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An exercise in glacier length modeling: Interannual climatic variability alone cannot explain Holocene glacier fluctuations in New Zealand

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ABSTRACT

Recent model studies suggest that interannual climatic variability could be confounding the interpretation of glacier fluctuations as climate signals. Paleoclimate interpretations of moraine positions and associated cosmogenic exposure ages may have large uncertainties if the glacier in question was sensitive to interannual variability. Here we address the potential for interannual temperature and precipitation variability to cause large shifts in glacier length during the Holocene. Using a coupled ice-flow and mass-balance model, we simulate the response of Cameron Glacier, a small mountain glacier in New Zealand's Southern Alps, to two types of climate forcing: equilibrium climate and variable climate. Our equilibrium results suggest a net warming trend from the Early Holocene (10.69 ± 0.41 ka; 2.7 °C cooler than present) to the Late Holocene (CE 1864; 1.3 °C cooler than present). Interannual climatic variability cannot account for the Holocene glacier fluctuations in this valley. Future studies should consider local environmental characteristics, such as a glacier's climatic setting and topography, to determine the magnitude of glacier length changes caused by interannual variability.

1. Introduction

Moraines in mountain valleys represent past glacier termini and afford an opportunity to infer past climate through glacier modeling (Porter, 1975; Oerlemans, 2001). Meteorological shifts in temperature and precipitation occur on short (hours-to-years) and long (years-to-centuries) timescales, and will cause changes in glacier mass balance. A glacier integrates mass balance changes over time, potentially resulting in glacier length fluctuations. Here, we assess the possibility that stochastic interannual meteorological variability could cause 'random walks' in glacier length without a shift in mean climate. Anderson et al. (2014) modeled glaciers at their Last Glacial Maximum (LGM, 19.5–26 ka) extents and their length response to stochastic variability. Their results suggest that (1) glacial standstills longer than 50 yrs 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. Because Anderson et al. (2014) used a one-stage linear glacier model, which translates a change in glacier mass to an instant change in glacier length (not accounting for glacier response times) resulting in frequent and large glacier length excursions, it is unlikely that their first two findings can be applied to glaciers of various geometries or climatic settings. We investigate their final point by quantifying the relative amounts of glacier advance that could be attributed to interannual variability and climate change. Ultimately, this paper aims to answer the question: Could the positions of moraines, and their associated ages, be a product of interannual climatic variability alone and if so, what are the implications for climate reconstructions?

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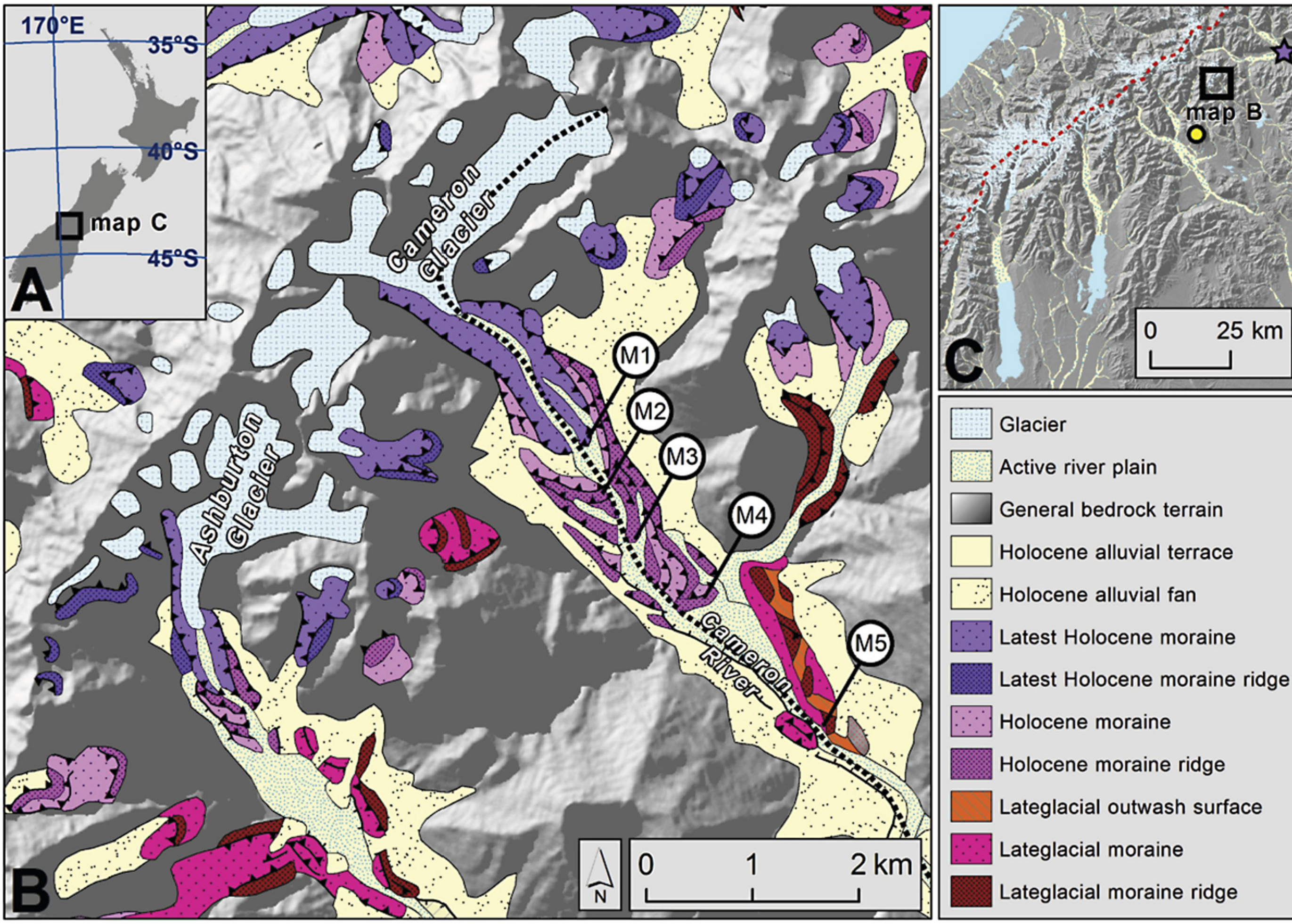

