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Global climate and tectonic controls on the denudation of glaciated mountains

Brian J. Yanites [a,b,*], Todd A. Ehlers [b]

[a] Department of Geological Sciences, University of Michigan, Ann Arbor, 48109-1005, USA
[b] Department of Geosciences, Universität Tübingen, Tübingen, D-72074, Germany

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ABSTRACT

Significant uncertainty exists concerning the efficiency of alpine glacial erosion relative to fluvial and hillslope processes. Latitudinal variations in temperature are important for determining the extent of glaciers, as are the rates of tectonic uplift that influence the elevation (and hence temperatures) that glaciers can form. The acute sensitivity of glacial erosion to temperature has complicated previous interpretations because temperatures must be cool enough to maintain ice yet warm enough to allow glacial sliding. Here we quantify the influence of climate and tectonics on glacial landscape evolution with a coupled glacial, fluvial, and hillslope landscape evolution model that systematically explores variations in rock-uplift rate and periodic variations in climate (i.e. glacial–interglacial periods) over million-year time scales. Emphasis is placed on understanding when a particular climate is either more (e.g. “buzzsaw” conditions) or less erosive than its preglacial landscape. Results indicate that the erosional efficiency of glaciers varies as a function of latitudinal controlled temperature and rock-uplift rate. An order of magnitude increase in erosion rates occurs in some scenarios for both localized (valley bottom) erosion and short-term (one glacial period) durations of glaciation. However, when averaged over the entire landscape for 2 Ma, increases in glacial erosion are typically less than double that of the preglacial landscape. In some scenarios, average glacial erosion rates are less than preglacial rates due to either small, inefficient glaciers or extensive cold-based glaciation. Model predictions are compared with a compilation of long-term denudation rates from glaciated mountain ranges and indicate models perform well at explaining patterns of glacial erosion efficiency. The findings presented here have clear implications for the impact of glaciations on the evolution of landscapes including: (1) the climatic “window” in which glaciers are more erosive compared to pre-glacial rates; (2) spatial and temporal variations in denudation that can lead to pulses of erosion; and (3) predictions of glacial erosional efficiency at different latitudes. We conclude that latitudinal and elevation dependent variations in temperature control the efficiency of glacial denudation and explain discrepancies between previous studies.

1. Introduction

Late Cenozoic cooling and climate variability produced repeated glacial conditions in previously ice-free landscapes. Such changes are hypothesized to increase denudation and limit orogen elevation (Brozović et al., 1997; Mitchell and Montgomery, 2006; Penck, 1905; Porter, 1989). Support for this comes from measurements of glacial sediment fluxes (Hallet et al., 1996) and correlations between topography and snowline altitude (Broecker and Denton, 1989; Egholm et al., 2009). Conversely, although some measurements of long-term denudation rates suggest an increase when glaciation intensifies (Shuster et al., 2005; Valla et al., 2011), denudation magnitudes amongst glacial and fluvial landscapes over long timescales appear similar (Koppes and Montgomery, 2009; Thomson et al., 2010). This discrepancy highlights a fundamental question: Do glaciated landscapes erode faster than unglaciated landscapes?

Three independent lines of evidence suggest glaciers are efficient agents of mountain denudation. First, observations over different timescales document an increase in Late Cenozoic mountain denudation in many glaciated landscapes. This is supported on long time scales (10^5–10^7 yr) from exhumation rates calculated from thermochronology (Berger et al., 2008; Densmore et al., 2007; Ehlers et al., 2006; Fitzgerald et al., 1993; Vernon et al., 2008). On shorter timescales (10^0–10^4 yr) high denudation rates are estimated from sediment fluxes from glaciated catchments (Hallet et al., 1996; Koppes and Hallet, 2006). Second, topographic comparisons between glaciated and nearby unglaciated catchments suggest more efficient erosion by glaciers than by the preceding fluvial system (Brocklehurst and Whipple, 2002). Third, numerical models of glacial landscape evolution reproduce many geomorphic features observed in glaciated landscapes (Egholm et al., 2009; Herman and Braun, 2008; Herman et al., 2011; MacGregor et al., 2000; Pelletier et al., 2010; Tomkin and Braun, 2002) and suggest increased glacial denudation over short and

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* Corresponding author at: Department of Geological Sciences, University of Michigan, Ann Arbor, 48109-1005, USA.
E-mail address: yanites@umich.edu (B.J. Yanites).

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intermediate timescales (10^3–10^5 yr) (Egholm et al., 2009; Tomkin and Braun, 2002) though in some scenarios, numerical modeling predicts decreased denudation rates due to the development of cold-based glaciers (Tomkin and Braun, 2002).

Here we quantify the effects of climate on the evolution of glaciated landscapes undergoing different rates of rock uplift and aim to constrain when a glaciated landscape is more or less erosive than a pure fluvial system. Specifically, we use an orogen-scale coupled precipitation and landscape evolution model (Fig. 1) that incorporates fluvial, hillslope, and glacial processes (Braun and Sambridge, 1997; Braun et al., 1999; Herman and Braun, 2008; Tomkin and Braun, 2002). We simulate the transient response of landscapes to the onset of glaciations to identify what climatic and tectonic scenarios lead to an increase in landscape-wide denudation. We compare these results to characteristics of a number of glaciated landscapes spanning a range of latitudes and rates of tectonic activity (rock-uplift).

