Landscape response to climate change: Insights from experimental modeling and implications for tectonic versus climatic uplift of topography

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ABSTRACT

We present the results of an experimental investigation of the concurrent action of tectonic uplift and climate variation on relief evolution. We designed an experimental apparatus that allows the study of erosion of laboratory-scale topographies that evolve under given uplift and rainfall rates. For constant uplift and rainfall rates, the experimental topography evolves toward a statistical steady state defined by a mean elevation constant with time. Starting from such a steady state and keeping the input uplift rate constant, a subsequent change in the rainfall rate yields a change in the mean elevation of the landscape to a new equilibrium elevation. An increase in precipitation yields a lower mean steady-state elevation, whereas for a decrease in precipitation the surface is uplifted. We define this phenomenon as a climatically induced surface uplift, as opposed to a tectonically induced surface uplift. The climatically and tectonically induced surface uplifts correspond to different dynamics of denudation so that it is theoretically possible to differentiate between the climatic or tectonic causes of surface uplift from records of output sediment fluxes.

Keywords: geomorphology, landscape evolution, erosion, steady state, climate change, uplift.

INTRODUCTION

The topography of compressional mountain ranges evolves following the competing effects of tectonic uplift and erosion. When erosion does not compensate uplift, the topography is uplifted; England and Molnar (1990) defined this as surface uplift (surface uplift being equal to tectonic uplift minus erosion). However, geomorphic systems may tend to equilibrate with tectonic uplift because of negative feedbacks. For example, an increase in tectonic uplift rate can lead to a higher relief, then to a higher denudation rate that possibly decreases the elevation (Ahnert, 1970). It has been argued that geomorphic systems that evolve under constant uplift, climate, and lithology tend toward a steady state because of the establishment of a dynamic equilibrium between erosion and uplift (Hack, 1960; Willet and Brandon, 2002).

Except in some rare cases like the Southern Alps of New Zealand (Adams, 1980), very few examples of steady-state landscapes exist (Whipple, 2001). Rather, there is a multitude of examples of disequilibrium, uplifting landscapes (Molnar and England, 1990; Zhang et al., 2001). Starting from an initial steady-state topography, surface uplift results either from an increasing tectonic uplift rate or from decreasing erosion efficiency. Numerical models incorporate both uplift rate and erosion efficiency to simulate landscape dynamics (e.g., Kirkby, 1980; Willgoose et al., 1991; Howard, 1994; Tucker and Slingerland, 1994; Crave and Davy, 2001). These models correlate the erosion efficiency with the water flux and thus with climate through rainfall. The models assume a potential link between surface-uplift dynamics and climate. Currently, no physical demonstration supports this theoretical approach, which is based on intuitive assumptions concerning geomorphic processes.

To observe the landscape response to climate change, we developed a physical approach based on the study of erosion of laboratory-scale experiments under variable uplift and rainfall rates. Our goal is not to reproduce all the complexity of the natural landscape response to climate change, but rather to extract first-order behaviors from a simple physical system. Here we focus on the effect of the increase or decrease of rainfall rate on the average elevation of the topography and on the implications for the occurrence of surface uplift.

EXPERIMENTAL TOPOGRAPHY

Experimental Apparatus

We studied experimentally the erosion of rectangular models uplifted at a constant rate under the action of a specific rate of rainfall. We only briefly describe the experimental apparatus herein. More details can be found in Crave et al. (2000) and Lague et al. (2002).

The material eroded is a paste made by mixing granular silica (median grain diameter between 10 and 20 μm) with water. This paste is introduced in a box (hereafter called ''erosion box'') with an internal area of 14 × 20 cm and a depth of 18 cm. Its base can be moved upward or downward within the box, and its movements are driven by a screw and a computer-controlled stepping motor. During an experiment, the base moves upward at a constant rate. It pushes the silica paste outside the top of the erosion box at a rate defined as the uplift rate (between 0.5 and 5 cm/h). The experiment runs within a 1 m^3 box (''fog box'') where an artificial fog is produced by atomization of a high-pressure water flow through as many as 44 sprinklers (droplet size ~5 μm). The uplifted silica paste is therefore eroded by running water at its surface. It is important to note that the size of raindrops is small enough to avoid any splash dispersion at the surface of the model. Rainfall rate is measured by collecting water in pans introduced within the fog box. Various rainfall rates are produced by changing the number of active sprinklers, their orientation and configuration, or the water pressure. For our purpose, rainfall rate varies from 50 to 350 mm/h.

