Uncertainty in geomorphological responses to climate change

Harrison, S., Mighall, T., Stainforth, D. A., Allen, P., Macklin, M., Anderson, E., Knight, J., Mauquoy, D., Passmore, D., Rea, B., Spagnolo, M. and Shannon, S. ORCID: https://orcid.org/0000-0002-7644-2724 (2019) Uncertainty in geomorphological responses to climate change. Climatic Change, 156 (1-2). pp. 69-86. ISSN 1573-1480 doi: 10.1007/s10584-019-02520-8 Available at https://centaur.reading.ac.uk/125144/

To link to this article DOI: http://dx.doi.org/10.1007/s10584-019-02520-8

CentAUR

Central Archive at the University of Reading

Reading's research outputs online

Uncertainty in geomorphological responses to climate change

Stephan Harrison[1] · Tim Mighall[2] · David A. Stainforth[3] · Philip Allen[4] ·
Mark Macklin[5] · Edward Anderson[6] · Jasper Knight[7] · Dmitri Mauquoy[2] ·
David Passmore[8] · Brice Rea[2] · Matteo Spagnolo[2] · Sarah Shannon[9]

Abstract

Successful adaptation to climate change at regional scales can often depend on understanding the nature of geomorphological responses to climate change at those scales. Here we use evidence from landscapes which are known to be environmentally sensitive to show that geomorphological change in response to shifts in climate can be highly nonlinear. Our study sites are two mountain massifs on the western coast of Ireland. Both sites have similar geological and Pleistocene glacial histories and are similar topographically, geomorphologically and in their climate histories. We show that despite these similarities their response to late Holocene, climate change has differed. Both massifs have responded to short-term climate changes over the last 4500 years that are considered to have been uniform across the region, but these climate changes have resulted in highly differentiated and nonlinear landscape responses. We argue this reflects nonlinearity in the forcing–response processes at such scales and suggests that current approaches to modelling the response of such systems to future climate change using numerical climate models may not accurately capture the landscape response. We end by discussing some of the implications for obtaining decision-relevant predictions of landscape responses to climatic forcing and for climate change adaptation and planning, using regional climate models.

1 Introduction

Information about climate change impacts at local and regional scales is widely sought in support of adaptation strategies and as motivation for mitigation efforts (Jenkins et al. 2009; Wise et al. 2014; Lowe et al. 2018). Understanding the impacts of climate change on Earth systems is crucial because of the implications for food production, water resources, ecosystem services, physical infrastructure and land carbon sinks (e.g. Ramankutty et al. 2006; Burrows et al. 2011). However, in contrast to the direct consequences of climate change on weather patterns and their consequences for policy and resource management, the geomorphological

---

✉ Stephan Harrison
stephan.harrison@exeter.ac.uk

Extended author information available on the last page of the article

implications of ongoing anthropogenic climate change have received relatively little attention (Knight and Harrison 2011, 2013; Lane 2013; Spencer et al. 2017). Substantial efforts have been made to quantify uncertainty in the climate's response at spatial scales relevant for adaptation planning, but the consequences of any given change in climatic variables on the landscape are either not considered or at best assumed to be linearly proportional to forcing.

Understanding the future impacts of climate change on land surface stability and the sediment fluxes associated with soil erosion, river incision and coastal erosion is crucial for assessing their contribution to climate forcing through their relationship to continental weathering and geochemical cycling. There is a tendency, however, to assume that so long as individual geomorphological processes are understood, then the responses can be predicted with confidence. When adaptation planners, such as water managers, use climate projections, they implicitly assume that the geomorphological response is predictable as a consequence of a given climate projection. An important question for geomorphologists and adaptation planners then is to what extent is this actually the case? We explore this question here by discussing the nature of uncertainty in predictions of the climate and of terrestrial Earth system responses to climate change. Geomorphological sensitivity to climate forcing varies significantly according to the type of geomorphic system, but our results indicate that very similar geomorphological systems can also exhibit radically different responses to the same forcings; this represents an uncertainty similar to that arising from the initial value sensitivity of many nonlinear systems.