2. Methods

2.1. Model set-up

To quantify the effects of climate on glacial landscape evolution over a range of rates in tectonic rock-uplift, we use a modified version of the ICE-Cascade numerical model (Herman and Braun, 2008). There are two main components to the numerical model used in the simulations, a landscape evolution model (Braun and Sambridge, 1997; Herman and Braun, 2008) and an orographic precipitation model (Roe et al., 2003). Within the landscape evolution model, individual modules for fluvial, hillslope (including landsliding), and glacial processes are responsible for eroding, transporting, and depositing material across the model domain (Herman and Braun, 2008; Tomkin and Braun, 2002). Both the fluvial and glacial modules are coupled to an orographic precipitation model that determines both the river discharge based on the precipitation upstream of a point on the landscape and the water equivalent ice input for regions below freezing. The governing equations used in the model are published in the above-cited work and will not be repeated here for brevity.

The general model setup used in each simulation is as follows. A set of user-defined input values are chosen including the tectonically driven rate of rock-uplift, erosional parameters, and climate parameters (Table 1). The initial condition of each landscape is a random (white noise) topography seeded with elevations between 0 and 1 m. Piedmont glacier flow out of the orogen front occurs on a low-sloping continental shelf (slope of 0.001) with no rock-uplift added to edges of this initial landscape. This shelf is added to prevent runaway ice velocities that would otherwise occur if glaciers extended beyond the model domain. The edges of the shelf are held fixed at their initial elevations (i.e. Dirichlet boundary condition). The shelf is not shown in figures (e.g. Figs. 1 and S1) to improve visibility of region where glaciers form. Simulations were run for a total duration of up to 20 My. During this time, sea-level temperature varied as a sinusoid function with a frequency of either 100 or 40 ky and amplitude of 6 °C. Erosion time-steps are variable to ensure model stability and are typically ~10–100 yrs for fluvial and hillslope processes and 0.01 yrs for glacial processes. Note that the terms 'sea-level' and 'base-level' temperatures are used interchangeably hereafter because the elevation of the mountain front is set to 0 m for convenience in interpreting the results. Results from this study can be applied to any orogen so long as the sea/base-level temperature at the base of the orogen is used for comparison.

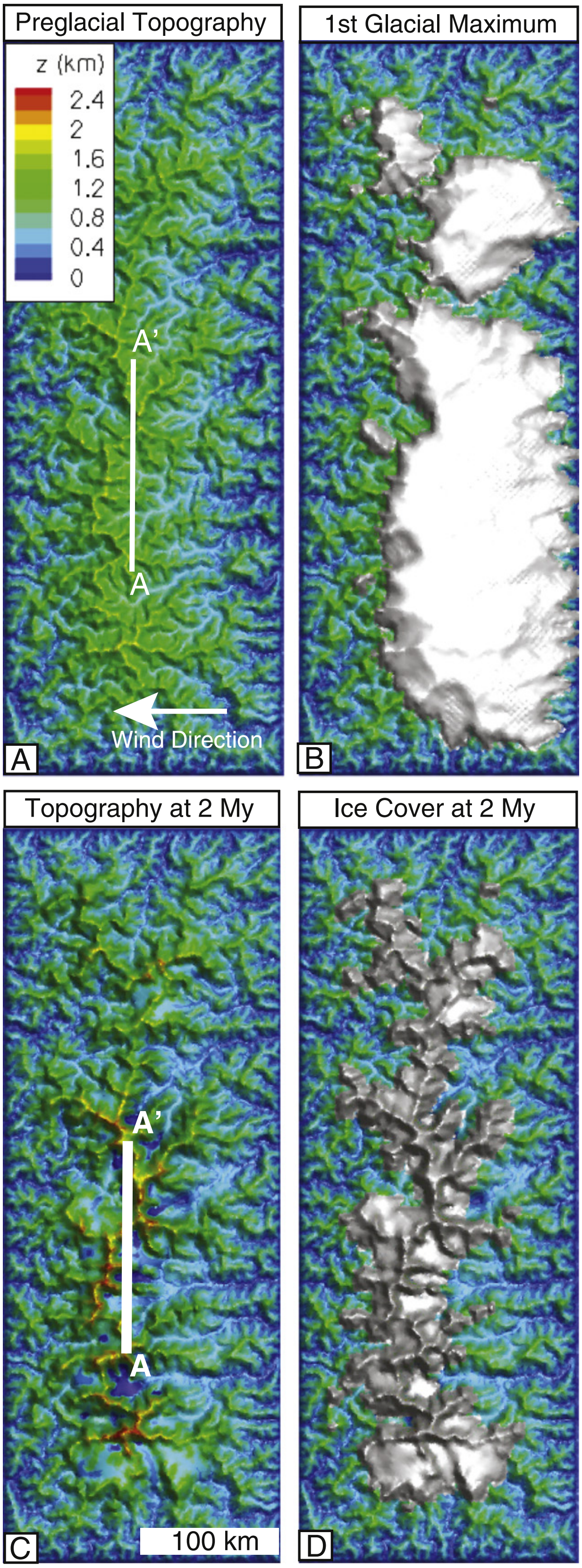

Fig. 1. Modeled topography and ice cover. Shown is both the initial and 2 My topography and ice cover for model run m01 with a rock uplift rate 0.42 mm/yr, glacial sea-level temperature of 2 °C (interglacial 8 °C) and 100 ky glacial–interglacial periodicity. The continental shelf has been removed for illustration clarity. Note the existence of 'buzzsaw' like conditions where glacial extent reduces over time as topography is driven to lower elevation in accumulation zones. Ice cover is shaded in B and D for visualization purposes. Cross-section A–A′ is shown in Fig. 2 and highlights some of the greatest changes to the topography. The strong asymmetry in ice cover in B is the likely the result of not including wind-blown snow transport in the mass balance model.