Climatic controls on hillslope angle and relief in the Himalayas

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ABSTRACT

Comparison of rainfall data and mean hillslope angles in the Himalayas of central Nepal shows that mean hillslope angles decrease with increasing mean annual rainfall. Higher pore pressures and higher rates of chemical weathering in the wetter regions may decrease the threshold angle of hillslopes prone to landsliding. When valley spacing is held constant, the sensitivity of mean hillslope angle to climate implies that relief, in the absence of limits due to rock strength, is also dependent on climate. These results suggest that wet-to-dry climatic changes increase relief in regions with incising bedrock channels and that dry-to-wet climatic changes reduce relief.

Keywords: threshold hillslopes, climatic geomorphology, relief, Himalayas, Nepal, landslides.

INTRODUCTION

One of the fundamental characteristics of mountain ranges that immediately appeals to our senses is hillslope relief, the elevation difference between ridge crests and valley bottoms. If it is assumed that that rock-mass strength is uniform and does not limit relief (cf. Schmidt and Montgomery, 1995), then the shape of a mountain with straight hillslopes may be approximated as an isosceles triangle in which the two lower apices represent the valley bottoms; the relief is simply a function of valley spacing and hillslope angle. If it is further assumed that valley spacing changes very slowly, changes in hillslope relief must arise from changes in hillslope angle.

In tectonically active regions with incising bedrock channels, hillslopes steepened above a threshold angle are rapidly denuded until the slope is brought back down to the threshold angle (Carson and Petley, 1970). Because precipitation affects slope stability through its control on pore pressure, Carson (1976) proposed that threshold slope angle may adjust to climate through landsliding. Here we explore the influence of annual rainfall on hillslope angles in the Nepalese Himalayas, and we extend this analysis to propose a mechanistic link between changes in climate and changes in hillslope relief.

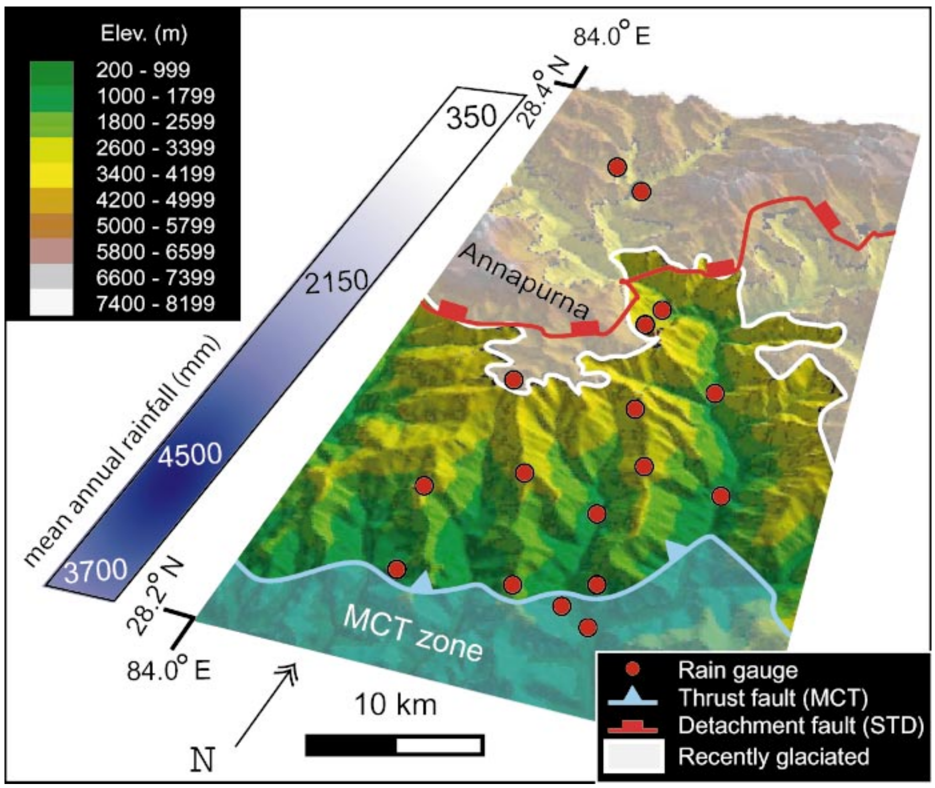

Figure 1. Map of study region. Rainfall gradient strikes approximately north-south; area receives ~4500 mm of mean annual rainfall in south and 350 mm in north, but note that maximum rainfall is 10 km north of southern boundary. MCT—Main Central thrust; STD—Southern Tibetan detachment.