Fig. 1. Study area location (A, C) and glacial geomorphological map (B) showing the Holocene to late-glacial moraines of the Cameron Glacier (after Barrell et al., 2011), indicating the terminal positions of Moraines 1–5. The dotted black line approximates the central flowline of the Cameron Glacier along which glacier lengths were calculated. Map C shows the locations of the Mt Potts rain gauge (yellow dot), the drainage divide of the Southern Alps (dashed red line) and the Rakaia valley (purple star).

Previous efforts to simulate glacier response to interannual variability have considered a range of model and forcing types. For example, ice flow has been characterized using 3-D full-Stokes models (Farinotti, 2013), 1-D flowline models (Oerlemans, 2000; Malone et al., 2015) or linear models (Anderson et al., 2014; Roe and Baker, 2014). Mass balance has been calculated using energy balance models (Malone et al., 2015), positive degree-day models (Farinotti, 2013) or a simplified seasonal climate forcing (Oerlemans, 2000; Anderson et al., 2014; Roe and Baker, 2014). Some studies imposed interannual variability by generating random temperature and precipitation anomalies (e.g., Malone et al., 2015) and others generated mass balance anomalies (e.g., Oerlemans, 2000). Here, we use a coupled, vertically integrated, 2-D ice-flow and mass-balance model (Anderson et al., 2010; Doughty et al., 2013) and force the model with annual temperature and precipitation anomalies.

The Cameron valley in the Southern Alps of New Zealand (43.35°S, 171.00°E, Fig. 1; Burrows, 1975; Putnam et al., 2012) contains thirteen Holocene moraine ridges. This moraine sequence is particularly well preserved because the Cameron River down-cut perpendicularly through small portions of each Holocene moraine over a 1700 m distance. Ages of successive moraine belts established by surface-exposure dating (Putnam et al., 2012) afford us a unique opportunity to compare five of the mapped and dated moraines (Moraines 1–5) to modeled terminus fluctuations.

2. Methods

2.1. Model description

This study simulates glacier fluctuations due to interannual variability using a coupled 2-D ice-flow and mass-balance model on relatively complex 2-D topography. The 1-stage linear model used in previous studies has been shown to exaggerate glacier length variability (Roe and Baker, 2014). The model used in our study accounts for complex bed topography, glacier response time, mass-balance variability, and glacier size, resulting in realistic glacier terminus fluctuations.

