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Frequency-dependent landscape response to climatic forcing

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[1] Whereas the existence of pronounced orbitally controlled periodicities is a major feature of Earth climate, its impact on landscape dynamics remains poorly understood. We use a Landscape Evolution Model (LEM) to systematically investigate the response of landscapes to a range of periodic oscillations in precipitation. The resulting sediment-flux evolution displays a pronounced sensitivity to the period of the input precipitation signal, such that, for a given erodibility, a specific periodicity maximizes the amplitude of the response. This optimal period of "resonance" scales as the inverse of the erodibility, but is progressively filtered out of the response when the intensity of hillslope diffusion increases. This frequency-dependent landscape behavior displayed by our model provides a mechanistic perspective on Molnar's (2004) proposition that ubiquitous changes in Late Cenozoic continental denudation could result directly from modifications in the spectral content of the climatic signal.

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1. Introduction

[2] Climate and its variations through geological time are believed to exert a fundamental influence on landscape evolution and erosion rates [*Kuhlemann et al.*, 2002; *Whipple*, 2009; *Clift*, 2010]. The Late Cenozoic Era is characterized by major climate changes [*Zachos et al.*, 2001] with (1) a generalized cooling associated with the development of Northern Hemisphere ice sheets and (2) pronounced periodic fluctuations directly reflecting the oscillating nature of the orbital parameters and resulting insolation. Whether this progressive shift toward cooler climate was associated with a coeval geomorphic response and a worldwide change in denudation is a current matter of debate. Due to the non-unique interpretations of sedimentary records and the diversity of factors that might influence continental denudation and cause fluctuations through time, no currently accepted consensus exists[*Métivier et al.*, 1999; *Clift*, 2006; *Charreau et al.*, 2011]. It has been proposed, however, that changes in the periodicity of the climatic forcing may represent a common mechanism that could lead to a synchronous geomorphic response in diverse regions of the globe [*Zhang et al.*, 2001; *Molnar*, 2004]. The widely identified shift from the dominance of 40 to 100 kyr oscillations at ~700 ka [*Ruddiman et al.*, 1986] could be an example of such a fundamental modification of the periodicity of the climatic forcing (Figure 1).

[3] Several studies have already investigated landscape response to changes in the nature of climatic parameters, in terms of either amplitude or temporal patterns [*Tucker and Slingerland*, 1997; *Allen and Densmore*, 2000; *Coulthard et al.*, 2000; *Meade*, 2005]. However, even if some studies suggest that orbital cycles are in part present in the detrital fluxes out of the continent [*Tachikawa et al.*, 2011], the specific influence of the frequency content of the input climatic signal has received less attention, despite being one of the most salient characteristics of climate evolution at geological time scales.

[4] In this study, we use numerical modeling to investigate the influence of diverse periodicities of climatic oscillation on the evolution of the climate/landscape system. After presenting the main characteristics of our model setup, we analyze how different frequencies in climatic forcing lead to contrasting responses in terms of sediment export from the landscape and how parameters such as erodibility or diffusivity modulate these responses.

2. Approach and Methods

[5] We investigate the problem of the sensitivity of landscapes to the frequency content of the climatic signal using the numerical model of surface processes CHILD [*Tucker et al.*, 2001]. We use a simplified model setup in which detachment-limited fluvial incision, which is defined as proportional to specific stream power, and linear hillslope diffusion act upon a block of constantly uplifted topography (additional details on our model setup are provided in the Supporting Information).

[6] A one-dimensional representation of the evolution of elevation z with time t and space x is given by the following partial differential equation:

$$\frac{\partial z}{\partial t} = U - KQ^m \left|\frac{\partial z}{\partial x}\right|^n + D\frac{\partial^2 z}{\partial x^2}, \tag{1}$$

where U is the uplift rate, K is the erodibility coefficient, Q is discharge (equal to the product of annual precipitation P and upstream drainage area A), and D is the diffusion coefficient. If we assume that fluvial incision is proportional to specific stream power, then the discharge and slope exponents are $m = 0.5$ and $n = 1$.

All Supporting Information may be found in the online version of this article.