MATERIALS AND METHODS

Rugged topography and strong climatic gradients make the Himalayas in central Nepal (Fig. 1) a useful site for investigating climatic controls on relief production and reduction. High rates of uplift and erosion (Burbank et al., 2003; Vance et al., 2003) and the presence of bedrock channels lining the bottoms of deep valleys should lead to a predominance of threshold hillslopes (Montgomery, 2001) and suggest that the landscape exists near a topographic steady state. In the unglaciated regions of the Himalayas, landsliding is the main erosional agent (Shroder and Bishop, 1998), and this process creates and maintains hillslopes that are roughly linear. Monsoon storms, advancing northward from the Bay of Bengal, impinge against the southern flank of the Annapurna Range to create a strong precipitation gradient. Data from a network of 17 meteorological stations (Barros et al., 2000) indicate that mean annual rainfall (MAR) drops from a maximum of 4500 mm to 350 mm in only 40 km (Fig. 1).

To investigate the relationship between hillslope angle and rainfall, MAR values for three years (1999–2001) were interpolated from the meteorological station data onto a 3 arcsecond (~90 m spacing) digital elevation model (Fig. DR1[1]). Mean hillslope angles were then calculated for each precipitation zone (note that, because the slope angle of each grid cell is calculated from the elevation of its uphill and downhill neighbors, the length scale of the slope angle measurement is ~270 m). Only slopes at elevations <4200 m were included in the analysis to minimize the inclusion of any areas that may have been glaciated during the Last Glacial Maximum (Fort, 1987; Pratt et al., 2002a). Also eliminated from the analysis were three valleys in the north where we found evidence of occupation by valley glaciers below 4200 m (Fig. 1). Additionally, because inner gorges (Densmore et al., 1997) and flat valley bottoms may be transitory landscape features, a 500-m-wide buffer around the fluvial network was excluded from the analysis. All precipitation zones had areas of >100 grid cells, thus ensuring reasonable sample sizes.

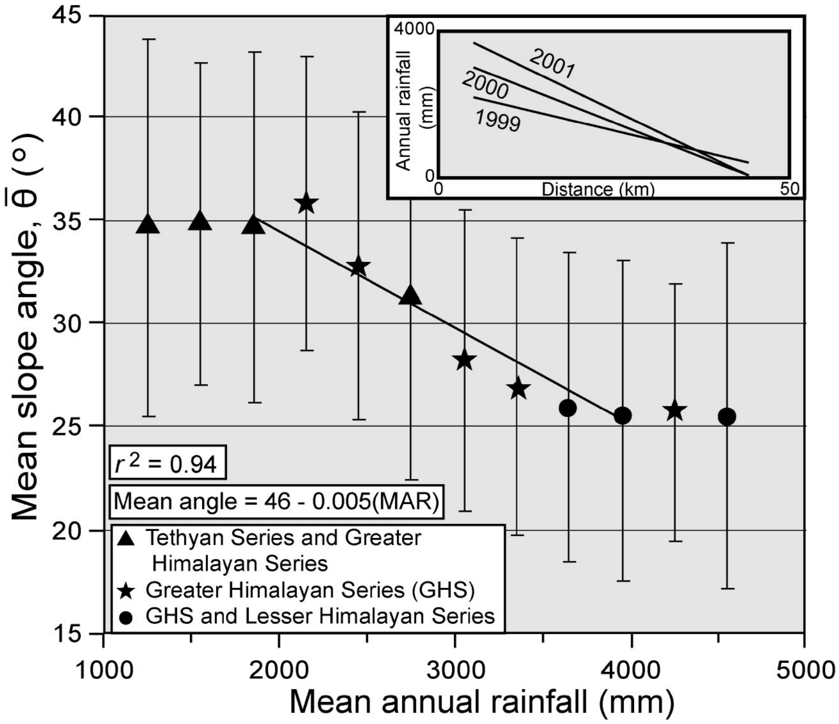

Figure 2. Mean annual rainfall (MAR) vs. mean slope angle. Increase in mean annual rainfall between 1800 and 4000 mm is matched by decrease in mean hillslope angles. Error bars represent 1σ. Best-fit linear regression applies only to MAR data between 1800 and 4000 mm. Although linear regression was used for simplicity, residuals may suggest more complex relationship between rainfall and slope angles. Inset: Best-fit linear regressions through each year of rainfall data demonstrate that, although annual rainfalls vary, there is consistent south-to-north gradient. Distance is straight-line distance from southern boundary to northern boundary of map in Figure 1.

