Geomorphology 179 (2012) 269–285

Contents lists available at SciVerse ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Far-flung moraines: Exploring the feedback of glacial erosion on the evolution of glacier length

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A R T I C L E I N F O

Article history:
Received 16 February 2012
Received in revised form 25 August 2012
Accepted 28 August 2012
Available online 4 September 2012

Keywords:
Moraine
Alpine landscapes
Glaciers
Flowline model
LGM
Glacial extent

A B S T R A C T

Over many glacial cycles, the glacial erosion of alpine valleys can be sufficient to reduce the length of glaciers in the most recent cycles. We document field cases illustrative of this erosional feedback and model the long-term evolution of glacier lengths analytically and numerically. The general feature we target is a moraine deposited well beyond the last glacial maximum (LGM) limit, which we refer to as a "far-flung" moraine. Firstly, we assemble published observations to illustrate that far-flung moraines are documented around the world. The observations suggest that the downvalley distance to such far-flung moraines can exceed the distance to LGM moraines by up to twofold. Secondly, we address the problem analytically, making several simplifying assumptions, to demonstrate that glacier length scales linearly with erosion depth. Finally, we employ a numerical model to test the analytical solution. This 1D (depth-integrated) flowline model includes: (i) a depth-averaged longitudinal coupling stress approximation, (ii) prescribed winter and summer surface mass balance profiles, (iii) evolving ice temperature calculated via the conventional heat equation, and (iv) glacier sliding velocity parameterized as a function of basal ice temperature and spatially and temporally variable prescribed flotation fraction. The simulated alpine landscape is modified through the competing processes of glacier erosion, which is dependent on glacier sliding velocity and prescribed bedrock erodibility, and prescribed uplift rate. The climate controlling surface mass balance is prescribed by time series of air temperature and snowfall approximated by the sum of two sinusoidal cycles. The recurrence statistics of these prescribed climate drivers closely match those of the marine isotopic record; hence the prescribed climate drivers faithfully mimic observed long-term climate drivers.

Consistent with earlier landscape evolution studies, we find that the primary effect of repeated glaciations is to flatten a valley floor and steepen its headwall, effectively cutting a longitudinal notch in a fluvial valley profile. Analytical and numerical model results also demonstrate that far-flung moraines are an inevitable consequence of repeated glaciations: glaciers in tectonically inactive regions can sufficiently erode their valleys so that the earliest glaciations leave moraines many kilometers down-valley from moraines left by the latest glaciations, despite similar climates. This suggests that a different landscape, rather than a different climate, is capable of explaining the early glacier extents. As a corollary, the long-term drift toward reduced glacier length favors the survival of early moraines in the face of later glacial advances. Finally, rock uplift can defeat this erosional feedback, while rock subsidence enhances the feedback.

1. Introduction

In many alpine settings, the glacial history of the landscape is recorded by a succession of terminal and/or lateral moraines. These successions, with the oldest terminal moraine being the farthest from the contemporary glacier terminus, provide direct evidence for repeated glaciations over glacial–interglacial timescales. In an attempt to explain the typical number of preserved moraines, Gibbons et al. (1984) suggested that glacier lengths are randomly distributed over time and that after ten glacial cycles, a contemporary moraine succession would most likely contain two to three moraines from past glaciations. We assume that mountain glacier lengths are not driven by a random regional climate but rather broadly follow the benthic $\delta^{18}O$ record, a proxy for global ice volume. The benthic $\delta^{18}O$ record (see Fig. 1A) suggests that the Last Glacial Maximum (LGM)

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0169-555X/$ – see front matter
http://dx.doi.org/10.1016/j.geomorph.2012.08.018