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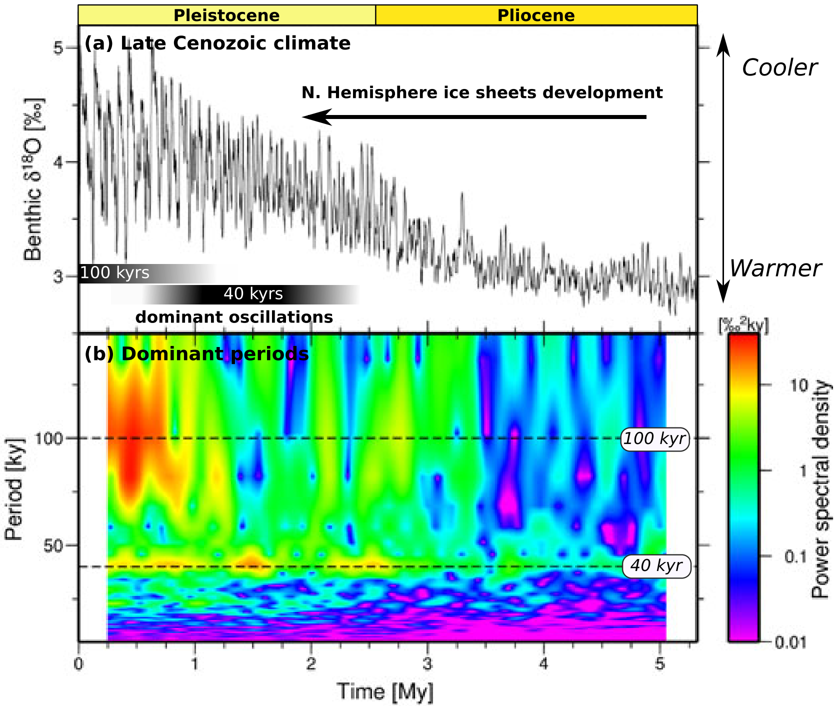

Figure 1. (a) Compilation of variations in oxygen isotopic composition of benthic foraminifers over the last 5 Myr [*Lisiecki and Raymo*, 2005], illustrating the progressive cooling and amplification of climatic oscillations during the Late Cenozoic. (b) Periodogram of the above signal showing the change in spectral content and the recent shift from ~40 to ~100 kyr oscillations. Continental precipitation has also been shown to display such periodic variations, which are mostly reflecting an orbital control, through insolation, of the climatic system [*Cruz et al.*, 2005; *Wang et al.*, 2008].

[7] By introducing the characteristic horizontal L and vertical H length scales, as well as a characteristic time scale T, we can define the following non-dimensional variables and parameters: $z' = z/H$, $x' = x/L$, $t' = t/T$, $A' = A/L^2$, and $U' = UT/H$. Then, the corresponding non-dimensional form of equation (1) is

$$\frac{\partial z'}{\partial t'} = U' - KP^m TH^{n-1} L^{2m-n} A'^m \left|\frac{\partial z'}{\partial x'}\right|^n + \frac{DT}{L^2}\frac{\partial^2 z'}{\partial x'^2}, \qquad (2)$$

From equation (2), we can extract $T_f = 1/(KP^m H^{n-1} L^{2m-n})$ and $T_d = L^2/D$, which represent the characteristic times for fluvial and diffusion processes, respectively. The ratio between these two characteristic times yields the Péclet number similar to that introduced by *Perron et al.* [2008]:

$$Pe = \frac{KP^m H^{n-1} L^{2(m+1)-n}}{D} \qquad (3)$$

For the case in which channel incision is directly proportional to specific stream power, these relations simplify as $T_f = 1/(KP^{1/2})$ and $Pe = KP^{1/2}L^2/D$.

[8] In a typical model run, we first allow topography and sediment flux to reach steady state under constant precipitation. Then, we introduce sinusoidal oscillations of precipitation around an average value (Figure 2b). Note that, in the results presented here, these oscillations have a constant amplitude of ±10% around a mean of 1 m/yr, irrespective of frequency (Figures S3 and S4). This amplitude of variability is a conservative estimate when compared to reported ranges of variations for site-specific paleo-rainfall over the Quaternary [*Maher and Thompson*, 1995].

[9] In using a deliberately simple model of an evolving landscape, our aim is to discover the logical consequences of basic formulations for hillslope and channel evolution under conditions of cyclic variation in precipitation and runoff. In particular, we study whether this theory implies specific frequency-dependent behavior, and, if so, what sets the characteristic response magnitude and time scale.