RESULTS AND DISCUSSION

As MAR values increase from 1800 to 4000 mm, mean slope angles decrease (Fig. 2). In this rainfall range, the relationship between mean slope angle and MAR appears to be roughly linear, bounded on both sides by plateaus where slope angles are approximately constant. Whereas the annual precipitation at any station may vary from year to year, the three years of rainfall data show a consistent south-to-north trend in MAR (Fig. 2, inset); a similar trend is apparent in a compilation of rainfall data covering 10–20 yr (Chalise et al., 1996) from the region (note that these data, collected by the Nepal Department of Hydrology and Meteorology, were not used in our analysis because of a lower density of weather stations in our field area and data-quality issues). In addition, Burbank et al. (2003) suggested that a similar trend existed during glacial times. Finally, because it is the spatial coincidence of the rainfall distribution in conjunction with the distribution of slope angles that is important, the true values of MAR may be of only secondary importance.

Although the data strongly suggest a relationship between mean slope angle and annual rainfall, other factors might be invoked to explain the observed distribution of slope angles. First, lithological differences might be responsible for the distribution of slope angles. The bedrock in the field area is grouped into three broad categories: the Tethyan Series primarily comprises sedimentary units; the Greater Himalayan Series consists mainly of gneisses; and the Lesser Himalayan Series includes schists, limestones, and quartzites (Colchen et al., 1986). An examination of the spatial distribution of rock types reveals no consistent relationship between lithology and mean hillslope angle (Fig. 2). It is possible that the distribution of slope angles reflects spatial differences in the degree of rock fracturing, particularly given that the gentlest slopes are near the Main Central thrust (Fig. 1). It seems unlikely, however, that the influence of the Main Central Thrust on rock fracturing would extend northward 20 km. Furthermore, our visual observations of the bedrock along a north-south transect through the study area revealed extensive fracturing only in close proximity to the fault (<1 km).

Second, the observed pattern of slope distributions might be caused by differential erosion rates of the valley bottoms, such that the steeper hillslopes are associated with more rapid incision of their lower boundary (Penck, 1953). Erosion rates, however, are nearly identical along a transect perpendicular to the rainfall gradient in the same study area (Burbank et al., 2003). Furthermore, a hillslope already at its threshold angle will respond to higher rates of river incision by an increase in landslide frequency rather than a steepening of its slopes.

Third, regions undergoing rapid rock uplift and denudation might be expected to have steeper slopes than those undergoing slower rates of uplift and denudation (Kirkby, 1973; Penck, 1953). For example, to the southeast of our field area, Wobus et al. (2003) noted a sharp south-to-north increase in hillslope gradients associated with a rapid decrease in $^{40}Ar/^{39}Ar$ cooling ages and attributed these observations to recent activity along an unmapped fault. Although their study (Wobus et al., 2003) supports a relationship between differential uplift rates and hillslope gradients, the gradients in the low-uplift region are significantly lower than what would be expected for threshold hillslopes. Because the hillslopes in our field area appear to be at their threshold angle, their gradients will depend only on rock-mass strength and climate (Carson, 1976) and will not be sensitive to rates of uplift and denudation.

[1]GSA Data Repository item 2004101, Figure DR1, interpolated precipitation map, is available online at www.geosociety.org/pubs/ft2004.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

At least two mechanisms, likely operating together, could explain the decrease in mean slope angle with increasing mean annual rainfall. First, the regolith and bedrock of hillslopes in the wetter regions are subjected to more frequent and higher positive pore-water pressures, which decrease slope stability (Carson, 1976; Hoek and Bray, 1977; Terzaghi, 1962). Of the two main types of landslides, shallow and deep-seated, it is most likely the latter that are responsible for controlling the hillslope angles. Although shallow landslides are ubiquitous throughout the area (Gabet et al., 2004), and Pratt et al. (2002b) inferred a dramatic increase in shallow landsliding due to enhanced precipitation at 7000 yr B.P., the frequency of these failures is limited by the production of regolith. In contrast, a deep-seated landslide with a failure plane extending through the bedrock is not limited by regolith production and can reshape a mountainside in a single failure (Selby, 1993; Terzaghi, 1962). Large landslides in the Himalayas are not uncommon (Fort, 1987; Shroder, 1998; Shroder and Bishop, 1998; Yamanaka and Iwata, 1982), and the time scale of these deep-seated failures is consistent with seasonal rainfall amounts (Iverson, 2000). Nonetheless, our results imply a sensitivity of bedrock landsliding to MAR that is astonishing considering the hydrological complexity of bedrock flow paths. Second, White and Blum (1995) showed that rates of chemical weathering increase linearly with precipitation and that this effect is particularly important in warm climates (e.g., central Nepal). Because chemical weathering reduces rock-mass strength (Carson, 1976; Selby, 1993; Terzaghi, 1962), a decline in mean hillslope angles may also reflect more intense weathering (Kirkby, 1973).

