit being the duration of the LGM sea-level lowstand (Clark et al., 2009). Alternatively, a natural choice for D is the time interval separating two dated moraines we wish to attribute to either climate change or interannual weather variability.

Mean Length and Signal-to-Noise Results

For glaciers with areas between 56 and 4 km^2, the most likely mean glacier length is 10%–15% up valley from L_{max} (Table 2, column 8). Bounds on the potential location of the mean length—3% to 50% up valley from L_{max}—represent cases in which all parameters are simultaneously given their extreme values (Table 2, columns 7 and 9). As this is unlikely, this range should be considered an outer bound on $\overline{L}$. Interpreting the cause of glacier length changes requires that we discern the competing influences of a signal (a change in $\overline{P}$ or $\overline{T}$ leading to a change in $\overline{L}$; Fig. 1B; Equation 3) and a noise component (climate noise σ_P, σ_T driving length fluctuations, σ_L; Equation 2). Glaciers with area less than 2 km^2 have a σ_L comparable to their $\overline{L}$ (Table 2), and so perhaps flickered in and out of existence or hung on as small stagnant ice bodies during periods of the local LGM.

DISCUSSION

Historical records of advance and retreat show that 1- to 20-m-tall moraines can form from interannual variability–forced advances (Table 3; see the references in the Data Repository). They also support the notion that valley glaciers fluctuate on multi-decadal time scales in response to interannual variability. It is often assumed that long glacial standstills (century scale) were required to form large LGM terminal moraines (often >10 m in height). Our results suggest that century-scale glacial standstills (e.g., the terminus remaining within ~50 m of the same location) did not occur for the modeled glaciers. Rather, our numerical model shows that the longest standstills lasted ~50 yr (glaciers with longer response times have a propensity for longer standstills) (Fig. 2C; Item DR4; Johnson and Gillam, 1995).

Glacier length fluctuations forced by interannual variability can be viewed as a smaller-scale example of the moraine survival problem (e.g., Gibbons et al., 1984). Broad LGM terminal moraine complexes (Fig. 3D), which are often conglomerates of many moraines formed by different advances, may represent cycles of kilometer-scale retreat and re-advance that are independent of true climate change. The glacier likely formed one moraine, then left the terminal moraine complex and returned, forming a second moraine (Figs. 2C and 3D). Terminal moraines between $\overline{L}$ and L_{max} are therefore not necessarily "recessional" moraines in the classic sense.

Because maximum moraines reflect advances formed sometime after the glacier reached $\overline{L}$, dating the maximum moraine provides a minimum estimate of when a climate change initiated. Constraining the timing of retreat from $\overline{L}$ provides an estimate of when $\overline{P}$ and $\overline{T}$ changed (e.g., Young et al., 2011; Fig. 1B). The sampling of boulders deposited by multiple advances could explain the variation of cosmogenic radionuclide exposure (CRN) ages from some LGM terminal deposits assumed to be formed by a single advance (Fig. 3). Sampling the highest ridge in a moraine complex may not provide dates from the oldest advance (Fig. 3D). The potential for sporadic exposure of bedrock between L_{max} and L_{min} could also impact the interpretation of CRN concentrations in bedrock for either exposure ages or production rates.

Incoherent patterns of interannual variability from region to region (coherence can be expected over an ~500 km length scale; Letréguilly and Reynaud, 1989) could have resulted in glacier advances and retreats at different times around the western United States during the regional LGM. This effect could potentially explain the spread of ages derived from maximum terminal moraines across the western United States (e.g., Young et al., 2011; Fig. 2D) and even globally (Schäfer et al., 2006).

Moraines reflect maximum advances, and our results suggest that climate noise (weather) is likely to force kilometer-scale advances beyond what the mean climate conditions support. Climate estimates derived from maximum glacier geometries do not represent the local LGM-mean climate. Rather, they have a one-sided bias due to glacial length excursions down valley from $\overline{L}$. Equilibrium-line altitudes (ELAs) and climate change estimates derived from glacier models directly reconstructed from maximum moraines will therefore overestimate the climate change. In our setting, the central parameter range suggests this is a 10%–15% effect for LGM moraines.

