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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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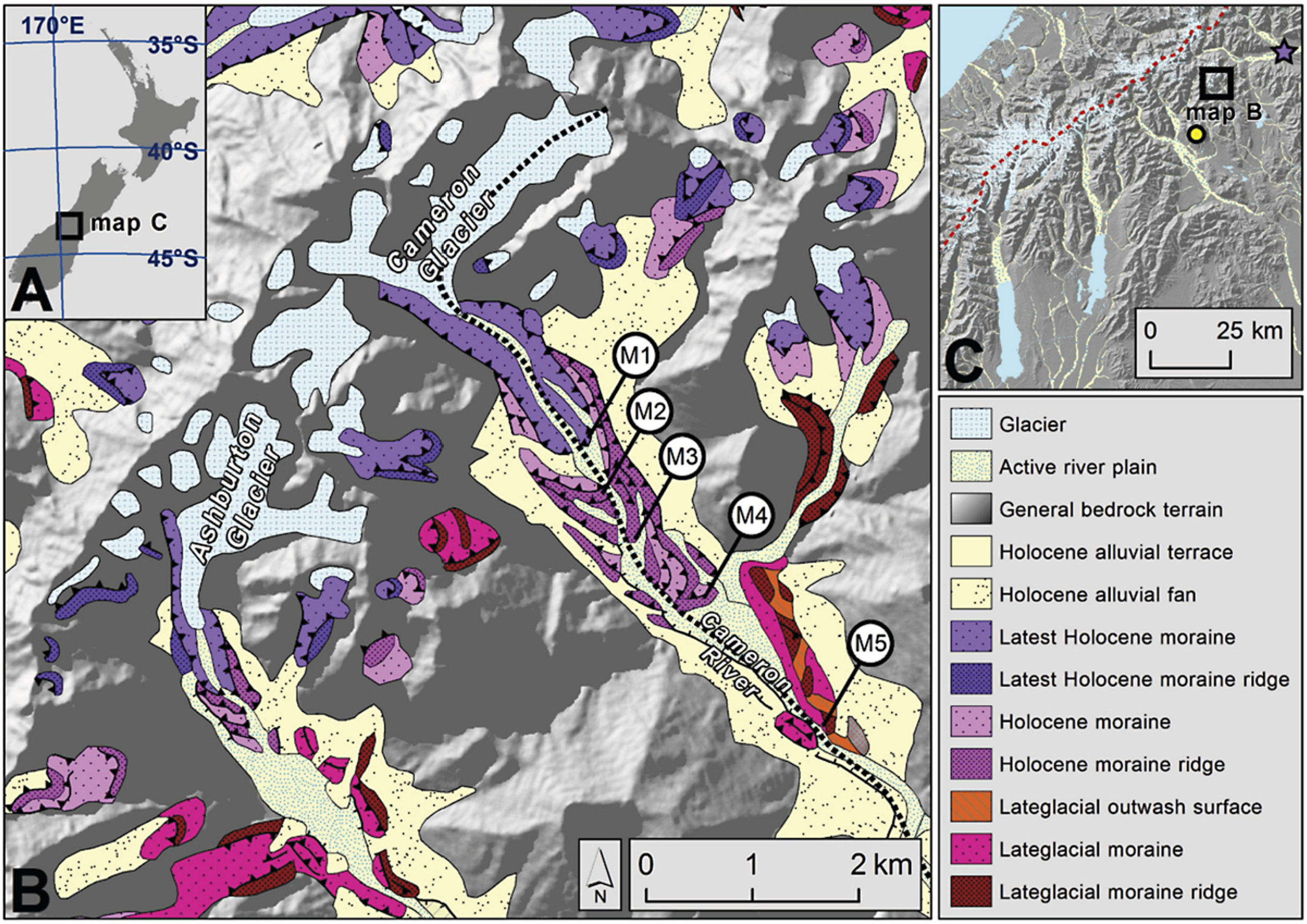

Fig. 1. Study area location (A, C) and glacial geomorphological map (B) showing the Holocene to late-glacial moraines of the Cameron Glacier (after Barrell et al., 2011), indicating the terminal positions of Moraines 1–5. The dotted black line approximates the central flowline of the Cameron Glacier 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.