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SYNOPSIS

Evaluating the Impacts of Global Warming on Geomorphological Systems

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INTRODUCTION

Ongoing climate change (global warming) is a major forcing factor on Earth's ecological services including agricultural production, biodiversity, and carbon cycle. Climatic regime and climate change is also a major driver of the dynamics of Earth's geomorphological systems, including its glaciers, rivers, mountains and coasts, especially over longer (10^3–10^5 year) time scales that correspond to climate forcing by orbital cycles. Many studies have considered how geomorphological systems have responded to climate forcing over long time scales, where system responses are approximately in phase with forcing (Lal 2004; Lowe et al. 2008). Over shorter time scales, however, geomorphological systems do not respond in phase with climate forcing, are affected by human (anthropogenic) activity, and yield nonlinear responses that cannot be fully predicted based on their previous behaviour (Perry 2002; Murray et al. 2009). The response of geomorphological systems to climate forcing can be examined by monitoring changes to their morphology and geomorphological processes during the recent past (last <150 years) for which instrumental climate data are available. This comparison allows for a more complete understanding of the relationship between climate forcing and geomorphological response.

Global warming has given a new impetus to studies of climate forcing of geomorphological systems. This is because, despite the ability of global climate models (GCMs) to predict future temperature, precipitation and sea level, they do not consider likely responses of geomorphological (land surface) systems despite there being important feedbacks between surface processes and climate. These feedbacks include variations in snow/ice cover that result in changes to albedo and energy balance; changes in terrestrial ecosystems and land surface erosion that result in changes in carbon storage; and variations in continental weathering that lead to variations in cation flux to the ocean that influences its capacity for carbon dioxide (CO_2) downdraw.

Despite feedbacks being a significant source of uncertainty in GCMs (Boer and Yu 2003), the land surface conditions and geomorphological processes that give rise to these feedbacks are generally poorly known. GCMs do not consider the nature of the land surface, except at very broad scales, and cannot incorporate these feedbacks. Studies of geomorphological processes are usually based on small geographic areas, over short time scales, and are not closely linked to inputs or outputs from GCMs. Identifying the relationships between climate forcing and geomorphological response can yield a better understanding of the sensitivity of geomorphological systems to such forcing. Ongoing global warming in combination with landuse change, urbanisation and geoengineering, is now making geomorphological systems work at rates and within structural limitations unprecedented throughout human history. It is therefore critical to know how, where and at what rates these geomorphological systems will respond to climate and anthropogenic forcing.

In this article, we describe how and why ongoing global warming is causing changes to the workings of geomorphological systems. We argue that the concept of geomorphological sensitivity is a useful means by which to understand why these changes occur, and provide a context for monitoring and modelling these changes into the future. This article first explains climate sensitivity from which we derive the concept of geomorphological sensitivity. We then apply this concept to consider how sediment yield changes as a result of climate forcing. A useful analogue for geomorphological system behaviour under present global warming is that of paraglacial processes under conditions of ice retreat. We argue that understanding the response of geomorphological systems to global warming has major implications for climate policy and adaption strategies.

CLIMATE SENSITIVITY AND GEOMORPHOLOGICAL SENSITIVITY

Climate sensitivity is a concept commonly used in climate science and refers to the equilibrium temperature response to a doubling of pre-industrial atmospheric CO_2, and is dependent on interrelationships between carbon fluxes of the atmosphere, ocean and land surface. Most ensemble GCMs agree on sensitivity values in the range +1.5 to +4.5°C but cannot exclude higher values (Andronova et al. 2007). The temperature response most commonly reported is known as Charney sensitivity (centred around +3°C) in which land surface and atmospheric feedbacks are excluded and temperatures attain equilibrium over a short time scale. Such Charney sensitivity is better seen as a transient response to climate forcing. Consideration of longer time scale feedbacks that better incorporate land surface responses and which can be considered to be a more accurate measure of equilibrium temperature response has been termed Earth system sensitivity (Lunt et al. 2010). Earth system sensitivity includes nonlinear feedbacks in the atmosphere, ocean and land surface including tropospheric water vapour, albedo, sea and land ice and land vegetation. Recent palaeoclimate reconstructions that consider Earth system feedbacks suggest significantly higher sensitivity (e.g. Lunt et al. 2010; Pagani et al. 2010), and show that these feedbacks are significant contributors to climate amplification.