When considering uncertainty in the future evolution of geomorphological systems, it is informative to reflect on the types of uncertainty studied in weather and climate forecasts. For the climate change focused members of the geomorphological community, this is of direct relevance because it influences how one should interpret such forecasts as regards the future climate forcing for a particular landscape of interest. The connections and synergies between climate modellers and geomorphologists are, however, much closer than this. There is, arguably, a need to consider the same diverse sources of uncertainty when studying geomorphological systems.

Nonlinearities in the dynamics of the atmosphere, the ocean and the coupled atmosphere/ocean system lead to sensitivity of these systems to their initial conditions. That is to say, the future evolution of these systems can depend on the finest details of the starting conditions for a forecast. This sensitivity leads to uncertainty in their future state and is the rationale for ensemble weather forecasting where the aim is to produce a probability distribution for different future weather conditions; if accurate, reality will be one sample from that distribution. Recent work has highlighted that initial condition sensitivity is also important for the evolution of 'climate' (Stainforth et al. 2007; Deser et al. 2012; Xie and Deser 2015) even when considering climate forecasts as forecasts of a changing climate distribution (Daron and Stainforth 2013; Hawkins et al. 2015). The weather case represents an essentially stationary system within which there are rapid dynamic fluctuations while the climate case represents much slower changes (e.g. in decadal means or in the probability distributions themselves) in a transient situation of changing forcing (Daron and Stainforth 2013). The relatively slow rate of landscape change under a stable, stationary climate, suggests that parallels with weather forecasting are unlikely to be pertinent on decadal to centennial timescales. Under a changing climate, however, the climate forcing of geomorphological systems will change and their response may itself be sensitive to the details of their initial state in a way which somewhat parallels the climate case. Nonlinear geomorphological processes, and nonlinear interactions and feedbacks between such processes (which may involve thresholds), could lead to unanticipated responses to changes in climatic forcing. That is to say, the same change in forcing

could lead to different responses due to differences in the details of the geomorphological initial conditions. Similarly, the nonlinear processes could generate different responses as a consequence of small differences in the changing climate forcing on the geomorphological system, itself a potential consequence of initial condition sensitivity in the climate system. Together, these lead to aleatory uncertainty in the future behaviour of such systems.

The importance of initial condition uncertainty in climate projections, and the need for large ensembles to study it, is only beginning to be addressed. Consequently, climate modelling studies often assume, or conclude, that the uncertainty in the large-scale multi-decadal response (for instance of a region the size of northern Europe) to increased atmospheric greenhouse gases is to a large degree deterministic within any given model. Uncertainty in the forcing of the system and epistemic uncertainty in the interacting climatic processes which control the response (which have been termed 'model imperfections' (Stainforth et al. 2007)) are however widely studied. Models are run with different forcing scenarios, and multi-model and perturbed physics ensembles are used to study the consequences of model imperfections which are themselves taken to represent uncertainties in process behaviour and interactions. How to study and quantify the various forms of uncertainty and communicate this to policymakers and end users is a source of much debate in the climate sciences (eg Smith 2002; Hawkins and Sutton 2009; Collins et al. 2011; Maslin and Austin 2012; Stainforth and Smith 2012; Knutti 2008; Knutti and Sedláček 2012; Oppenheimer et al. 2016).

For the geomorphological community, and for studies of impacts and adaptation plans in the context of landscape change, it is valuable to ask: whatever the sources of uncertainty in climate change projections, can we consider the landscape response to future climate as essentially deterministic or does it too have a significant element due to initial value uncertainty? Can the landscape response depend on the small-scale details of landscape geomorphological structure and environmental drivers, or is it constrained by larger-scale, emergent and predictable aspects of the geomorphological system? These are the questions we address herein.

Variability in how similar river catchments respond to synchronous and uniform environmental forcings is termed 'complex response' (Schumm 1979). This is a characteristic of processes that amplify, dampen or filter feedbacks within geomorphic systems in response to climate shifts (Phillips 2010). However, there are few catchment-scale studies that test this concept and relate river/catchment responses over space and time to documented and dated environmental events such as climate perturbations or major human disturbances. Phillips (2010) suggests that some fluvial systems may be highly resistant to climate change-driven variations in runoff (e.g. bedrock-controlled river channels), whereas others, where abundant sediment stores are available, may show rapid responses to variations in runoff. He argues 'that at one extreme filters may completely obscure geomorphic responses to changes in climate, while at the other extreme climate change may be amplified to produce dramatic geomorphic change in response to small climate perturbations' (p 574).

