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Temporal buffering of climate-driven sediment flux cycles by transient catchment response

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ABSTRACT

The marine sedimentary record can exhibit a systematic cyclicity that is consistent with climate variability driven by Milankovitch-scale forcing. Milankovitch-band cyclicity is widely interpreted in the hemipelagic and pelagic sediments of the marine realm, and in terrestrial paleoenvironments has been observed in lacustrine sediments, soils and river floodplain successions. It remains unclear, however, if and how mountain catchments, as a primary sediment source, respond to these high frequency ($<10^6$ yr) climatic cycles, and whether particulate sediment flux signals can be expected to be recorded in the clastic sedimentary record of adjacent basin-fills. Recent field and theoretical studies suggest that mountain catchments respond transiently to high frequency forcing, and so sediment discharge from the catchment is a non-linear function of forcing variables. Using a catchment–basin model, we demonstrate that climate-driven cyclicity in particulate sediment discharge is strongly damped when the period of climate variability is shorter than the response timescale of the eroding landscape. Given that the response timescale of landscapes is of the order of 10^6 yr, and that Milankovitch-driven climate cyclicity is of the order of 10^4–10^5 yr, it is likely that climate-driven perturbation of upland catchments at these periods will be strongly damped by transient landscape behaviour. Our results therefore suggest that stratigraphy built by particulate fluxes from upland catchments, and long-term trends in the sediment delivery to the ocean, may be relatively insensitive to short-term climate variability.

1. Introduction

There is widespread acknowledgement of the impact of orbitally forced (Milankovitch) climate variations on Earth, principally recorded in the sedimentary record (Päike et al., 2006; Strasser et al., 2006; Hilgen, 2007; Hilgen et al., 2010). The occurrence of Milankovitch-period cyclicity (ca. 20, 40, 100, and 400 kyr) in marine stratigraphy is widely recognized, particularly in pelagic and hemipelagic environments, where the cyclicity is manifested in variations in the concentrations of the skeletons of planktonic micro-organisms (calcareous or siliceous; Beaufort et al., 1997), detrital silts and clays, and volcanic and other wind-blown dust, as well as in stable isotope ratios (Emiliani, 1955; Imbrie et al., 1984) and trace element abundance (Decisneros and Vera, 1993; Elderfield et al., 2012). In these environments, such variations reflect regular changes in either organic productivity, dilution by detrital components, or chemical dissolution, oxidation and diagenetic overprinting, or a combination of these factors (Fischer, 1986). Some pelagic–hemipelagic and shelfal marine sedimentary sequences have been subjected to time series analysis of variations in bedding thickness to confirm Milankovitch-band cyclicity (Fischer and Schwarzacher, 1984; Weedon, 1989; Weedon and Jenkyns, 1990; Hilgen et al., 2010). In all these cases, the orbital control of sedimentary rhythms is overwhelmingly by a direct impact on the depositional environment of changing climate and seasonality, with little mediation by sediment transport systems. Cyclicity in shallow water marine environments, such as carbonate platforms, is more controversial, partly because biostratigraphic resolution is inferior to that in pelagic environments, partly that erosional gaps are more likely, and partly that sedimentary rhythms may reflect sediment advection in complex, heterogeneous depositional mosaics. The classic succession of the Middle Triassic Latemar carbonate platform of the Alps, for instance, has been interpreted as an excellent example of Milankovitch-band orbital forcing (Hardie et al., 1986; Hinnov and Goldhammer, 1991; Zuhlke et al., 2003), backed up by spectral analysis

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(Preto et al., 2001), whereas improved biostratigraphy and radiometric dating (Brack et al., 1996; Mundil et al., 1996) make an orbital forcing interpretation problematical.

In terrestrial environments, Milankovitch-scale cyclicity is recorded in lake successions as cycles in 'non-glacial varves' comprising both organic–siliciclastic–carbonate sediments, as in the Eocene Green River Formation of Utah and Wyoming (Bradley, 1929), and evaporites, as in the Triassic Lockatong Formation of the Newark rift of New York–New Jersey (Van Houten, 1964; Olsen, 1984) and the Jurassic Todilto Formation of New Mexico (Anderson and Kirkland, 1960). Climatic influences attributed to Milankovitch band forcing are also recognized in trends in aridification (Dupont-Nivet et al., 2007), strengthening and weakening of monsoonal circulation (Xiao et al., 2010) and in the stacking of paleosols in floodplain successions (Aziz et al., 2008). Once again, in all these cases the influence of climate variability is to exert a direct control on the nature of the depositional environment through changing hydrology and chemistry.

A key question is whether external ('allogenic') orbital forcing can be recognized in more complex sedimentary systems where time-averaged sediment discharges are affected by the transient response of erosional and depositional landscapes to climate perturbations (Allen, 2008a). Milankovitch forcing, for example, has been inferred to explain variations in water and sediment discharge on alluvial fans and in the supply and rate of accumulation of sediment in the deep sea (Van der Zwan, 2002; Waters et al., 2010; Covault et al., 2011), and has been invoked to explain periodic development of anoxia in shallow Cretaceous seas controlled by river input of nutrients (Beckmann et al., 2005).