A similar concept to climate sensitivity can be applied to the response of geomorphological systems to climate forcing, which can be termed their geomorphological sensitivity (Harrison 2009). The concept of geomorphological sensitivity is useful because it describes the net outcome of geomorphological responses to climate forcing and is not dependent on knowledge of the system's nonlinear feedbacks and time lags, which are often unknown. In addition, evaluating geomorphological sensitivity can be ideally undertaken in a geomorphological systems context, because system properties, including feedback, scale and threshold, are also important controls on system sensitivity (Allison and Thomas 1993). Downs and Gregory (1993) describe how geomorphological sensitivity could be measured in river systems, including recovery from flood events, and changes in channel pattern, channel morphology and sediment load. Here, geomorphological sensitivity refers to the propensity of river channels to undergo change in response to catchment disturbance, which may include reservoirs/damming, landuse change, urbanization and channelization, as well as climate (Harnischmacher 2007). The net result is a reorganization of river sediments and formation of fluvial landforms including overbank and floodplain deposits, levees, deltas and terraces. Geomorphology, sediments and radiometric dating can be used in combination to quantify river responses to climate forcing over decadal to millennial time scales. This approach can help evaluate the responsiveness of geomorphological systems to climate forcing on the longer time scales that are required for these systems to attain equasi-equilibrium. This contrasts with many studies that are concerned with land surface responses over short (minutes-to-years) time scales (e.g., Keiler et al. 2010), which therefore cannot be used to determine equilibrium response of geomorphological systems and their geomorphological sensitivity.

Examining the evolution of geomorphological systems during climate warming of the late Pleistocene–Holocene transition (around 15,000–8000 years before present) can reveal the timing and dynamics of geomorphological processes in the absence of human activity. Ice retreat is a significant driver of processes in glacial, periglacial, slope, river and coastal environments, which can be collectively termed paraglacial processes. As a result, paraglacial responses to ice retreat, forced by climate change into the Holocene, are a useful analogue to present day global warming.

GLOBAL WARMING AND PARAGLACIATION

Most glaciers worldwide are in retreat as a result of global warming, particularly in mountains and lower latitudes where glaciers exist near their climatic limits. Accelerated glacier retreat over recent decades, and in the future, will result in a renewed period of paraglacial response, similar to that during the late Pleistocene–early Holocene. The term paraglacial refers to those geomorphological processes that are conditioned by glaciation (Church and Ryder 1972). The nature of this 'conditioning' is through changes in sediment availability that are brought about by a combination of ice retreat (liberation of glacigenic sediments), cold-climate weathering, steep and unstable surface slopes, and seasonal water availability. Sediment yield is at its maximum during initial ice retreat, decreasing exponentially over time as sediment is progressively reworked (Fig. 1).

Glacial meltwater production increases river discharge and leads to changes in river geomorphology and sediment supply (Church and Ryder 1972; Huss et al. 2008). Over short (decadal to centennial) time scales, increased sediment supply leads to river gravel aggradation within mountain catchments, nearest to where sediment is being released. Sediment supply into valley bottoms also takes place down steep, unstable slopes (Fig. 2). Slope failure can contribute a pulse of loose sediment into these river systems so that sediment yield undergoes a temporary spike (Fig. 1). Worldwide, many paraglacial sediments are trapped within upland basins and are unlikely to contribute to future downstream sediment supply (Hewitt 2006).

Studies of river systems displaying a paraglacial response during the late Pleistocene–early Holocene use a combination of geomorphological, sedimentary and radiometric dating evidence in order to track changes in sediment yield over time. For example, Macklin and Lewin (2008) distinguish between the different forcing factors that in combination result in river system sensitivity in European and African rivers during different time periods of the late Pleistocene–Holocene, and the resolution of dating techniques that can be used to identify any forcing-response time lags. They argue that more continuous records of river sedimentation since the mid-Holocene are caused by anthropogenic changes in landuse, which have acted to subdue any signal of climate forcing.