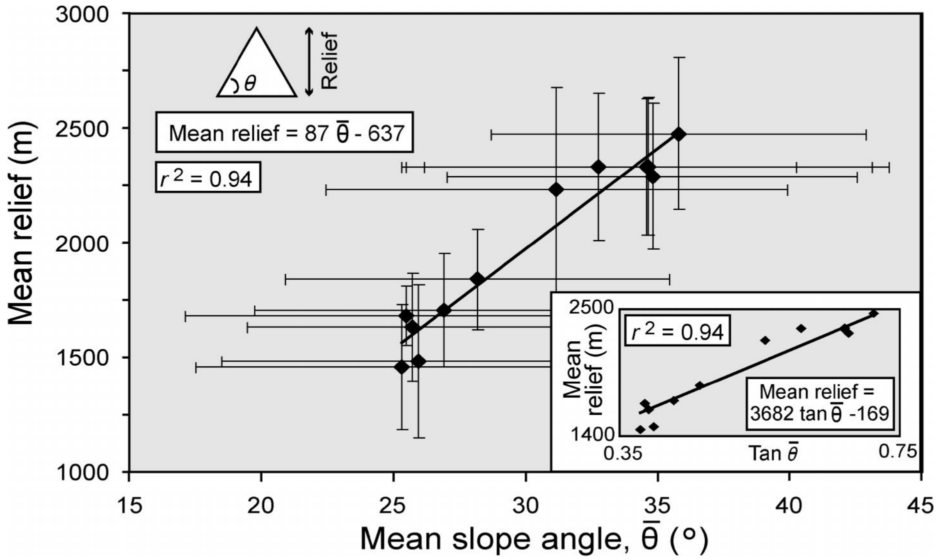

Figure 3. Mean relief vs. mean hillslope angle. Relief was determined as difference between maximum and minimum elevations measured over 5-km-diameter moving window. Slope and relief data are grouped according to rainfall bins as in Figure 2; error bars represent 1σ. If relief were limited by rock-mass strength, relief would decrease with increasing hillslope angles. Inset: Relief vs. tangent of mean hillslope angle; *y*-intercept of best-fit linear regression is statistically indistinguishable from 0 (*t*-test, 95% confidence interval), thus supporting approximation of mountain ranges as isosceles triangles (i.e., tan $\theta = R/B$, where *R* is relief and *B* is constant proportional to width of triangle's base and size of analysis window).

As previously noted, the hillslope angles are sensitive to mean annual rainfall between 1800 and 4000 mm but, at both ends of the rainfall range, slope angles are approximately constant. Rainfall in the lower range (MAR $<$ 1800 mm) may be insufficient to generate pore pressures needed to trigger large landslides or to drive chemical weathering rates high enough to significantly weaken the bedrock; the slope angles, then, may be solely a function of the unweathered rock-mass strength. For MAR $>$ 4000 mm, chemical weathering rates may be at a maximum, and the hillslopes may be saturated such that any additional rainfall is superfluous.

A fundamental implication of this study is that the adjustment of threshold slope angles to MAR decouples climate from hillslope erosion rates. The angle of threshold hillslopes will adjust to precipitation such that hillslope erosion and the lowering of ridge crests are not dependent on climate, but are driven solely by valley incision. By extension, the adjustment of threshold slope angle to MAR complicates attempts to correlate erosion rates with relief (e.g., Montgomery and Brandon, 2002). The positive linear relationship between the tangent of the mean slope angle and relief (Fig. 3, inset) suggests that the mountains in our field area may be approximated as isosceles triangles. Furthermore, the positive linear relationship between mean slope angle and relief (Fig. 3) suggests that, for this study area, rock-mass strength is not a controlling factor on relief (cf. Schmidt and Montgomery, 1995). Under these conditions, if mean slope angle is dependent on annual rainfall and valley spacing is approximately uniform, then relief must also depend on annual rainfall. Therefore, studies that express erosion rates as a function of relief (e.g., Montgomery and Brandon, 2002) may need to take into account the role that a precipitation gradient may play in the spatial distribution of topography. Our results predict that a precipitation gradient across a tectonically active mountain range in topographic steady state will create spatial differences in mean slope and relief, despite spatially uniform erosion rates.

