Stormy Geomorphology ESEX Commentary Paper

Title: Stormy Geomorphology: an introduction to the Special Issue

Authors and affiliations:

Spencer T[1], Naylor LA[2], Lane SN[3], Darby SE[4], Macklin MG[5,6], Magilligan FJ[7], Möller, I[1]

[1]Cambridge Coastal Research Unit, Department of Geography, University of Cambridge, Downing Place, Cambridge CB2 3EN, UK. Email: ts111@cam.ac.uk; im10003@cam.ac.uk

[2]School of Geographical and Earth Sciences, University of Glasgow, East Quadrangle, Glasgow, G12 8QQ, UK. Email: larissa.naylor@glasgow.ac.uk

[3]Institute of Earth Surface Dynamics, Géopolis, Université de Lausanne, CH1015 Lausanne, Switzerland. Email: Stuart.Lane@unil.ch

[4]Geography and Environment, University of Southampton, Highfield, Southampton, SO17 1BJ, UK. Email: S.E.Darby@soton.ac.uk

[5]Department of Geography and Earth Sciences, Llandinum Bldg, Aberystwyth, Dyfed SY23 3DB, UK. Email: mvm@aber.ac.uk

[6]Innovative River Solutions, Institute of Agriculture and Environment, Massey University, Palmerston North, New Zealand

[7]Department of Geography, Dartmouth College, Hanover, NH, 03766. Email: magilligan@dartmouth.edu

Abstract: The degree to which the climate change signal can be seen in the increasing frequency and/or magnitude of extreme events forms a key part of the global environmental change agenda. Geomorphology engages with this debate through extending the instrumental record with palaeogeomorphological research; studying resilience and recovery of geomorphic systems under extreme disturbance; documenting the mediation by catchment organisation of transport processes during extreme events; applying new monitoring methods to better understand process-response systems; and illustrating how process, experimental and modelling insights can be used to define the buffering of geomorphic systems and human assets from the effects of extremes, providing practical outcomes for practitioners.

Keywords: climate change; disturbance regime; climate extremes; landscape recovery; Intergovernmental Panel on Climate Change

Introduction

In a previous ESEX Commentary, Lane (2013) reviewed recently published work relating to the relationship between climate change and geomorphology. Lane argued that, despite the poor representation of geomorphological research in the 4th Assessment Report (AR4, 2007) of the Intergovernmental Panel for Climate Change (IPCC), geomorphology was making important contributions in disentangling the complex linkages between climatically-driven and human-driven impacts of environmental variability (e.g. land-use change); in thinking about the challenges of modelling geomorphic futures; and in the appreciation of the role that geomorphic processes play in the flux of carbon and the carbon cycle. In this Commentary, which follows the publication of IPCC AR5 (2013-2014), we introduce an ESPL Special issue concerned with the relations between geomorphology and another key concern in the climate change debate, the potential changes in the frequency and magnitude of extreme weather events. Here we use the definition of 'an extreme weather event', from the IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX; Seneviratne *et al.*, 2012), as one that is rare at a particular place and/or time of year. Definitions of 'rare' vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of a probability density function estimated from observations.

Climate Means, Weather Extremes and Types of Environmental Change

Climate change includes not only changes in mean climate but also in weather extremes. These extremes can be characterised, either singly or in combination, by changes in the mean, variance, or shape of probability distributions (IPCC, 2012). For example, significant trends in heavy-precipitation and high-temperature extremes over the recent decades have been observed (Rahmstorf and Coumou, 2011; Perkins *et al*., 2012) and attributed to human influence, initially in relation to particular extreme events (e.g. Pall *et al.,* 2011; Otto *et al*., 2012; Schaller *et al*., 2016) but more recently by application to all globally occurring heavy precipitation and hot extremes (Fischer and Knutti, 2015; Stott, 2016). In this context, the IPCC AR5 identifies, in particular, the greater risks of flooding at regional scales and increases in extreme sea levels post-1970 (IPPC, 2014).

This emphasis on precipitation, temperature and sea level is perhaps not surprising. Environmental change can be seen as consisting of two components, systemic and cumulative change (Turner *et al.*, 1990). Systemic change refers to occurrences of global scale, physically interconnected phenomena, whereas cumulative change refers to unconnected, local to intermediate scale processes which have a significant net effect on the global system. Hydroclimate and sea level change, a prime focus of the IPCC Assessment Reports, are drivers of systemic change which is highly amenable to large-scale atmosphere and ocean systems modelling. By contrast, cumulative change refers to unconnected, local to intermediate scale processes which have a significant net effect on the global system and where the human footprint is strong, and often dominant. Topographic relief, and land cover and land use changes, are drivers of cumulative change but their spatial and (in the case of surface characteristics) temporal variability, and hence the difficulties of both definition and spatial resolution, make the incorporation of their effects into Global Circulation Models a continuing challenge (Slaymaker *et al.,* 2009). In addition, whilst hydrometeorological and sea surface datasets can be described by smooth time series distributions, their landscape impacts are decidedly non-linear, with clear thresholds to landscape change in the disturbance regime. Any approach, therefore, that sees the land surface as a passive vehicle for the transmission of climate change, and adaptive strategies as a response to at best continental-scale changes in climatic extremes, can only provide a very simplified view of the implications of climate change for human lives and livelihoods. Furthermore, it offers few clues as to how to explore i) societally acceptable levels of landscape change and variability and ii) the extent to which landscapes can recover from extreme weather events and how locally-specific management strategies can improve the detailed trajectory of system recovery.