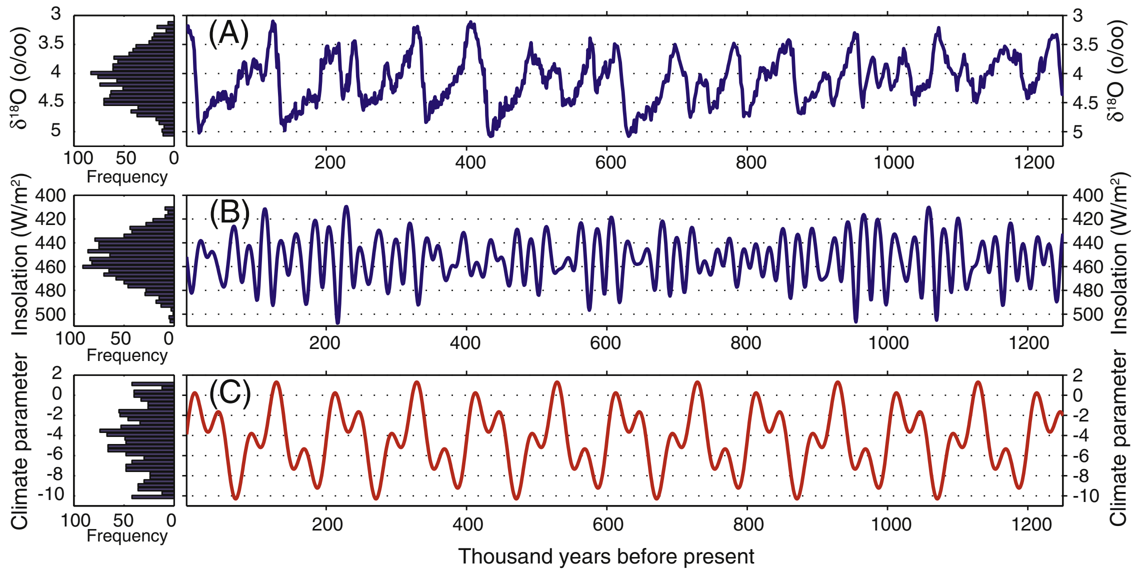

Fig. 1. Time series of potential proxies for climate forcing of glaciers and their histograms. (A) Compilation of benthic oxygen isotope record since the mid-Pleistocene transition (from Lisiecki and Raymo, 2005). (B) Average June–July–August insolation at 65° N, calculated following Huybers (2006). Both the MIS and insolation records show a strong tendency to occupy the mean state and symmetrical decaying distributions about them. (C) Double sine curve (here of surface air temperature) employed in our glacial model. In this example the chosen periods are 100 and 40 ky, and amplitudes are adjusted so that the peak of the histogram is centered and decays symmetrically toward both highly glacial and highly interglacial conditions.

was as large as any previous glaciation with at least four glacial maxima of similar amplitude (Lisiecki and Raymo, 2005). If the benthic δ^{18}O data does indeed serve as a reliable proxy for the glacier extent in alpine valleys we would – based on the amplitude of the four major past glaciations – expect a succession of terminal moraines that do not show major differences in position. Examples from most major mountain ranges, however, indicate that glacial extents in the past were tens of percent longer than the LGM moraines (Fig. 2). If we assume that the regional climate driving glaciation in most mountain ranges mimics the global ice volume record, that the LGM was about as large as any previous Plio-Pleistocene glaciation, an alternative explanation is required to explain the preservation of multiple moraines outboard of the LGM moraine (Table 1).

One alternative explanation for the apparent drift toward reduced glacier length through time is long-term valley profile erosion. Oerlemans (1984) and MacGregor et al. (2000) suggested that long-term erosion of a glacier bed decreases ice-surface elevation and the surface mass balance of a glacier. Glacial erosion has repeatedly been shown to be efficient at modifying alpine landscapes (e.g., Hallet et al., 1996). Glacial erosion rates, averaged over several timescales, are typically 1 mm/y. This significantly outpaces fluvial erosion rates, especially in headwaters where river discharge is low. It is therefore reasonable to expect that tens of Quaternary glaciations would result in several hundred meters of valley floor lowering.

Kaplan et al. (2009) echoed this notion. They noted the pattern decreasing glacial extent in Patagonia was not reflected in trends in Southern Hemisphere paleoclimate records and benthic δ^{18}0, and suggested that the observed pattern could be attributed to long-term glacial erosion and consequent decline in glacier surface mass balance. To our knowledge, while Singer et al. (2004) touch upon the potential role of tectonics in governing the glacial evolution in the Patagonian setting, Kaplan et al. (2009) were the first to explore this erosion — glacier length feedback in a field setting. The complex nature of the Pleistocene Patagonia Ice Sheet, with multiple tributaries and outlet glaciers, and absence of initial bedrock topography, makes their site particularly challenging to simulate in long-term landscape evolution models. In this manuscript, we quantitatively explore the long-term relation between glacier erosion and glacier length in a characteristic longitudinal valley profile, using idealized initial bedrock topography and climate forcing.

We first employ a simple analytical model to explore the relation between bedrock lowering caused by glacier erosion and glacier length. This exercise demonstrates that the reduction in moraine length is proportional to the mean lowering of the valley floor. We then employ a numerical model that, in contrast to the numerical model used by Kaplan et al. (2009), solves the evolving ice temperature field at discrete time steps and calculates the surface mass balance based on separate summer and winter profiles. This allows us to simulate long-term landscape evolution by glacier erosion, under warm- and cold-based glacier conditions, while honoring seasonal and daily cycles in meltwater production and glacier hydrology. We chose a generic fluvial valley profile as the initial condition to explore the evolution of glacier length in response to glacier erosion. We also explore the influence of tectonic uplift and subsidence by varying uplift and subsidence rates over a plausible range.

2. Assessing a global compilation of far-flung moraines

The succession of terminal moraines described by Kaplan et al. (2009) is not uncommon. Fig. 2 shows that well-documented, far-flung moraines are found in most mountainous regions glaciated during the Plio-Pleistocene.

This diverse population of far-flung moraines was compiled to satisfy the following criteria: (i) paleoglacier lengths could be clearly measured along plausible flow lines from a cirque headwall or modern ice divide to the far-flung moraines; (ii) glacier lengths were only measured for valley glaciers whose far-flung moraines did not extend downstream of a major glacier confluence to eliminate the possibility of glacier coalescence during some glaciations but not others; (iii) Outlet lobes were used in place of far-flung moraines in settings where an ice cap glaciation likely transitioned to a valley glaciation. Numerical moraine ages, or relative moraine age criteria correlated to numerical ages, were available for 87% of cases. The remaining 13% of the moraine ages were inferred from logical marine isotope stage (MIS) assignment based on numerical ages from other moraines within the same valley.