A topography acquisition facility (Lague et al., 2002) made of five telemetric lasers is used to produce high-resolution digital elevation models (DEMs) of the experiments (Fig. 1). It allows the digitization with a vertical accuracy of 40 μm and a horizontal accuracy to 500 μm. During an experiment, the evolution of the topography is measured by producing DEMs at different time intervals, usually from 10 to 30 min of erosion.

Evolution of Topography up to Steady State

Experiments begin with the erosion box filled with silica paste up to the top of the box so that the first stages of evolution correspond to a plateau uplift. Figure 1 shows the evolution of mean and maximum elevation of a topography that evolves under constant uplift and rainfall rates. The evolution of such an experiment typically involves a growth phase and a steady-state phase (Lague et al., 2002). During the growth phase, some topographic incisions form along the four borders of the model. As uplift continues, they grow and propagate inward until there is complete dissection of the plateau. This phase is characterized by an increase in both the mean and

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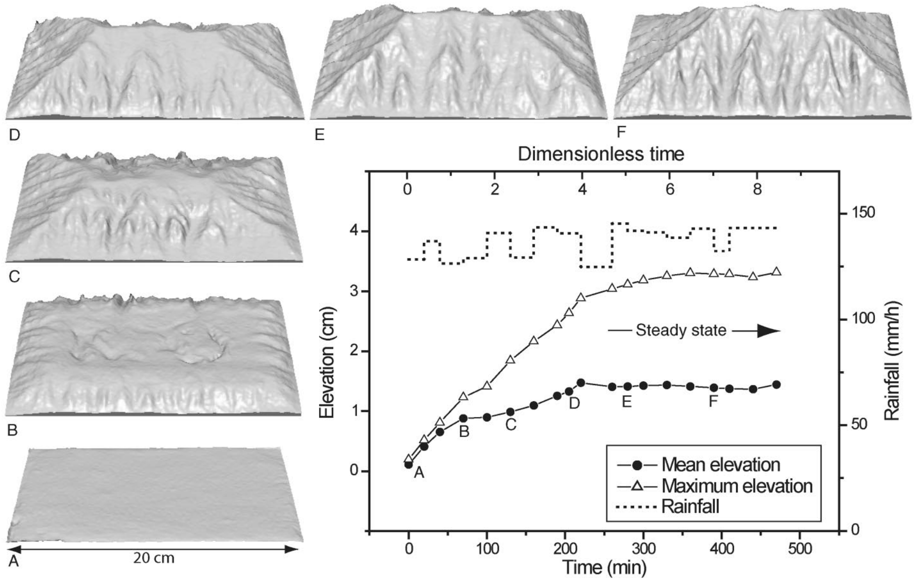

Figure 1. Evolution of mean and maximum elevation of experiment TC22 up to steady state, calculated from high-resolution digital elevation models (DEMs) taken at different time intervals (pixel size 1 mm). Uplift rate is 1.5 cm/h and mean rainfall rate is 137 ± 7 mm/h. A–F are three-dimensional views of DEMs (A–D: growth phase; E–F: steady state). Statistical steady state is defined by constant elevation.

