Geomorphology 303 (2018) 456–466

Contents lists available at ScienceDirect

Geomorphology

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

Modulation of the erosion rate of an uplifting landscape by long-term climate change: An experimental investigation

Bérangé Moussirou, Stéphane Bonnet *

Université de Toulouse, Géosciences Environnement Toulouse, UPS, CNRS UMR 5563, 14 avenue E Belin, 31400 Toulouse, France

ARTICLE INFO

Article history:
Received 24 August 2017
Received in revised form 3 December 2017
Accepted 3 December 2017
Available online 07 December 2017

Keywords:
Landscape evolution
Experimental modeling
Relief
Erosion
Climate

ABSTRACT

Whether or not climatic variations play a major role in setting the erosion rate of continental landscapes is a key factor in demonstrating the influence of climate on the tectonic evolution of mountain belts and understanding how clastic deposits preserved in sedimentary basins may record climatic variations. Here, we investigate how a change in precipitation influences the erosional dynamics of laboratory-scale landscapes that evolved under a combination of uplift and rainfall forcings. We consider here the impact of a decrease in the precipitation rate of finite duration on the erosive response of a landscape forced by a constant uplift and initially at a steady state (SS1). We performed several experiments with the same amplitude but different durations of precipitation decrease (*Tp*). We observe that the decrease in precipitation induces a phase of surface uplift of landscapes to a new steady state condition (SS2); however, the details of the uplift histories (timing, rate) differ between the experiments according to *Tp*. We also observe a decrease in the erosion rate induced by the precipitation change; however, the timing and amplitude of this decrease vary according to *Tp*, defining a delayed and damped erosion signal. Our data show that the landscape response to precipitation change is dictated by a critical water-to-rock ratio (ratio of precipitation over uplift) that likely corresponds to a geomorphic threshold. Our study suggests that variations in precipitation that occur at a geological time scale ($>10^6$ years) may have a weak impact on the erosion of landscapes and on the delivery of siliciclastic material to large rivers and sedimentary basins.

1. Introduction

Whether or not climatic variations, and in particular precipitation variations, play a major role in defining the long-term erosion rates ($>10^{5-6}$ years) of continental landscapes is a key factor in demonstrating the influence of climate on the tectonic evolution of mountain belts, as expected from analytical, numerical, and analog modeling approaches (e.g., Dahlen et al., 1984; Willett, 1999; Whipple and Meade, 2006). These models demonstrate that modifications in the erosion rate that would significantly affect the gravitational loading of the continental crust might change its state of stress and consequently its deformation. However, field evidence of these interactions has proved challenging to unambiguously demonstrate (Whipple, 2009), the question of climatic control on erosion efficiency at a geological time scale being among the most critical issues (Whipple, 2009). If we only consider precipitation, for example, its effect on long-term erosion is controversial because erosion rates inferred from cosmogenic or thermochronologic studies sometimes correlate with its mean annual value (e.g., Reiners et al., 2003; Thiede et al., 2004; Moon et al., 2011; Bookhagen and Strecker, 2012) but do not or only weakly correlate in other cases (e.g., Riebe et al., 2001; Burbank et al., 2003; von Blanckenburg, 2005; Carretier et al., 2013; Godard et al., 2014). Similarly, a link between precipitation and landscape metrics is rarely observed in nature (e.g., Champagnac et al., 2012) or is difficult to highlight (D'Arcy and Whittaker, 2014), whereas it is expected theoretically (e.g., Whipple et al., 1999). Our inability to distinctly understand the effect of precipitation on landscape and erosion may be related to many phenomena. Taking into account orographic effects, for example, modifies the expected relationship between landscape metrics, such as the steepness index and precipitation rate (D'Arcy and Whittaker, 2014). Actually, although theory indicates that high steady state reliefs develop under low erosional efficiency conditions (dry climate) (Whipple et al., 1999), in many cases topography and climate are coupled, and consequently precipitation increases because of orographic effects during the uplift of a high mountain. Orographic precipitation, however, is not at a maximum at the highest elevations but commonly between 1000 and 2000 m (e.g., Bookhagen and Burbank, 2006). In such a context, deconvolving the climatic and tectonic influences on erosion rates is difficult (D'Arcy and Whittaker, 2014; Deeken et al., 2011), a problem that was likely magnified by the development of glaciations during the Plio-Pleistocene, which enhanced erosion in mountains worldwide (Herman et al., 2013).