Throughout the Holocene, paraglacial sediment yield has been in long-term decline in the midlatitudes (Fig. 1). Amplified alpine warming and further glacier retreat will take place in mountain source areas including the European Alps, Caucasus, Rockies, Andes, and Southern Alps. As a result, over the next decades these regions will experience an increase in geohazards including river floods, landslides, debris flows, mudflows, and glacial lake outburst floods. These threaten human life and infrastructure, land surface stability and biodiversity. There are also other hazardous

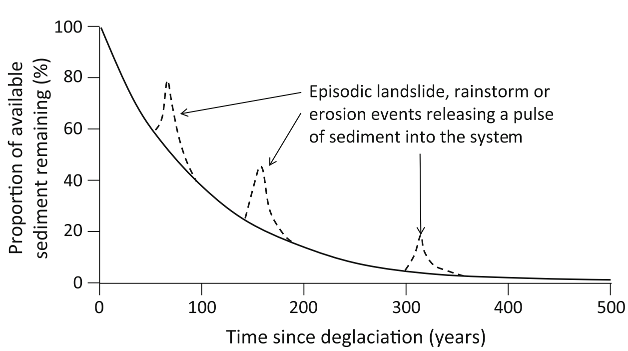

Fig. 1 Schematic graph showing decline in sediment yield over time during the period of paraglacial readjustment, and the role of episodic high-magnitude events such as landslides, rainstorms or periods of enhanced erosion in temporarily increasing he sediment yield (after Church and Ryder 1972; Ballantyne 2002)

outcomes of paraglacial responses to global warming. With the decline of mountain glaciers will be a decline of glacier-fed water supplies and sediment yield to river lowlands and coasts. Many rivers worldwide are already experiencing sediment starvation on lower-reach floodplains (Phillips and Slattery 2006). Reduction of coastal sediment supply will leave sandy coasts more vulnerable to sea-level rise, coastal erosion, barrier breaching and sea flooding (Nicholls and Cazenave 2010). These unanticipated downstream impacts of global warming require knowledge of geomorphological systems and an understanding of their sensitivity to climate forcing.

GEOMORPHOLOGICAL SENSITIVITY AS A MONITOR OF THE IMPACTS OF GLOBAL WARMING

Geomorphological sensitivity describes the degree to which geomorphological systems are perturbed by climate forcing. Suitable metrics to define geomorphological sensitivity may include sediment flux per unit area and time, measures of changing topography over time, or rate of weathering. These estimates are likely to be scale-dependent, site- and time-specific, and show significant spatial and temporal lags over decadal time scales that are relevant to climate policy. Monitoring of mountain-sourced river systems is needed in order to identify the strength and longevity of the paraglacial signal, but paraglacial processes and hazards will dominate midlatitude and mountain settings in the next decades to centuries (Knight and Harrison 2009).

Evaluating geomorphological sensitivity has important implications for helping to develop climate change adaptation strategies, particularly where an understanding of landscape responses to climate forcing is required, such as in biodiversity and carbon management. Much adaptation guidance assumes that climate change will produce a largely predictable geomorphological response which can be embedded in adaptation and management plans. Research over recent decades, however, shows that the climate response of Earth systems as a whole may be both nonlinear and unpredictable (Wolman and Gerson 1978), setting difficult challenges for policymakers. Improved understanding of geomorphological responses to climate forcing is crucial for models of future landscape change and adaptation strategies. Predicting geomorphological responses is also hampered by the stochastic and contingent (i.e. dominated by historical accidents) nature of landscape evolution. This means that nonlinear responses to climate forcing are likely to be a significant limitation on the extent to which regional-scale predictions of landscape response to climate change can be made. This provides

Fig. 2 **a** Paraglacial readjustment of a recent glaciated landscape in Patagonia, southern Chile, showing steep bedrock slopes and valley infills composed of talus slopes and alluvial fans. **b** Paraglacial readjustment of a late Pleistocene glaciated landscape in northwest Ireland, showing talus slopes and sediment transport to coastal lowlands

challenges to developing adaptation strategies of ecological, agricultural, cultural and socioeconomic systems. As GCMs do not consider geomorphological sensitivity, an important question is whether we are using the correct range of metrics to measure and monitor climate change and its impacts.

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