3. Results

[10] We test the response of the landscape to a range of precipitation forcing periods and observe the resulting impact on sediment flux. By calculating the amplitude of the peak-to-peak oscillation in sediment flux as a fraction (expressed in percent) of the steady state or average flux (Figure 2b), we evaluate the importance of this impact.

[11] We submit our reference model (Figure 2c) to various precipitation forcings whose periods span three orders of magnitude: 5 kyr to 5 Myr. This sinusoidal precipitation forcing induces a similar time evolution of runoff which transmits the climatic signal to the geomorphic system. We observe an increase up to ~15% of the response amplitude at ~450 kyr followed by a decrease for longer periods, such that we see almost no response at periods exceeding a few million years. If we ignore the influence of hillslope processes, this model response is largely independent of catchment size (Figure S2), such that, as long as we consider fluvial incision to be driven by specific stream power, this behavior can be extrapolated to larger basins.

[12] This sensitivity to the period of forcing depends on a combination of different processes. First, if oscillation periods are significantly shorter than the characteristic

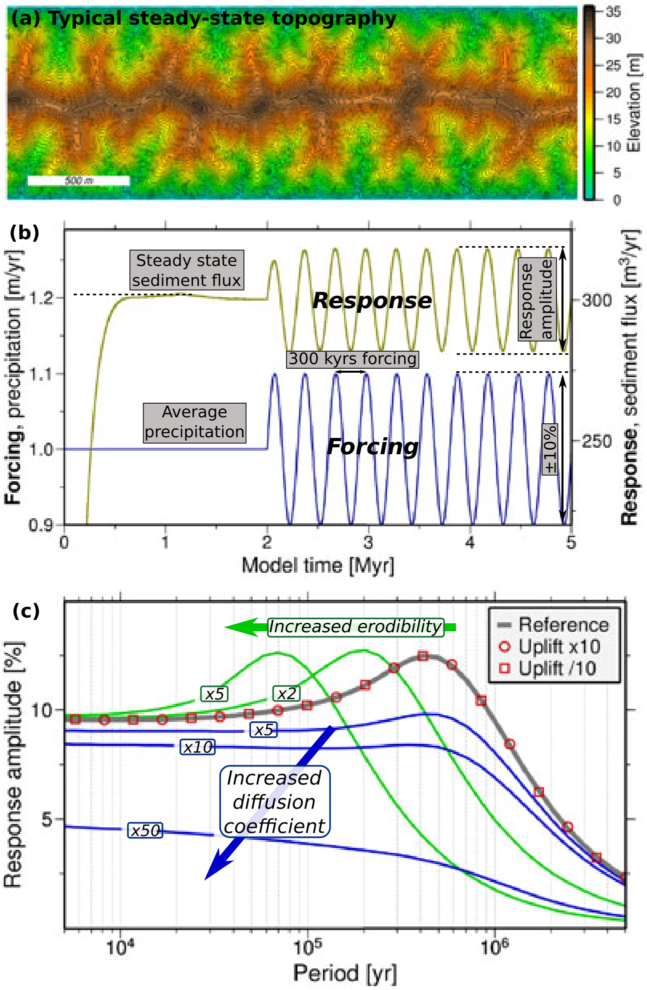

Figure 2. (a) Example of topography obtained at steady state with the following parameters : uplift rate $U = 0.1$ mm/yr, erodibility $K = 2.4 \times 10^{-5}$ m$^{-0.5}$yr$^{-0.5}$, precipitation $P = 1$ m/yr, diffusion coefficient $D = 0.01$ m^2/yr. (b) Example of time evolution, where the landscape is allowed to reach steady state under constant precipitation, before oscillations are introduced (300 kyr period and ±10% amplitude). (c) Response amplitude for different periodicities of precipitation oscillations. Thick dark gray line is the reference model (same parameters as Figure 2b). Red squares and circles are model results where the uplift rate has been divided or multiplied by a factor 10, respectively. Green curves are model results where the erodibility has been increased with respect to the reference model. Blue curves are model results where the diffusion coefficient has been increased with respect to the reference model.

response time of landscapes, the erosion response is only local, with no global adjustment to changing conditions through the propagation of incision waves over the full extent of the landscape (Figure S1). Second, at intermediate periods, these perturbations have enough time to propagate along the whole fluvial network during one climatic cycle, thereby maximizing the landscape's response to the forcing as shown by the maximum response amplitude (Figure S5). Finally, for very long periods, the forcing oscillations are so slow that the landscape is always adjusted to the precipitation conditions and in steady state, with no significant perturbation propagating across the river network (Figure S1). In this case, the output sediment flux is always equal to the uplifted rock volume and constant in time, which corresponds to an amplitude response of 0%.