The difficulty in deciphering high frequency climate variability in continental settings may be due to the buffering of sediment discharge signals within alluvial systems due to the 'downstream dynamics' of intermittent transport and storage (Métivier and Gaudemer, 1999; Castelltort and van der Driessche, 2003; Allen, 2008a, 2008b; Romans et al., 2009; Armitage et al., 2011), which Jerolmack and Paola (2010) refer to as 'shredding'. Such buffering or shredding should smooth out high frequency fluctuations in signals, such as long-term sediment discharge, during propagation from upstream sources through the alluvial system. Large rivers may act as diffusive buffers to sedimentary signals where perturbations are of a period less than the 'intrinsic', 'equilibrium' or 'basin' time scale of the basin (Howard, 1982; Paola et al., 1992; Marr et al., 2000; Densmore et al., 2007; Allen, 2008a). This intrinsic time scale of the basin has the form of a diffusive time scale, which depends on the square of system size and its diffusivity. The intrinsic times for 93 of the world's major rivers are estimated to be between 10^4 and 10^6 yr (Castelltort and van der Driessche, 2003), considerably greater than the periodicity of climatic variability associated with orbital (Milankovitch) forcing. From field studies of relatively short (ca. 10 km) catchments responding to changes in rate of slip on extensional faults in the central Apennines of Italy, footwall landscapes respond transiently over timescales in the order of 10^6 yr by the cutting of upstream-migrating gorges with convex longitudinal profiles (Whittaker et al., 2008). Numerical models of detachment and transport limited systems suggest similar timescales for their response to an instantaneous change in uplift rate or mean annual precipitation (Carretier and Lucazeau, 2005; Densmore et al., 2007).

An alternative, which we address here, is the possibility that output signals of long-term sediment discharge from upland catchments are damped from the 'upstream dynamics' of the coupled response of hillslopes and channels to a periodic external driver (e.g. Snow and Slingerland, 1987; Howard, 1982, 1994). Catchment landscape response may also be coupled to boundary conditions and internal dynamics of down-system depositional regions (Humphrey and Heller, 1995; Carretier and Lucazeau, 2005; Densmore et al., 2007; Pépin et al., 2010), rather than acting independently as source and sink.

We previously showed that the reaction of sediment flux and grain size to a single instantaneous change in tectonic uplift or runoff can be captured by a 1-D transport-limited catchment-fan model (Armitage et al., 2011), the details of which are given in Section 2. We expand on that model by focusing on how the system responds to repeated, cyclical change in climatic forcing, manifested in variations in precipitation (Bar-Matthews et al., 2003; Ruddiman, 2006) and test if it is reasonable to expect the time-integrated stratigraphic archive of clastic sedimentary systems to be a faithful recorder of high-frequency climate change.

Use of a simplified 1-D model is justified since it is not possible to know the detailed 2-D topographic evolution of ancient eroded landscapes. We adopt a 1-D modelling approach in order to understand the primary factors that control the sediment efflux of mountain catchments, the delivery of sediment to the ocean and the building of stratigraphy, where a complex set of erosional, transport and depositional processes operating over a wide range of spatial and time scales can be distilled into a relatively simple and physically transparent model. In this way the first order relationship between the change in input signal and output record can be better understood. We specifically wish to investigate whether high-frequency climate-driven cyclicity is recorded in down-system continental stratigraphy under conditions of variable catchment dimensions, and amplitude and period of climatic forcing captured as a cyclic variation in precipitation. In this contribution, we describe our physical model and the results of a number of model simulations, and conclude that high-frequency climate variations in the Milankovitch band are damped over time by the slow response time of the catchment relative to the time scale of the forcing.

2. Methods

We use a simple 1-D catchment-fan model based upon that presented in Armitage et al. (2011) (Fig. 1) to explore how a simplified sedimentary system will respond to an oscillating mean annual precipitation from 1 to 2 m yr^{-1}, with periodicities of 100, 400 kyr and 1.2 Myr, representing short and long-eccentricity cycles, as well as the long, ~1.2 Myr eccentricity modulation of climatic precession. Erosion is modelled using time dependent diffusive–concentrative equations, while deposition is calculated by a volume balance assuming a continuity of slope between the two domains. We do not treat deposition with a separate time-dependent equation, as the change in response times between the two systems, if there is one, will lead to internal oscillations in sediment flux (see for example Humphrey and Heller (1995)). While such internal dynamics may exist, we wish to understand if the signal of change in precipitation can be preserved in the sedimentary record; consequently, we do not want to obscure the model results by adding further sources of signal deterioration.

The approach we take to model erosion is to define the simplest set of equations that are capable of capturing both 'diffusive' hillslope processes and the 'concentrative' effects of fluvial processes (Smith and Bretherton, 1972; Simpson and Schlunegger, 2003). We assume that the change in catchment elevation is related to the tectonic uplift and the downstream change in sediment discharge, where erosion is controlled by the capacity of the landscape to transport sediment:

$$\frac{\partial h}{\partial t} = -\frac{\partial q_s}{\partial x} + U(x,t) \tag{1}$$

and the uplift field is taken from the domino fault block model of Anders et al. (1993). Following Smith and Bretherton (1972),