The conclusion that hillslope relief may be strongly dependent on climatic characteristics has implications for the effects of climate change on the evolution of mountainous terrain. The relief of triangular-shaped mountains with threshold-angle hillslopes is simply a function of mean hillslope angle and valley spacing. Previous studies suggest that valley spacing is set early in the development of mountain ranges (Hovius et al., 1998) and scales with range width (Hovius, 1996; Talling et al., 1997). Additionally, Gregory (1976) found that drainage density is relatively constant for MAR $>$ 1500 mm. In any case, the time necessary for a hillslope to adjust to a change in MAR is likely much shorter than the time necessary to change the spacing of valleys. An increase in rainfall will therefore lead to the reduction of hillslope relief as hillslopes respond by failing and relaxing to shallower, more stable angles (Fig. 4A). This hillslope response is strongly supported by evidence indicating that the failure of large landslides in the northwest Himalayas during the late Pleistocene and middle Holocene coincided with periods of increased precipitation (Bookhagen et al., 2003). Our data (Fig. 2) suggest that a doubling of MAR from 2000 mm to 4000 mm would result in a 33% decrease in relief between valley and ridge crest; this reduction in relief would lead to a similar decrease in the topographic mass (after the failed material is removed), which should have important geodynamic implications. In contrast, a decrease in rainfall will lead to relief production. If we assume that the valleys continue to be lowered through incision of the bedrock channels, the drier conditions will allow the slopes to steepen and lengthen until the hillslopes reach a new threshold slope an-

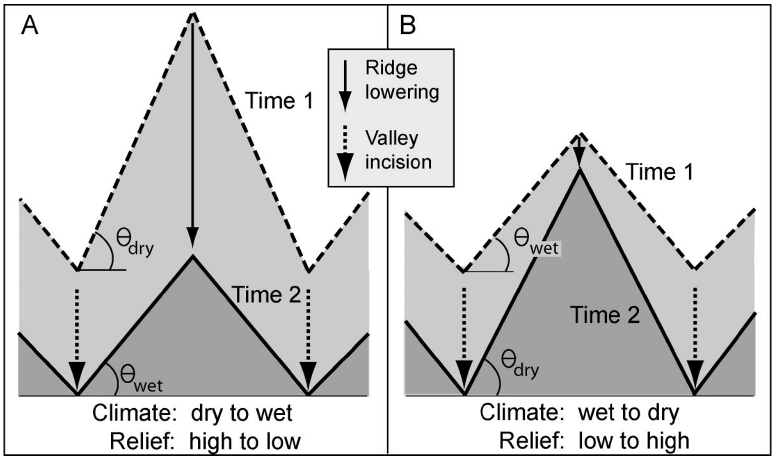

Figure 4. A: Relief reduction during change from dry climate to wet climate. Threshold slope angle is shallower in wet conditions. To allow comparison with B, lowering of valleys by bedrock-channel incision is indicated, although this condition is not necessary for relief reduction. Rate of relief reduction is determined by magnitude and frequency of landsliding. B: Relief production during change from wet climate to dry climate. Threshold angle is steeper in dry conditions such that, as valleys are lowered through incision of bedrock channels, elevation difference between ridge crest and valley bottoms increases. Rate of relief production is set by rate of bedrock-channel incision.

gle (Fig. 4B). By analyzing the relationship between climate and the longitudinal profile of rivers, Whipple et al. (1999) came to similar conclusions regarding changes in precipitation and basin relief. However, if hillslopes adjust to climate via deep-seated landslides, lower-order channels, potentially significant sources of basin relief, may be superficial features that have little consequence on the topographic evolution of the range.

CONCLUSION

Rainfall data from the Annapurna region of Nepal, combined with topographic analysis, suggest an inverse relationship between mean annual rainfall and mean slope angle. Higher pore pressures and higher rates of chemical weathering may decrease slope stability and lead to gentler hillslopes in the wetter regions. Because the region's mountains are roughly triangular and the rock-mass strength does not appear to limit relief, changes in slope angle lead to changes in hillslope relief such that an increase in rainfall reduces relief and a decrease in rainfall produces relief.

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