Our coupled 2-D ice-flow and mass-balance model reproduces past glacier configurations from altered annual mean temperature and total annual precipitation. The 2-D ice-flow model estimates ice deformation based on the shallow ice approximation and estimates sliding using equations from Kessler et al. (2006) (see Appendix, for details). Gridded topography in this model was smoothed with a window of 5 × 5 grid cells to ensure mass conservation in localized parts of the model domain that have steep bed slopes. The rates of flow depend on the distribution of ice mass, which is updated at a yearly timestep from the mass-balance model. The mass-balance model includes a spatially distributed energy-balance model (Anderson et al., 2010) and a gravitational snow-mass transport and deposition parameterization (Gruber, 2007) to simulate snow avalanche input from steep rock walls in the catchment.

Table 1
Equilibrium temperature and precipitation changes used to force the modeled glacier out to each moraine with and without the avalanche parameterization. Moraine position is given in terms of glacier length. Moraine ages are from Putnam et al. (2012).

	Moraine-1	Moraine-2	Moraine-3	Moraine-4	Moraine-5	Moraine- 1	Moraine-4
Age ± uncertainty (ka):	0.18 ± 0.048	0.52 ± 0.061	8.19 ± 0.23	10.69 ± 0.41	c. 13–15	(No avalanche model)	
Glacier length (m):	4200	4700	5070	5860	7600	4300	6000
ΔT (°C) when:							
$\Delta P = +20\%$	−0.8	−1.5	−1.8	−2.3	−2.8	−0.8	−2.1
$\Delta P = 0\%$	−1.3	−2.1	−2.4	−2.7	−3.3	−1.3	−2.6
$\Delta P = -20\%$	−1.8	−2.6	−2.9	−3.4	−4.0	−1.8	−3.2

Bedrock topography in non-glacierized parts of the 9 km × 9.2 km model domain was based on a Digital Elevation Model (DEM) with a 50-m cell size [GeographX (NZ) Ltd]. Modern glacier thickness was calculated using a simplification of the Farinotti et al. (2009) scheme, constrained by ground-penetrating radar surveys (Doughty, 2013) and was removed from the DEM to generate an 'ice-free' topography. Monthly mean temperature data were interpolated between long-term, lowland meteorological stations (CE 1981–2010, cliflo.niwa.co.nz) and scaled with elevation using a temperature lapse rate of 5 °C/km, which was calculated from daily temperatures measured at the nearby Mt. Potts weather station (43°30′S, 170°55′E, 2128 m asl; Fig. 1) from June 2009 to July 2012. Monthly mean precipitation data from nearby rain gauges were interpolated across the domain using a mean-annual precipitation surface for the Southern Alps (CE 1971–2000, Stuart, 2011), following the approach of Anderson and Mackintosh (2012) and Doughty et al. (2013). We increased the gridded precipitation data by 20% to account for rainfall undercatch in rain gauges (Trenberth et al., 2007).

2.2. Equilibrium glacier length simulations

The targeted moraine belts date to CE 1864 (Moraine-1), 0.52 ± 0.061 ka (Moraine-2), 8.19 ± 0.23 ka (Moraine-3), and 10.69 ± 0.41 ka (Moraine-4), while Moraine-5 is associated with the late-glacial climate episode in New Zealand (c. 15.6–11.7 ka; Barrell et al., 2013; Putnam et al., 2012; Table 1; Fig. 1). To estimate past temperature and precipitation for each of the five equilibrium experiments (EM1-EM5), we set ΔP equal to −20%, 0%, and +20% and allowed ΔT to vary until the modeled glacier terminus is within 100 m of the inferred paleoglacier terminus (Fig. 1). The combination of ΔT and ΔP was held constant for 300 model years to allow the modeled glacier to equilibrate with the input climate.

2.3. Interannual variability simulations

The three variability experiments (VM1, VM2, and VM4) with mean glacier lengths terminating at Moraine-1 (4200 m), Moraine-2 (4700 m) and Moraine-4 (5860 m; Table 2) simulate glacier length response to interannual temperature and precipitation anomalies. We chose to force the model with measured meteorological variability rather than mass-balance variability because local and regional climatic variability is relatively well constrained by station data and long-term mass balance data do not exist for most New Zealand glaciers. We generated 4000 artificial annual temperature anomalies with a normal distribution and a standard deviation (σ_T) of 0.4 °C following meteorological data (Dean and Stott, 2009). The mean value of this sequence equals the ΔT obtained from the EM1, EM2, and EM4 simulations (Table 2). We also generated 4000 random precipitation anomalies with a normal distribution (bound between ±30% to be consistent with data in areas as wet as Cameron valley, ~2500 mm/a; Stuart, 2011), a standard deviation (σ_P) of 18%, and a mean of 0%. Annual anomalies are applied uniformly to each month, have no year-to-year persistence and have no trend.