[13] For a given landscape, a specific period of climatic oscillations exists that will maximize the erosional response to the forcing, in a similar way to the period of vibration corresponding to the normal mode of a mechanical oscillator. Notably, the response is independent of the imposed uplift rate (Figure 2c), which sets the steady state value of the sediment flux out of the landscape, but does not affect the relative amplitude of the sediment flux variability around this steady state value. When increasing the diffusion coefficient, hillslope diffusive processes progressively dominate over fluvial advection, and the maximum amplitude period is removed from the response spectrum.

[14] Variation of the erodibility coefficient also appears to exert a major control on the sensitivity of the landscape to oscillating precipitation forcing (Figure 2c), as implied by the dimensional analysis above. We observe that increasing the erodibility coefficient shifts the maximum response amplitude toward shorter periods, but leaves the amplitude of the maximum (∼15%) unchanged. Such behavior is consistent with the influence of erodibility on the response time of the landscape: greater erodibility corresponds to shorter responses.

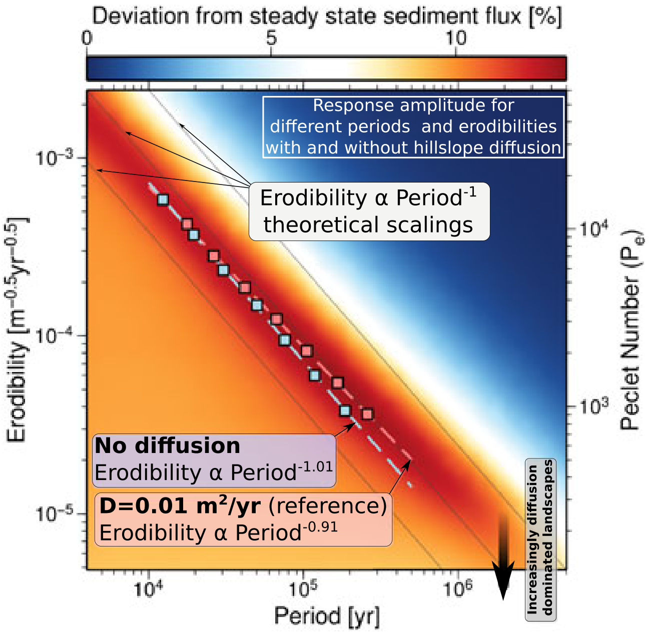

Figure 3. Amplitude of the sediment flux response with respect to the steady state value associated with every combination of erodibility and forcing period (other parameters are similar to Figure 2). The right-hand side vertical axis is the Péclet number calculated for each erodibility according to equation (3). Thin oblique lines represent theoretical inverse relationships between period and erodibility. Red squares indicate the position of the period of maximum response for selected erodibilities. Dashed red line is a power-law fit through these results. Blue squares indicate the position of the period of maximum response for selected erodibilities when hillslope diffusion is neglected. Dashed blue line is a power-law fit through these results.

[15] In order to investigate this behavior in more detail, we perform a systematic exploration of the sensitivity of the system to the erodibility coefficient and the forcing period (Figure 3). We observe a well-defined band of maximum response ($\sim$15%) that appears as a continuous trend in the period-erodibility space. Equation (2) predicts that a characteristic fluvial response time for the landscape should be proportional to the inverse of the erodibility coefficient. Our results with a diffusion coefficient $D = 0.01$ m^2/yr depart slightly from this scaling (exponent –0.91, light red squares in Figure 3) due to contribution of constant linear hillslope diffusion in our model. Removing hillslope diffusion yields a scaling that closely matches the theoretical prediction (exponent –1.01, light blue squares in Figure 3).