Stormy Geomorphology

In 2014, the British Society for Geomorphology (BSG) established a Fixed Term Working Group (FTWG) on ‘Stormy Geomorphology’ to help raise awareness of the ways in which geomorphological science can critically contribute to understanding, measuring and managing the impacts of two aspects of extreme weather events – coastal storms and river floods - on changing landforms and landscape systems and their human inhabitants. The aim of the FTWG has been to bring together world-leading experts in this field, combining state of the art syntheses alongside empirical papers documenting the impact of particular extreme weather events, or cluster of events, on the physical and ecological landscapes; the approach has been an interlinked International Discussion Meeting, held at the Royal Geographical Society (with IBG) in London in May 2015, and this Special Issue of Earth Surface Processes and Landforms.

When designing this Special Issue we identified five key ways in which geomorphological science contributes to a fuller understanding of the impacts of coastal storms and river floods. For the first theme, the fundamental role palaeogeomorphological studies play, both in extending the instrumental record and in improving flood risk estimates, is explored. The short length (generally ≤ 50 years) of systematic river flow records worldwide, most of which start in the mid-twentieth century, make forecasting hydrological extremes that have an annual exceedance probability of 0.01 or less highly problematic. Non-stationarity in flooding resulting from climate and catchment land-cover change also introduces further uncertainty in flood predictions based only on instrumental series. Coastal and fluvial sedimentary archives of past storms and floods with event-scale resolution are increasingly being used to extend flood records back over several centuries (Foulds and Macklin, 2016; Fruergaard and Kroon, 2016) and in some cases millennia (Toonen et al., 2016). These are providing new insights to the significant effects of short-term climatic variability on the incidence of extreme events which suggest that future flood estimation will need re-thought in the light of anthropogenic climate change. The second and third themes draw on research from both landform evolution and process traditions. In the second theme, current process and palaeogeomorphological research is used to examine how the magnitude and frequency of extremes influences the resilience and recovery of geomorphic systems to disturbances triggered by extreme storms and floods. The theme presents the empirical and theoretical dimensions of geomorphic responses to extreme events by characterizing and quantifying the shifts in boundary conditions generated by climate change (Yellen *et al*., 2016), anthropogenic disturbances (Brandon *et al*., 2016), or the cumulative effects of both (Slater, 2016). In particular, these papers reveal the reach scale (Croke *et al*., 2016) and watershed scale processes (Dethier *et al*., 2016) that dictate the suite of geomorphic responses to extreme events and the potential for large scale system changes to geomorphic perturbations (Phillips and Van Dyke, 2016). The third theme uses a series of empirical papers to demonstrate the critical role that catchment organisation plays in mediating water and sediment transport during extreme events (Boardman, 2015; Boardman and Vandaele, 2016; Rigon *et al*., 2016; Rickenmann *et al*., 2016; Rinaldi *et al*., 2016). The last two themes move into the realm of the process geomorphology tradition, employing novel technologies to gather empirical data and modelling to improve our predictive capacity. In the fourth group, a suite of empirical papers illustrate the fundamental role that near real-time, quantitative field measurements during extreme events can play in advancing our understanding of process-form responses in coastal (Brooks *et al*., 2016; Masselink *et al.,* 2016; Naylor *et al*., 2016; Terry *et al*., 2016) and hillslope (Rinaldi et al., 2016)settings. Lastly, a series of papers (Smith *et al*., 2016; Dixon *et al*., 2016; Balke and Friess, 2016) demonstrate how geomorphological process knowledge, and particularly knowledge gained from physical and numerical modelling of water flows within and across estuarine and coastal landforms and associated ecosystems, can help to inform flood and erosion management approaches. Applied in this way, such knowledge has a direct impact on society; it points the direction towards practical solutions for the more sustainable and robust protection of human assets from the effects of extremes.

Conclusion

Geomorphology has an obligation to inform society as to what level of disturbance the Earth's landforms and landscapes can (and cannot) absorb and over what time periods the landscape will respond to, and recover from, disturbance. We hope that this series of papers helps take this debate, and this responsibility, forward, in relation to one of the key emerging environmental challenges for contemporary society: flood hazard.