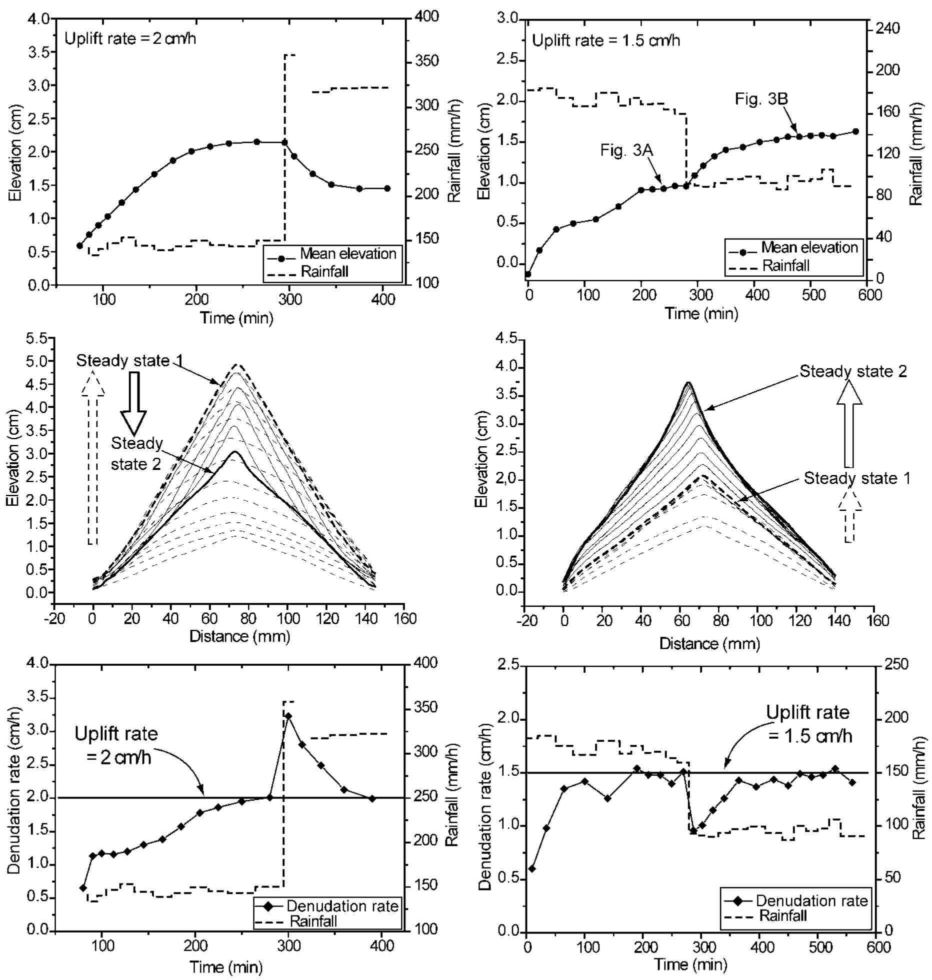

Figure 2. Influence of sudden increase (left; experiment TC8) and decrease (right; experiment TC18) in rainfall rate on erosion in experiments submitted to constant uplift rate (TC8: 2 cm/h; TC18: 1.5 cm/h). Top: Rainfall rates and evolution of mean elevation calculated from 1-mm-square grid digital elevation models (DEMs). Middle: Evolution of topographic profiles for time intervals of topography acquisition; each line is mean elevation along 7-cm-wide swath calculated from DEMs. Dotted and solid lines show evolution toward first and second steady states, respectively. Bottom: Denudation rates calculated from mass balance. At steady state, denudation rate equals uplift rate.

maximum elevations. After the growth phase, the mean and maximum elevations remain stable with time (Fig. 1) even if local geometry evolves. A constant mean elevation with time is a criterion used to define a statistical steady state of the topography (Montgomery, 2001; Willet and Brandon, 2002). This criterion does not imply that the geometry of the topography is stable at the local scale (Hasbargen and Paola, 2000), but only that the output sediment flux equals the input uplift flux. Here we also use the mean elevation criteria to define a steady state at the model scale. For geological purpose, a dimensionless time t^* can also be written as (Whipple and Tucker, 1999; Hasbargen and Paola, 2002): $t^* = Ut/\langle h\rangle_{eq}$, where U is the uplift rate, t is time, and $\langle h\rangle_{eq}$ is the mean elevation at steady state. This is an indicator of the progress of an experiment expressed as the amount of input matter required to reach steady state. For the experiment in Figure 1, steady state is attained for $t^* \approx 4$.

Lague et al. (2002) studied the influence of uplift rate on the steady-state topographies of such models. They demonstrated that the mean elevation at steady state increases with the uplift rate following a threshold-linear relationship. This result agrees with the existence of linear relationships between denudation rate and relief (Ahnert, 1970) or between denudation rate and mean elevation (Pinet and Souriau, 1988).

EFFECT OF CLIMATE CHANGE

We study the effect of climate change by varying the rainfall rate of experiments at steady state (Fig. 2). Figure 3 shows two stages of an experimental landscape at steady state with the same uplift rate, but under high and low rainfall conditions.

Starting from steady state, the increase in rainfall rate (Fig. 2) modifies the topography to a lower mean steady-state elevation. Mean topographic profiles (Fig. 2) show that the landscapes at steady state differ by their mean topographic slope. At equilibrium, topography under low precipitation has a higher mean slope than topography under high precipita-

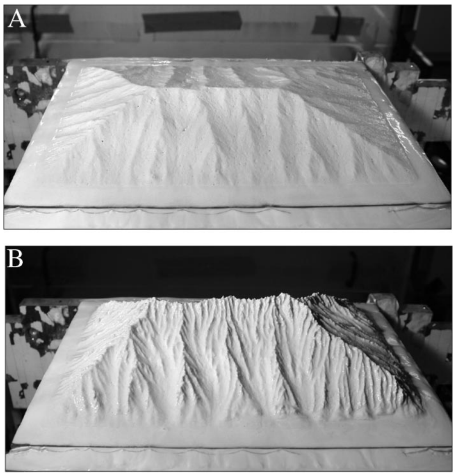

Figure 3. Oblique views of experiment TC18 (cf. Fig. 2). A: t = 240 min. B: t = 480 min. Topographies are at steady state with uplift rate of 1.5 cm/h and under high rainfall rate conditions (top: mean rainfall rate 166 ± 5 mm/h) and low rainfall rate conditions (bottom: mean rainfall rate 98 ± 7 mm/h).