4. Discussion and Conclusions

[16] We have explored the response of a model landscape to oscillating changes in precipitation by sweeping through a range of periods consistent with the spectral content of the orbitally controlled Cenozoic climatic signal (tens to hundreds of thousand years). One of the most notable aspects of this response appears to be the existence, for a given landscape, of a specific forcing periodicity that maximizes the amplitude of the corresponding oscillation of the sediment flux. The first-order influence of erodibility on landscape response could lead to drastically different impacts due to modifications of the spectral content of the climatic signal, such as the Late Cenozoic shift from 40 to 100 kyr periodicities (Figures 1 and S6). Landscapes carved in highly resistant bedrock with "resonance" periods of several hundreds of thousand years to million years would display almost no sensitivity to this change, whereas in softer lithologies, closer to the tipping point, a frequency change could trigger a significant increase or decrease in the amplitude of the sediment flux variations. On the other hand, landscapes with low Péclet numbers show almost no sensitivity to the dominant period of the imposed precipitation forcing. When propagating over diffusive hillslopes, the perturbations originating from the fluvial network are progressively dampened, such that landscapes where diffusion is dominant over fluvial processes are very efficient at filtering out the imposed oscillations [*Furbish and Fagherazzi*, 2001].

[17] Our model setup consists of a very simplified representation of denudation processes and ignores important aspects of the dynamics of geomorphic systems that have received wide attention recently, such as threshold effects [*Snyder et al.*, 2003; *DiBiase and Whipple*, 2011], the stochastic nature of precipitation distribution through time [*Tucker and Bras*, 2000; *Lague et al.*, 2005; *Molnar et al.*, 2006], nonlinearity in fluvial and hillslope processes [*Tucker and Whipple*, 2002; *Roering et al.*, 2007], or influences of climate change on diffusivity [*Anderson et al.*, 2012]. However, the use of (1) specific stream power as a proxy for the efficiency of fluvial processes and (2) a linear relationship between sediment flux and hillslope gradient remain simple and efficient ways to describe the dynamics of soil-mantled landscapes. In addition, our detachment-limited approach does not account for transient storage of sediments in the landscape. Recent studies focused on the interplay between climatic signals and sediment transport have proposed contrasting views on the ability of transport limited systems to transmit high frequency signals [*Jerolmack and Paola*, 2010; *Simpson and Castelltort*, 2012]. Sediment storage can act in two different ways: as a buffer that will filter out the rapid fluctuations in sediment transport such that they become imperceptible when looking at the sediment flux out of the landscape, but also as a threshold-driven process, where amplified oscillations could trigger rapid flushing of previously trapped sediments. Which of these two tendencies will prevail may be different from one geomorphic environment to another, and understanding how the spectral content of the climatic signal is transmitted or not in more complex situations will require further investigation.

[18] The nature of Late Cenozoic changes in continental denudation is currently much debated, both because the exact mechanisms for such changes remain unclear, and because the very existence of a worldwide recent increase in denudation is questioned [*Willenbring and von Blanckenburg*, 2010]. Our study suggests that the use of a simple and widely used formulation for denudation implies that the modeled landscapes behave as forced oscillators with marked resonance-like phenomena. These resonant responses can be activated, in terms of sediment export, by particular climatic frequencies that are transmitted through changes in precipitation regime and that are in the range of orbitally controlled climatic oscillations. *Molnar* [2004] proposed that a change in the periodic nature of the climatic forcing imposed on landscapes could be a possible explanation for an eventual worldwide change in denudation affecting a range of different environments. In our simulations, a change in precipitation frequency significantly affects the amplitude of the sediment flux oscillations, but it should be noted that the net sediment flux averaged over several cycles is constant and equal to the volume of rock uplifted by tectonic processes. Thus, this frequency-dependent behavior of landscapes cannot be the sole explanation for an increase in denudation at the end of the Cenozoic, but we suspect that when combined with neglected processes in our analysis, such as nonlinear and threshold-driven sediment transport laws, it might leave a distinct signature in sedimentary records [*Armitage et al.*, 2011; *Simpson and Castelltort*, 2012].

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References

Allen, P. A., and A. L. Densmore (2000), Sediment flux from an uplifting fault block, *Basin Res.*, *12* (3-4), 367–380, doi:10.1111/j.1365-2117.2000.00135.X.