The question of landscape sensitivity to the time-scale of climatic variations is another major issue that needs to be considered in

---

* Corresponding author.
E-mail address: stephane.bonnet@get.omp.eu (S. Bonnet).

https://doi.org/10.1016/j.geomorph.2017.12.010

understanding the impact of precipitation on landscapes and erosion. It has been proposed, for example, that the change in the periodicity of the global climate during the Plio-Pleistocene could explain the global increase in continental erosion deduced from the terrigenous sedimentation rate observed in oceans worldwide (e.g., Zhang et al., 2001). However, this latter observation is strongly disputed (see, for example, the synthesis of Willenbring and Jerolmack, 2016). Numerical models have shown that the response of a landscape to periodic changes in precipitation depends on the frequencies considered (Godard et al., 2013; Braun et al., 2015), with a specific periodicity that maximizes the erosional response (Godard et al., 2013); thus, if forced by an uplift, the erosion rate of such a landscape continuously oscillates around the uplift rate value. In contrast, for longer forcing periods, the landscape is always adjusted to the precipitation conditions and is in a steady state so its erosion rate is always equal to that of the uplift and remains constant in time (Godard et al., 2013; 'reactive landscapes' of Allen, 2008). This result is important because it indicates that depending on the forcing periodicity, erosion rates are related (or not) to precipitation, depending on the equilibrium state of the landscape (see also Bonnet and Crave, 2003). The landscape response to climatic variation and its related erosional signal are also potentially influenced by the presence of geomorphic thresholds that are sensitive to climate. It has been suggested for example that the location of channel heads is governed by a threshold for runoff erosion related to shear stress (Horton, 1945; Montgomery and Dietrich, 1992) and then, that the extent of the channel network (drainage density) could vary according to climate (Montgomery and Dietrich, 1992; Rinaldo et al., 1995; Tucker and Slingerland, 1997). Interestingly, numerical simulations show that the existence of such a threshold can drive a punctuated erosion in response to smoothly varying climate (Tucker and Slingerland, 1997).

We investigate here the landscape and erosive responses to climate change on laboratory experiments, following the work of Bonnet and Crave (2003). Such physical experiments offer a powerful means for understanding landscape evolution and testing hypotheses under controlled forcings (e.g., Hasbargen and Paola, 2000, 2003; Bonnet and Crave, 2003; Lague et al., 2003; Babault et al., 2005, 2007; Turowski et al., 2006; Bonnet, 2009; Reinhardt and Ellis, 2015; Singh et al., 2015; Sweeney et al., 2015). In the experiments here, the precipitation rate decreased after a first phase of precipitation and uplift and the attainment of a steady state between erosion and uplift (Lague et al., 2003; Bonnet and Crave, 2003), considering different durations of precipitation decrease. We will specifically document how this duration influences the surface uplift evolution of the landscape and rivers and how the resulting erosional signal is damped and delayed from the initiation of the decrease depending on this duration.