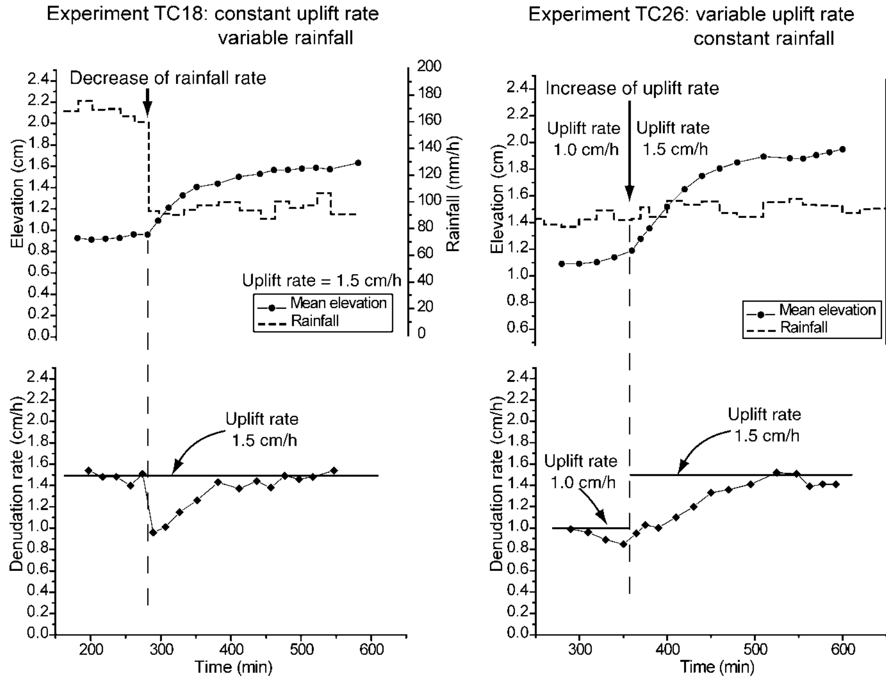

Figure 4. Surface uplift of experiments induced by decrease in rainfall rate (left: climatically induced surface uplift) or increase in uplift rate (right: tectonically induced surface uplift). See text for comments.

tion. Steady state then corresponds to a combination of low rainfall plus high slope or high rainfall plus low slope. The transition from low to high precipitation induces a strong increase in denudation rate followed by a decrease to the value of the uplift rate while the topography returns to steady state (Fig. 2). The peak in denudation rate is due to the combination of high rainfall rate and high topography slopes inherited from the previous low rainfall condition. Denudation rates higher than uplift rate reduce the topographic slope to the new steady-state topography.

The shift from high to low rainfall rate induces the surface uplift of a previous steady-state topography to a higher equilibrium elevation (Figs. 2 and 3). This climate-induced surface uplift corresponds to a progressive increase in the mean slope of the topography (Fig. 2). Starting from the initial steady state, a decrease in precipitation induces a fall in the denudation rate (Fig. 2) followed by an increase to the uplift rate value when the topography returns to steady state. The fall in denudation rate results from the combination of low precipitation and low slopes inherited from the previous high rainfall conditions. As a result, erosion cannot keep pace with uplift that consequently induces surface uplift of the topography. As the topography is uplifted, both its slopes and the denudation rate progressively increase to the new steady-state value (Fig. 2).

For a constant uplift rate, there is an inverse correlation between the steady-state elevation of the topography and the rainfall rate: the higher the rainfall rate, the lower the elevation. This relationship was predicted theoretically by Willgoose et al. (1991) and Tucker and Bras (1998, 2000). Whipple et al. (1999) developed an analytical approach of the climate influence on the topography of fluvial landscapes by changing the value of the coefficient K of the erosion law (Howard and Kerby, 1983; Howard et al., 1994; Whipple and Tucker, 1999). This coefficient incorporates the influence of many factors that can be climate related, including rock strength, channel width, or sediment load (Whipple and Tucker, 1999). They assumed that a shift from a low to a higher value of K represented a shift toward more erosive conditions, which they interpreted as a wetter climate. By increasing the value of K in their numerical simulations, they observed a decrease in elevation of all the components of the landscape, as we observe here by directly increasing the rainfall rate. Our results agree with those of Whipple et al. (1999) and also contradict the commonly accepted notion that increased precipitation leads to greater relief.