Anderson, R. S., S. P. Anderson, and G. E. Tucker (2012), Rock damage and regolith transport by frost: An example of climate modulation of the geomorphology of the critical zone, *Earth Surf. Process. Landforms*, p. in press , doi:10.1002/esp.3330.

Armitage, J. J., R. A. Duller, A. C. Whittaker, and P. A. Allen (2011), Transformation of tectonic and climatic signals from source to sedimentary archive, *Nature Geosci.*, *4*(4), 231–235, doi:10.1038/ngeo1087.

Charreau, J., et al. (2011), Paleo-erosion rates in Central Asia since 9 Ma: A transient increase at the onset of Quaternary glaciations? *Earth Planet. Sci. Lett.*, *304*(1-2), 85–92, doi:10.1016/j.epsl.2011.01.018.

Clift, P. D. (2006), Controls on the erosion of Cenozoic Asia and the flux of clastic sediment to the ocean, *Earth Planet. Sci. Lett.*, *241*(3-4), 571–580, doi:10.1016/j.epsl.2005.11.028.

Clift, P. D. (2010), Enhanced global continental erosion and exhumation driven by Oligo-Miocene climate change, *Geophys. Res. Lett.*, *37*(9), L09,402, doi:10.1029/2010GL043067.

Coulthard, T. J., M. J. Kirkby, and M. G. Macklin (2000), Modelling geomorphic response to environmental change in an upland catchment, *Hydrol. Process.*, *14* (11-12), 2031–2045, doi:10.1002/1099-1085(20000815/30)14:11/12<2031::AID-HYP53>3.0.CO;2-G.

Cruz, F. W., S. J. Burns, I. Karmann, W. D. Sharp, M. Vuille, A. O. Cardoso, J. A. Ferrari, P. L. S. Dias, and O. Viana (2005), Insolation-driven changes in atmospheric circulation over the past 116,000 years in subtropical Brazil, *Nature*, *434*(7029), 63–66, doi:10.1038/nature03365.

DiBiase, R. A., and K. X. Whipple (2011), The influence of erosion thresholds and runoff variability on the relationships among topography, climate, and erosion rate, *J. Geophys. Res.*, *116*(F4), F04,036, doi:10.1029/2011JF002095.

Furbish, D. J., and S. Fagherazzi (2001), Stability of creeping soil and implications for hillslope evolution, *Water Resour. Res.*, *37* (10), 2607–2618, doi:10.1029/2001WR000239.

Jerolmack, D. J., and C. Paola (2010), Shredding of environmental signals by sediment transport, *J. Geophys. Res.*, *37* (19), L19,401, doi:10.1029/2010GL044638.

Kuhlemann, J., W. Frisch, B. Székely, I. Dunkl, and M. Kázmér (2002), Post-collisional sediment budget history of the Alps: Tectonic versus climatic control, *Int. J. Earth Sci.*, *91*(5), 818–837, doi:10.1007/s00531-002-0266-y.

Lague, D., N. Hovius, and P. Davy (2005), Discharge, discharge variability, and the bedrock channel profile, *J. Geophys. Res.*, *110*(F4), F04,006, doi:10.1029/2004JF000259.

Lisiecki, L. E., and M. E. Raymo (2005), A Pliocene-Pleistocene stack of 57 globally distributed benthic δ^{18}O records, *Paleoceanography*, *20*(1), PA1003, doi:10.1029/2004PA001071.

Maher, B. A., and R. Thompson (1995), Paleorainfall reconstructions from pedogenic magnetic susceptibility variations in the Chinese loess and paleosols, *Quaternary Res.*, *44* (3), 383–391, doi:10.1006/qres.1995.1083.

Meade, B. J. (2005), Orogen evolution in response to oscillating climate, *Eos Trans. AGU , Fall Meet. Suppl.*, *86*(52), H33F–03.

Métivier, F., Y. Gaudemer, P. Tapponnier, and M. Klein (1999), Mass accumulation rates in Asia during the Cenozoic, *Geophys. J. Int.*, *137* (2), 280–318, doi:10.1046/j.1365-246X.1999.00802.X.

Molnar, P. (2004), Late Cenozoic increase in accumulation rates of terrestrial sediment—How might climate change have affected erosion rates? *Annu. Rev. Earth Planet. Sci.*, *32*, 67–89, doi:10.1146/annurev.earth.32.091003.143456.