.

Acknowledgements

The authors are grateful to the British Society for Geomorphology, Wiley and the Royal Geographical Society as lead sponsors in support of the Fixed Term Working Group on Stormy Geomorphology which led to this collection of papers. We also acknowledge meeting support from Marine Alliance for Science and Technology for Scotland (MASTS), NERC Coastal Biodiversity and Ecosystem Service Sustainability (CBESS) and EU FP7 Resilience-Increasing Strategies for Coasts – Toolkit (RISC-KIT). Underpinning research was funded through grants from UK NERC (NE/M010546/1 (Naylor), NE/J015423/1 (Spencer, Möller), NE/JO21970/1 (Darby)), USA National Science Foundation (BCS-1160301 and BCS-1222531, Magilligan) and the European Union (FP7-SPACE-2013 grant 607131 and FP7-ENV.2013 grant 603458, Möller, Spencer).

References

Balke T, Friess DA. 2016. Geomorphic knowledge for mangrove restoration: a pan-tropical categorization. Earth Surface Processes and Landforms **41** : 231-239. DOI: 10.1002/esp.3841

Boardman J. 2015. Extreme rainfall and its impact on cultivated landscapes with particular reference to Britain. Earth Surface Processes and Landforms **40** : 2121-2130. DOI: 10.1002/esp.3792

Boardman J, Vandaele K. 2016. Effect of the spatial organization of land use on muddy flooding from cultivated catchments and recommendations for the adoption of control measures. Earth Surface Processes and Landforms **41** : 336-343. DOI: 10.1002/esp.3793

Brandon CM, Woodruff JD, Orton PM, Donnelly JP. 2016. Evidence for elevated coastal vulnerability following large-scale historical oyster bed harvesting. Earth Surface Processes and Landforms 41 : 1136-1143. DOI: 10.1002/esp.3931

Brooks SM, Spencer T, McIvor A, Möller I. 2016. Reconstructing and understanding the impacts of storms and surges, southern North Sea. Earth Surface Processes and Landforms **41** : 855-864. DOI: 10.1002/esp.3905

Croke J, Fyirs K, Thompson C. 2016. Defining the floodplain in hydrologically-variable settings: Implications for flood risk management. Earth Surface Processes and Landforms. DOI: 10.1002/esp.4014

Dethier E, Magilligan FJ, Renshaw CE, Nislow KH. 2016. The role of chronic and episodic disturbances on channel–hillslope coupling: the persistence and legacy of extreme floods. Earth Surface Processes and Landforms **41** : 1437-1447. DOI: 10.1002/esp.3958

Dixon SJ, Sear DA, Odoni NA, Sykes T, Lane SN. 2016. The effects of river restoration on catchment scale flood risk and flood hydrology. Earth Surface Processes and Landforms **41** : 997-1008. DOI: 10.1002/esp.3919

Fischer EM, Knutti R. 2015. Anthropogenic contribution to global occurrence of heavy precipitation and high-temperature extremes. Nature Climate Change **5** : 560-564. DOI: 10.1038/nclimate2617

Foulds SA, Macklin MG. 2016. A hydrogeomorphic assessment of twenty-first century floods in the UK. Earth Surface Processes and Landforms **41** : 256-270. DOI: 10.1002/esp.3853

Fruergaard M, Kroon A. 2016. Morphological response of a barrier island system on a catastrophic event: the AD 1634 North Sea storm. Earth Surface Processes and Landforms **41** : 420-426. DOI: 10.1002/esp.3863

IPCC. 2012. Summary for Policymakers. In Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, Field CB et al. (eds). A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press: Cambridge, UK and New York, NY, USA; 1-19.

IPCC. 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva: Switzerland; 151 pp.

Lane SN. 2013. 21st century climate change: where has all the geomorphology gone? Earth Surface Processes Landforms **38** : 106–110. DOI: 10.1002/esp.3362

Masselink G, Scott T, Poate T, Russell P, Davidson M, Conley D. 2016. The extreme 2013/2014 winter storms: hydrodynamic forcing and coastal response along the southwest coast of England. Earth Surface Processes and Landforms **41** : 378-391. DOI: 10.1002/esp.3836

Naylor LA, Stephenson WJ, Smith HCM, Way O, Mendelssohn J, Cowley A. 2016. Geomorphological control on boulder transport and coastal erosion before, during and after an extreme extra-tropical cyclone. Earth Surface Processes and Landforms **41** : 685-700. DOI: 10.1002/esp.3900

Otto FEL, Massey N, van Oldenborgh GJ, Jones RG, Allen MR. 2012. Reconciling two approaches to attribution of the 2010 Russian heat wave. Geophysical Research Letters **39 :** L04702. DOI: 10.1029/2011GL050422