2. Experimental design and procedure

2.1. Experimental design

We studied the erosive response of an experimental landscape subjected to uplift and precipitation. We used a device initially developed at the Geosciences Rennes laboratory (Bonnet and Crave, 2003; Lague et al., 2003; Babault et al., 2005, 2007; Turowski et al., 2006; Bonnet, 2009) but newly installed at the Geosciences Environnement Toulouse laboratory in a modified version, as described below. This device allows us to simulate in the laboratory the development of landscapes formed by erosion induced by runoff of water over a cohesive material. As in previous studies (Bonnet and Crave, 2003, 2006; Babault et al., 2005, 2007; Turowski et al., 2006; Bonnet, 2009), the material used is a silica paste obtained by mixing silica powder ($D_{50} = 10$–20 μm) with water (20% weight of silica powder). This mixture is homogenized to saturate the porosity of the silica paste and to reduce infiltration phenomena and can then promote sediment transport by surface runoff (Lague et al., 2003). This mixture fills a rectangular box (400 × 600 mm in size and 500 mm in depth), whose base can move upward and downward within the box. The movements of the base are driven by a screw and a stepping motor and are controlled by an automaton. During an experimental run, the base of the box was raised at a constant rate. It pushed the silica outside the top of the box at a rate defined as the uplift rate (U; 1–30 mm/h). Precipitation was generated by a system of four industrial sprinklers that delivered water droplets (diameter < 50 μm) that were small enough to avoid any splash dispersion at the surface of the model, which reduces the action of diffusive hillslope processes (Lague et al., 2003; Sweeney et al., 2015). In the present version of the experimental setup, the water discharge from each sprinkler is controlled by an automaton, which allows precipitation to automatically change during a run. Precipitation was calibrated to be as homogeneous as possible by collecting water in 20 pans at the location of the model. During an experimental run, we used a high-resolution laser sheet (accuracy <0.2 mm) to regularly digitize the surface of the model with a spatial resolution of ~0.5 mm and to produce square-grid digital elevation models. We usually digitized the surface of the models every 5 min, except in the steady state phases when elevations and erosion rates are stable and where digitization intervals can reach 20 min. The erosion rates were computed by dividing the elevation change per pixel between two scans by the time between the scans. Local erosion rates were also averaged to obtain a mean value for the entire landscape.

2.2. Procedure

We present here the results of the experiments where we disturbed an initial topography at a steady state (Fig. 1) by decreasing the precipitation rate from 160 to 60 mm/h, considering different durations of the precipitation decrease (we hereafter referred to this duration as Tp). For this purpose, we calibrated nine intermediate fields of precipitation (Table 1). The coefficient of variation of the precipitation rates (standard deviation/mean) is <15% for the experiments carried out here (Table 1). We applied precipitation variations step-by-step rather than by continuously varying the discharge from the sprinklers in order to ensure good quality control of the precipitation history. These steps were of limited duration, usually <60 min; thus, we did not observe any adjustment of the landscape to the individual steps.

We consider here five experiments, one with an instantaneous precipitation decrease ($Tp = 0$) and four with progressive decreases with Tp values of 60, 300, 500 and 700 min (Table 2). Then, these experiments were conducted up to a second steady state between erosion and uplift. Fig. 2 shows a schematic evolution of an experiment with $Tp > 0$, which illustrates the terminology used in this paper.

3. Results

3.1. Steady state landscapes

All experiments began with a flat plateau that was uplifted and then progressively dissected by multiple channels that were initiated on the four sides of the model. They formed channel networks that propagated in toward the center of the model, while the mean elevation of the landscape increased (Fig. 1). Under constant uplift and precipitation forcing, the mean and maximum elevations then stabilized, which implies that the erosional flux balanced that of the uplift, thus defining a steady state landscape (SS1). On the basis of experiments presented here (Table 2) and the previous experiments of Babault et al. (2005, 2007), Turowski et al. (2006), Bonnet (2009), and some unpublished experiments, we observe a coevolution of the mean elevation of the experiments at steady state ($<h>_{ss}$) with rainfall and uplift rates (Fig. 3). As already noticed by Bonnet and Crave (2006) using a limited data set, $<h>_{ss}$ is inversely proportional to the precipitation rate (Fig. 3A); however, we observe a large dispersal in the $<h>_{ss}$ values for a given precipitation rate because of the dependency of $<h>_{ss}$ on the uplift rate. Similarly, we observe that $<<h>_{ss}$ is proportional to the uplift rate (Fig. 3B) but that a large dispersal in the $<h>_{ss}$ values occurs because