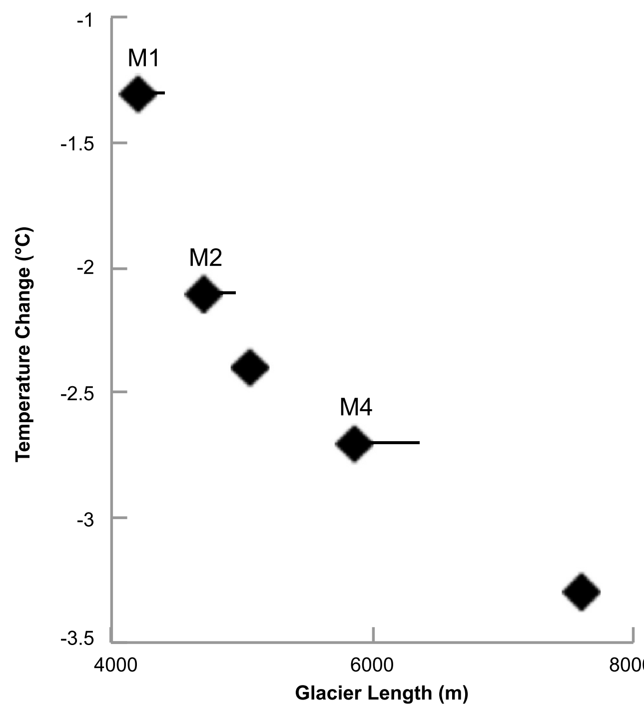

Fig. 2. Plot showing the non-linear relationship between temperature change from today and glacier length in Cameron valley. The dots representing Moraine-1, Moraine-2, and Moraine-4 have a horizontal bar depicting the maximum downslope excursions caused by interannual variability.

3. Results

3.1. Equilibrium paleoclimate estimates

Although we assessed the goodness of fit between modeled glacier extent and geomorphic evidence for a single point at a moraine terminus (Fig. 1), the lateral extents of the modeled glacier also showed a reasonable spatial fit with the mapped lateral moraines (Fig. A.1). The respective glacier lengths for Moraines 1–5 are 4200, 4700, 5070, 5860, and 7600 m and require ΔT values of −1.3, −2.1, −2.4, −2.7, and −3.3 °C from present, with $\Delta P = 0\%$ (Table 1; Fig. 2). An increase (decrease) in precipitation by 20% can be combined with a decrease (increase) in the ΔT values by 0.4–0.7 °C to reach each moraine. Omitting the avalanche model does not change the paleotemperature estimates, but does make a mass-balance pattern different from that observed on the glacier today (Doughty, 2013).

The relationship between temperature change and glacier advance is non-linear (Fig. 2). As the glacier grows larger and to lower gradient slopes, the temperature change required to advance the glacier by 100 m becomes smaller. For example, to model a glacier advance from Moraine-1 to Moraine-2 (500 m difference in glacier lengths) requires 0.8 °C of cooling, or 0.16 °C/100 m, whereas forcing an advance from Moraine-4 to Moraine-5 (1740 m difference) requires a cooling of 0.6 °C, or 0.03 °C/100 m.

Table 2
Comparison of equilibrium and variability runs for simulations where the glacier terminus ends at Moraine-1, Moraine-2, and Moraine-4. Table includes change in temperature (ΔT) and precipitation (ΔP) from today and standard deviations (model input) as well as glacier area and volume for the catchment, and length of Cameron Glacier.

	EM1	VM1	EM2	VM2	EM4	VM4
$\Delta T \pm \sigma_T$ (°C)	−1.3	-1.3 ± 0.4	−2.1	-2.1 ± 0.4	−2.7	-2.7 ± 0.4
$\Delta P \pm \sigma_P$ (%)	0	0 ± 18	0	0 ± 18	0	0 ± 18
Area (km^2)	7.71	7.35 ± 0.4	11.42	11.46 ± 0.5	15.64	15.03 ± 0.6
Volume (km^3)	0.38	0.37 ± 0.02	0.61	0.61 ± 0.04	0.9	0.87 ± 0.05
Glacier length (m)	4200	4160 ± 60	4700	4820 ± 90	5860	5820 ± 190