Pall P, Aina T, Stone DA, Stott PA, Nozawa T, Hilberts AGJ, Lohmann D, Allen MR. 2011. Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000. Nature **470** : 382-385. DOI: 10.1038/nature09762

Perkins, S. E., Alexander, L. V. & Nairn, J. R. Increasing frequency, intensity and duration of observed global heatwaves and warm spells. Geophysical Research Letters **39** : L20714. DOI: 10.1029/2012GL053361

Phillips JD, Van Dyke C. 2016. Principles of geomorphic disturbance and recovery in response to storms. Earth Surface Processes and Landforms **41** : 971-979. DOI: 10.1002/esp.3912

Rahmstorf S, Coumou D. 2011. Increase of extreme events in a warming world. Proceedings of the National Academy of Sciences USA **108** : 17905-17909. DOI: 10.1073/pnas.1101766108

Rickenmann D, Badoux A, Hunzinger L. 2016. Significance of sediment transport processes during piedmont floods: the 2005 flood events in Switzerland. Earth Surface Processes and Landforms **41** : 224-230. DOI: 10.1002/esp.3835

Rigon R, Bancheri M, Formetta G, de Lavenne A. 2016. The geomorphological unit hydrograph from a historical-critical perspective. Earth Surface Processes and Landforms **41** : 27-37. DOI: 10.1002/esp.3855

Rinaldi M, Amponsah W, Benvenuti M, Borga M, Comiti F, Lucía A, Marchi L, Nardi L, Righini M, Surian N. 2016. An integrated approach for investigating geomorphic response to extreme events: methodological framework and application to the October 2011 flood in the Magra River catchment, Italy. Earth Surface Processes and Landforms **41** : 835-846. DOI: 10.1002/esp.3902

Schaller N, Kay AL, Lamb R, Massey NR, van Oldenburgh GJ, Otto FEL, Sparrow SN, Vautard R, Yiou P, Ashpole I, Bowery A, Crooks SM, Haustein K, Huntingford C, Ingram WJ, Jones RG, Legg T, Miller J, Skeggs J, Wallom D, Weisheimer A, Wilson

S, Stott PA, Allen MR. 2016. Human influence on climate in the 2014 southern England winter floods and their impacts. Nature Climate Change **6** : 627-634. DOI: 10.1038/NCLIMATE2927

Seneviratne SI, Nicholls N, Easterling D, Goodess CM, Kanae S, Kossin J, Luo Y, Marengo J, McInnes K, Rahimi M, Reichstein M, Sorteberg A, Vera C, Zhang X. 2012. Changes in climate extremes and their impacts on the natural physical environment. In Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, Field CB et al. (eds). A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press: Cambridge, UK and New York, NY, USA; 109-230.

Slater LJ. 2016. To what extent have changes in channel capacity contributed to flood hazard trends in England and Wales? Earth Surface Processes and Landforms **41** : 1115-1128. DOI: 10.1002/esp.3927

Slaymaker O, Spencer T, Dadson S. 2009. Landscape and landscape-scale processes as the unfilled niche in the global environmental change debate: an introduction. In Geomorphology and Global Environmental Change, Slaymaker O, Spencer T, Embleton-Hamann C (eds). Cambridge University Press: Cambridge; 1-34.

Smith JM, Bryant MA, Wamsley TV. 2016. Wetland buffers: numerical modeling of wave dissipation by vegetation. Earth Surface Processes and Landforms **41** : 847-854. DOI: 10.1002/esp.3904

Stott P. 2016. How climate change affects extreme weather events. Science **352**: 1517-1518. DOI: 10.1126/science.aaf7271

Terry JP, Dunne K, Jankaew K. 2016. Prehistorical frequency of high-energy marine inundation events driven by typhoons in the Bay of Bangkok (Thailand), interpreted from coastal carbonate boulders. Earth Surface Processes and Landforms **41** : 553-562. DOI: 10.1002/esp.3873

Toonen WHJ, Middelkoop H, Konijnendijk TYM, Macklin MG, Cohen KM. 2016. The influence of hydroclimatic variability on flood frequency in the Lower Rhine. Earth Surface Processes and Landforms **41** : 1266-1275. DOI: 10.1002/esp.3953

Turner II BL, Kasperson RE, Meyer WB, Dow KM, Golding D, Kasperson JX, Mitchell RC, Ratick SJ. 1990. Two types of global environmental change: definitional and spatial scale issues in their human dimensions. Global Environmental Change **1** : 14–22. DOI: 10.1016/0959-3780(90)90004-S

Yellen B, Woodruff JD, Cook TL, Newton RM. 2016. Historically unprecedented erosion from Tropical Storm Irene due to high antecedent precipitation. Earth Surface Processes and Landforms **41** : 677-684. DOI: 10.1002/esp.3896