Molnar, P., R. S. Anderson, G. Kier, and J. Rose (2006), Relationships among probability distributions of stream discharges in floods, climate, bed load transport, and river incision, *J. Geophys. Res.*, *111*(F2), F02,001, doi:10.1029/2005JF000310.

Perron, J. T., W. E. Dietrich, and J. W. Kirchner (2008), Controls on the spacing of first-order valleys, *J. Geophys. Res.*, *113*(F4), F04,016, doi:10.1029/2007JF000977.

Roering, J. J., J. T. Perron, and J. W. Kirchner (2007), Functional relationships between denudation and hillslope form and relief, *Earth Planet. Sci. Lett.*, *264*(1-2), 245–258, doi:j.espl.2007.09.035.

Ruddiman, W., M. Raymo, and A. McIntyre (1986), Matuyama 41,000-year cycles: North Atlantic Ocean and Northern Hemisphere ice sheets, *Earth Planet. Sci. Lett.*, *80*(1-2), 117–129.

Simpson, G., and S. Castelltort (2012), Model shows that rivers transmit high-frequency climate cycles to the sedimentary record, *Geology*, *40*(12), 1131–1134, doi:10.1130/G33451.1.

Snyder, N. P., K. X. Whipple, G. E. Tucker, and D. J. Merritts (2003), Importance of a stochastic distribution of floods and erosion thresholds in the bedrock river incision problem, *J. Geophys. Res.*, *108*(B2), 2117, doi:10.1029/2001JB001655.

Tachikawa, K., O. Cartapanis, L. Vidal, L. Beaufort, T. Barlyaeva, and E. Bard (2011), The precession phase of hydrological variability in the Western Pacific Warm Pool during the past 400 ka, *Quaternary Sci. Rev.*, *30*(25-26), 3716–3727, doi:10.1016/j.quascirev.2011.09.016.

Tucker, G. E., and R. L. Bras (2000), A stochastic approach to modeling the role of rainfall variability in drainage basin evolution, *Water Resour. Res.*, *36*(7), 1953–1964, doi:10.1029/2000WR900065.

Tucker, G. E., and R. Slingerland (1997), Drainage basin responses to climate change, *Water Resour. Res.*, *33* (8), 2031–2047, doi:10.1029/97WR00409.

Tucker, G. E., and K. X. Whipple (2002), Topographic outcomes predicted by stream erosion models: Sensitivity analysis and intermodel comparison, *J. Geophys. Res.*, *107* (B9), 2179, doi:10.1029/2001JB00162.

Tucker, G. E., S. T. Lancaster, N. M. Gasparini, R. L. Bras, and S. M. Rybarczyk (2001), An object-oriented framework for distributed hydrologic and geomorphic modeling using triangulated irregular networks, *Comput. Geosci.*, *27* (8), 959–973, doi: 10.1016/S0098-3004(00)00134-5.

Wang, Y., H. Cheng, R. L. Edwards, X. Kong, X. Shao, S. Chen, J. Wu, X. Jiang, X. Wang, and Z. An (2008), Millennial- and orbital-scale changes in the East Asian monsoon over the past 224,000 years, *Nature*, *451*(7182), 1090–1093, doi:10.1038/nature06692.

Wessel, P., and W. H. F. Smith (1998), New, improved version of generic mapping tools released, *Eos. Trans. AGU*, *79*(47), 579.

Whipple, K. X. (2009), The influence of climate on the tectonic evolution of mountain belts, *Nature Geosci.*, *2*(2), 97–104, doi:10.1038/ngeo413.

Willenbring, J. K., and F. von Blanckenburg (2010), Long-term stability of global erosion rates and weathering during late-Cenozoic cooling., *Nature*, *465*(7295), 211–214, doi:10.1038/nature09044.

Zachos, J., M. Pagani, L. Sloan, E. Thomas, and K. Billups (2001), Trends, rhythms, and aberrations in global climate 65 Ma to present., *Science*, *292*(5517), 686–693, doi:10.1126/science.1059412.

Zhang, P., P. Molnar, and W. R. Downs (2001), Increased sedimentation rates and grain sizes 2-4 Myr ago due to the influence of climate change on erosion rates, *Nature*, *410*, 891–897, doi:10.1038/35073504.