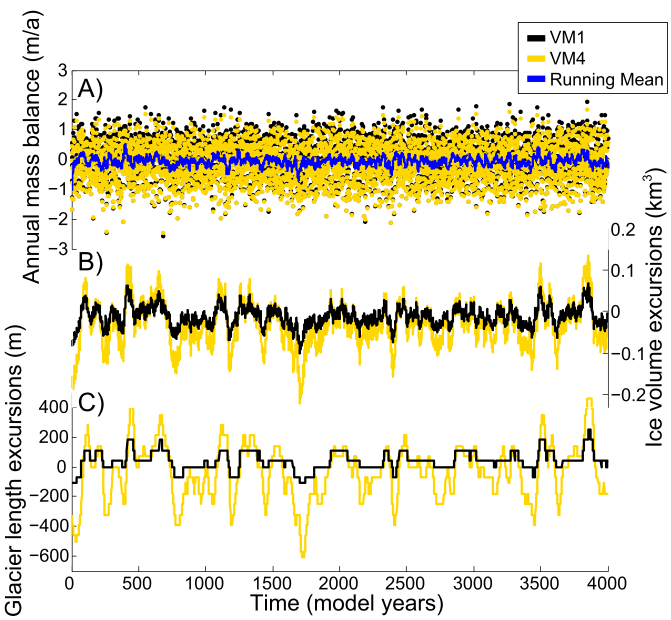

Fig. 3. Modeled glacier response to interannual temperature and precipitation anomalies (standard deviation in temperature, $\sigma_t = 0.4$ °C and precipitation, $\sigma_p = 18\%$) with the mean glacier length reaching Moraine-1 (glacier length = 4200 m, experiment VM1) in black and Moraine-4 (glacier length = 5860 m, experiment VM4) in yellow. Panel (A) shows annual mean mass balance for Cameron Glacier (over a fixed glacier area), with a blue line showing the 10-yr running mean, which looks similar in shape to the ice volume excursions in panel (B) and the glacier length excursions plotted in panel (C). Although the modeled mass balance changes in step with the interannual forcing (annually), the glacier length is slower to respond and shows a maximum advance of 500 m in the VM4 experiment. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2. Interannual-variability-induced glacier fluctuations

Downslope glacier length excursions in the VM1 simulation (with mean length at Moraine-1) reached a maximum of 210 m (5%), which was 290 m up-valley from Moraine-2 (Table 2, Fig. 3). The standard deviation of modeled mass balance was 0.67 m/a, which is similar to the standard deviation in contemporary mass-balance value, 0.8 m/a, modeled from daily meteorological data covering CE 1977–1995 (Doughty, 2013). Summer and winter mass balance (0.813 and 0.372 m w.e.) at Brewster Glacier (Cullen et al., 2016) are likely to be higher than at Cameron due to the wetter climate at Brewster. These comparative values indicate that the model is estimating appropriate mass-balance variability.

Downslope excursions in the VM2 simulation show a maximum of 250 m (5.2%) and a standard deviation in glacier length of 90 m. The VM4 results show a maximum downslope excursion of 500 m (8.6%) and standard deviation in length of 190 m (Table 2). The VM4 experiment produced fluctuations larger than those in VM1 and VM2 (Fig. 2). These variability simulations show that, although the modeled Cameron Glacier length fluctuates in response to interannual stochastic variability in temperature and precipitation, such fluctuations are minor. The Cameron Glacier fluctuated by 5–8.6% of its total glacier length, not by 10–15% that was suggested from Anderson et al. (2014). In addition, the simulated glacier lengths did not span the distance of the Holocene moraine sequence without a shift in mean climate.

4. Discussion

Assuming no change in precipitation from today, the late-glacial Moraine-5 was formed in a climate ~3.3 ± 0.7 °C cooler than present, which agrees with previous model and snowline reconstruction results for this period in New Zealand (Putnam et al., 2012; Doughty et al., 2013; Kaplan et al., 2013). Model results suggest that the Early Holocene (Moraine-4, 10.69 ± 0.41 ka; Putnam et al., 2012) was ~2.7 ± 0.7 °C colder than present, and the latest Holocene (Moraine-1, CE 1864) was ~1.3 °C colder than present. The net Early- to Late-Holocene (e.g., CE 1864) temperature change of +1.4 °C reconstructed using our model is, within respective uncertainties, similar to +0.9 °C reconstructed for the same interval using the accumulation-to-ablation-area ratio snowline reconstruction method by Putnam et al. (2012). Moraine-2 (dated to 0.52 ka; Putnam et al., 2012) abuts a moraine dating to 6.89 ka, suggesting similar climates during those times and an absence of temperatures 2.1 ± 0.6 °C cooler than today since 6.89 ka. A paleoglacier reconstruction from the Whale Stream valley in the Ben Ohau Range, southwest of the Arrowsmith Range, reinforces this overall pattern of progressively less cold cool climate episodes and glacier recession since the Early Holocene (Kaplan et al., 2013). Thus any viable explanation for regional and global drivers of Holocene climate evolution in this region will account for these constraints.