CLIMATIC VERSUS TECTONIC SURFACE UPLIFT

The surface uplift of a previous steady-state topography can occur in response to two different factors (Fig. 4). In the previous section, we described the case that we refer to as a climatically induced surface uplift. It occurs when a decrease in precipitation induces a fall in the denudation rate of a previous steady-state landscape, which is then uplifted. Surface uplift may also occur when the input uplift rate is increased (Fig. 4; also see Lague et al., 2002), what we call hereafter tectonically induced surface uplift. No major qualitative differences exist between the topographies that are uplifted because of a tectonic or a climatic change. However, they correspond to clearly different dynamics when looking at denudation rates (Fig. 4). Starting from a steady-state topography, climatically induced surface uplift occurs in response to a fall in denudation rate that then returns to the previous value (Fig. 4), whereas tectonically induced surface uplift leads to a progressive increase in the denudation rate from the previous value to the new uplift rate value (Fig. 4). It is then theoretically possible to differentiate between climatically and tectonically induced surface uplifts by looking at the dynamics of the sediment flux out of the system.

DISCUSSION

Area versus slope relationships of topographies at steady state (Crave et al., 2000; Lague et al., 2002) show that our experiments reproduce only a limited number of erosional processes. It is important to note that the laboratory equivalent of fluvial processes is not reproduced in small-size experiments such as those considered here, and the slope versus area scaling exponent value suggests that the dominant process is an analogue of debris-flow–dominated channels (Montgomery and Foufoula-Georgiou, 1993). Consequently, rather than simulating all the landscape components of a mountain chain, our experiments can be better viewed as an equivalent of the landmass that is between the main streams of the landscape. In this scheme, the four borders of the erosion box can be viewed as streams at equilibrium in which all the matter eroded from the landscape is transferred outside the system. At the core of the erosion versus climate problem is the hillcrest behavior (Molnar and England, 1990; Small and Anderson, 1998; Whipple et al., 1999), because relief production at the time of climate change depends mainly on the decrease or increase of summit and ridge elevations (Small and Anderson 1998). Consequently, even if our experiments do not simulate all the landscape components, they incorporate some fundamentals of the interactions between topography and climate. Our results are only valid if we do not consider the additional effect of vegetation development with climate, a phenomenon that probably introduces negative feedbacks but whose effects on natural systems are highly controversial (see discussion by Tucker and Slingerland [1997] and compilations of theoretical curves that relate erosion rates to precipitation by Summerfield [1991] and Riebe et al. [2001]).

Results from our experiments demonstrate that surface uplift occurs either when the input uplift rate increases or when the erosion rate is reduced because of a climatic change. These experiments constitute a physical demonstration that climate forcing can have the same range of consequences on geomorphic systems as tectonics in terms of mean elevation or surface uplift. This outcome agrees well with theoretical formulations of the dynamics of landscapes where both the tectonic and erosion components are explicitly expressed in the balance equations (e.g., Kirkby, 1980; Willgoose et al., 1991; Howard, 1994; Tucker and Slingerland, 1994; Crave and Davy, 2001). Therefore, a high mean elevation does not imply a high uplift rate, and the converse is true. Montgomery et al. (2001) claimed that climate exerts a strong control on the large-scale morphology of the Andes. They assumed that the low elevations of the northern Andes could result from high precipitation rates rather than lower crustal shortening. This phenomenon is plausible in view of our results. The interpretation of observed surface uplift simply as a consequence of tectonics is also problematic. In practice, we cannot discriminate the climatic or tectonic origin of surface uplift from the mean elevation evolution alone. On the basis of the experiments, the sediment flux variability appears more relevant because climatic and tectonic variations induce clearly different sediment-flux responses. Surface uplift linked to a decrease or to an increase in sediment flux is of climatic or tectonic origin, respectively. More generally, a climatic signature corresponds to a sediment-flux fluctuation with a maximum or minimum around a constant value equal to the uplift rate, whereas a tectonic signature shows a simple increase or decrease between two flux-rate values. This generalization can serve as a guide for interpreting surface uplift, provided that a good set of sediment-flux data in terms of time resolution and duration of record is available.

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