TABLE 3. HISTORICAL EXAMPLES OF MORAINES FORMED BY INTERANNUAL VARIABILITY–FORCED ADVANCES

Glacier	Time	Relief	Citation*
Engabreen, NO	<20 yr	15 m	Worsely and Alexander, 1976
Nigardsbreen, NO	<10 yr	<10 m	Nussbaumer et al., 2011
Six glaciers, NO	<10 yr	<3 m	Winkler and Matthews, 2010
Upper Grindelwald, CH	<10 yr	10 m	Zumbühl et al., 2008
Des Bossons, FR	~10 yr	20 m	Nussbaumer and Zumbühl, 2012
Mer de Glace, FR	~10 yr	<10 m	Zumbühl et al., 2008

Note: NO—Norway; CH—Switzerland; FR—France.
*Citations are given in the Data Repository (see text footnote 1).

CONCLUSIONS

Interannual variability is present in all climates and results in decadal-scale glacial length fluctuations around a mean length. We should therefore expect it to play an important role in kilometer-scale length fluctuations and moraine formation in the past and present, as well as in maritime, Alpine, and continental settings (e.g., Oerlemans, 2001). Glacier response times and the magnitude of σ_P and σ_T will determine the expected time scale and magnitude of length fluctuation. Several modeling efforts, historical glacier extent records, and documentation of modern moraine formation support our conclusions. Glacier length fluctuations due to year-to-year climate variability should therefore be included in the interpretation of the moraine record.

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REFERENCES CITED

Benn, D.I., and Evans, D.J.A., 1998, Glaciers and glaciation: London, Arnold, 734 p.

Burke, E.E., and Roe, G.H., 2013, The absence of memory in the climatic forcing of glaciers: Climate Dynamics, doi:10.1007/s00382-013-1758-0.

Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., Mitrovica, J.X., Hostetler, S.W., and McCabe, A.M., 2009, The Last Glacial Maximum: Science, v. 325, p. 710–714, doi:10.1126/science.1172873.

Gibbons, A.B., Megeath, J.D., and Pierce, K.L., 1984, Probability of moraine survival in a succession of glacial advances: Geology, v. 12, p. 327–330, doi:10.1130/00917613(1984)12<327:POMSIA>2.0.CO;2.

Jóhannesson, T., Raymond, C.F., and Waddington, E.D., 1989, Time-scale for adjustment of glaciers to changes in mass balance: Journal of Glaciology, v. 35, p. 355–369.

Johnson, M.D., and Gillam, M.L., 1995, Composition and construction of late Pleistocene end moraines, Durango, Colorado: Geological Society of America Bulletin, v. 107, p. 1241–1253, doi:10.1130/0016-7606(1995)107<1241:CACOLP>2.3.CO;2.

Letréguilly, A., and Reynaud, L., 1989, Spatial patterns of mass-balance fluctuations of North American glaciers: Journal of Glaciology, v. 35, p. 163–168.

Meier, M.F., and Post, A.S., 1962, Recent variations in mass net budgets of glaciers in western North America: International Association of Hydrological Sciences Publication 58, p. 63–77.

Oerlemans, J., 2001, Glaciers and climate change: Lisse, Netherlands, Swets and Zeitlinger, 160 p.

Reichert, B.K., Bengtsson, L., and Oerlemans, J., 2002, Recent glacier retreat exceeds internal variability: Journal of Climate, v. 15, p. 3069–3081, doi:10.1175/1520-0442(2002)015<3069:RGREIV>2.0.CO;2.

Roe, G.H., 2011, What do glaciers tell us about climate variability and climate change?: Journal of Glaciology, v. 57, p. 567–578, doi:10.3189/002214311796905640.

Roe, G.H., and O'Neal, M.A., 2009, The response of glaciers to intrinsic climate variability: Observations and models of late-Holocene variations in the Pacific Northwest: Journal of Glaciology, v. 55, p. 839–854, doi:10.3189/002214309790152438.

Schäfer, J.M., Denton, G.H., Barrell, D.J., Ivy-Ochs, S., Kubik, P.W., Andersen, B.G., Phillips, F.M., Lowell, T.V., and Schlüchter, C., 2006, Near-synchronous interhemispheric termination of the Last Glacial Maximum in mid-latitudes: Science, v. 312, p. 1510–1513, doi:10.1126/science.1122872.

Young, N.E., Briner, J.P., Leonard, E.M., Licciardi, J.M., and Lee, K., 2011, Assessing climatic and nonclimatic forcing of Pinedale glaciation and deglaciation in the western United States: Geology, v. 39, p. 171–174, doi:10.1130/G31527.1.

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