The glacier-length fluctuations caused by interannual variability were not large enough to cause the modeled Cameron Glacier to extend from the Late- to Early-Holocene moraine sequences, thus we quantified the relative contributions of glacier length changes from variability and shifts in climate. For example, the largest downslope excursion (210 m) from the Moraine-1 position can account for ~40% of the distance between Moraine-1 and Moraine-2. In this scenario, it is possible to explain the distance between these moraines with a temperature change of −0.46 °C with variability instead of −0.8 °C without variability. The distance between Moraine-4 and Moraine-5 is 1740 m and glacier excursions related to variability (500 m) could account for ~30% of the distance. These relative values would change if the standard deviation in interannual temperatures were greater during the Early Holocene. Thus, climate changes are largely responsible for the glacier fluctuations and 1700 m-long Holocene moraine sequence in this valley.

The sensitivity of glacier length to interannual climatic variability depends on climatic setting and topography (Oerlemans, 2001). Malone et al. (2015) also found that interannual stochastic variability was unlikely to account for observed glacier length fluctuations indicated by the moraine system, in their case for the Huancane Valley southwest of the Quelccaya Ice Cap in the tropical Andes. The glacier length fluctuations presented here are smaller than those estimated for other glaciers using various models. This difference could be attributed to several factors, including (1) special attributes of the Cameron Glacier climatic and topographic setting and (2) our experimental design.

Idealized model experiments suggest that, for a given mass balance regime, glacier length variability increases with increased bed slope and increased mass balance variability (Mackintosh et al., in press). The relatively low variability in Cameron Glacier length could be due to the gentle valley bed slope, the relatively long response time (∼70 yrs in model simulations) and the relatively low mass balance variability. In addition, gentle bed slopes enhance the equilibrium length sensitivity of glaciers to climate shifts. By comparison, the nearby Franz Josef Glacier is very sensitive to interannual climatic variability (Oerlemans, 2000; Mackintosh et al., 2017) due to its large catchment area feeding a steep, narrow, valley-confined tongue, short response time (∼20 yrs, Anderson et al., 2008) and large mass balance variability due to high precipitation rates (∼10 m/a). In addition, we suggest that large glaciers may produce larger absolute glacier length variability. For example, simulations of interannual variability of the ∼80-km-long glacier that occupied the nearby Rakaia valley (Fig. 1C) during the LGM show kilometer-scale terminus fluctuations (Rowan et al., 2014), which is ∼1% of the total glacier length. While climatic setting may have an influence on the response of Cameron Glacier, the topographic setting and glacier geometry seem to be the biggest difference between our results and previous studies.

The Holocene moraine sequence in Cameron valley is unusually useful for paleoclimate studies because of the abundance of well-preserved and dated moraine belts. Emerging Holocene moraine chronologies show similarities between valleys, suggesting regional climate forcing rather than stochastic variability (Kaplan et al., 2013; Putnam et al., 2012). The small mass balance variability and relatively low bed gradient of Cameron Glacier allow its fluctuations to be dominated by climate change rather than interannual variability.

5. Conclusions

By modeling equilibrium and stochastic variability climatic conditions of Holocene glacier fluctuations, we found that shifts in climate are necessary for the glacier terminus to span the distance covered by the Holocene moraine sequence (1700 m). The equilibrium runs suggest an average temperature cooling from today of ∼3.3 °C during the late-glacial period and ∼2.7 °C during the Early Holocene. Interannual variability causes minor terminus fluctuations in this valley (maxima of 210–500 m, depending on glacier size) and are smaller than those suggested by previous studies (up to 1000 m). Glacier length sensitivity to interannual variability decreases with decreased bed slope and decreased mass balance variability, and these attributes should be considered when interpreting ages and paleoclimate from moraine sequences.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.epsl.2017.04.032.

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