Computational modelling of fluvial catchments also shows that, even within a single catchment, sensitivity to environmental change may vary at the reach scale (Coulthard et al. 2005). This may be caused by subtle differences in catchment morphology or changes in the ways in which sediments are stored or mobilised during flood events (Benda and Dunne 1997; Lague et al. 2005). An example showing the variable geomorphic response to a single high magnitude convection storm illustrates this point. In June 1982, a storm in an upland catchment of the Northern Pennines in England destabilised catchment slopes and sediments and produced a number of geomorphologically and sedimentologically diverse alluvial fans at

tributary junctions (Wells and Harvey 1987). The storm was of high magnitude (return period of more than 100 years) and temporally short (less than 2.5 h) and triggered a series of geomorphological processes including overland flow landslides and debris flows. The 13 alluvial fans produced differed sedimentologically between debris-flow dominated facies and streamflow facies, and this was controlled by thresholds related to variables including catchment size and channel gradient, the nature of available sediment and position within the storm cell.

Such events pose important methodological and theoretical issues for climate modellers and adaptation specialists. Clearly, our current inability to model these variations at the small spatial scales relevant to adaptation planning makes prediction of system responses to climate change extremely difficult. High-resolution climate projections are, however, available. For instance in the UK, the new generation of climate projections from UKCP18 will include convection-permitting projections using an ensemble of ultra-high-resolution projections at 2.2 km resolution and run at sub-daily scales. Simulations at this resolution will provide model-dependent information on high impact events such as localised heavy rainfall in summer and potential improvements in modelling the diurnal cycle. These are significant model improvements, but it is important to remember that the fundamental epistemic uncertainties in climate model-based projections nevertheless remain (Stainforth et al. 2007).

Independent of the reliability of climate projections, there are significant challenges to understanding and representing the key physical processes involved in geomorphological responses to climate forcing and extreme weather events. To support this contention we present evidence from the climatically sensitive Atlantic fringe of Europe to show that in similar geomorphic systems and landscape settings the geomorphological responses to the same climate forcing can indeed be significantly different, in other words something akin to sensitivity to initial conditions. This raises important questions regarding how we consider the potential for such changes in the future, particularly in exploring landscape response uncertainties, the identification of the parts of geomorphological systems which may be particularly sensitive to climate change and the use of such information for adaptation planning.

1.1 Study area

Our study area is two adjacent mountain massifs in southwest Ireland, Brandon Mountain and Macgillycuddy's Reeks (Fig. 1a, b). These massifs are located on the extreme western seaboard of Europe and have been highly sensitive to past climate change, displaying a wide range of Pleistocene glacial and Holocene fluvial landforms (Anderson et al. 2000). The study sites lie 40 km apart and are located on the southwest seaboard of Ireland in the Macgillycuddy's Reeks (centred on 51° 59′ N; 09° 44′ W) and Brandon Mountains (centred on 52° 13′ N; 10° 14′ W). These are high relief massifs (maximum elevation 1039 m asl in Macgillycuddy's Reeks and 952 m asl at Brandon Mountain) with numerous other mountains over 800 m elevation in both regions. The massifs are composed of Devonian sandstones and shales, belonging to the Old Red Sandstone (ORS) series, and are part of a broad belt of such lithologies that extends from the western peninsulas of Iveragh and Corca Dhuibhne to County Waterford and County Cork in the east. These upper Palaeozoic rocks have been deformed into a series of SWS-ENE trending folds by Hercynian (416–359 Ma) tectonism.

The geomorphology of the study sites primarily reflects the legacy of Late Pleistocene deglaciation (22–16 ka) and subsequent episodes of severe cold climate conditions (especially between 12 and 11 ka). Both sites have been deeply dissected by long-term glacial action to
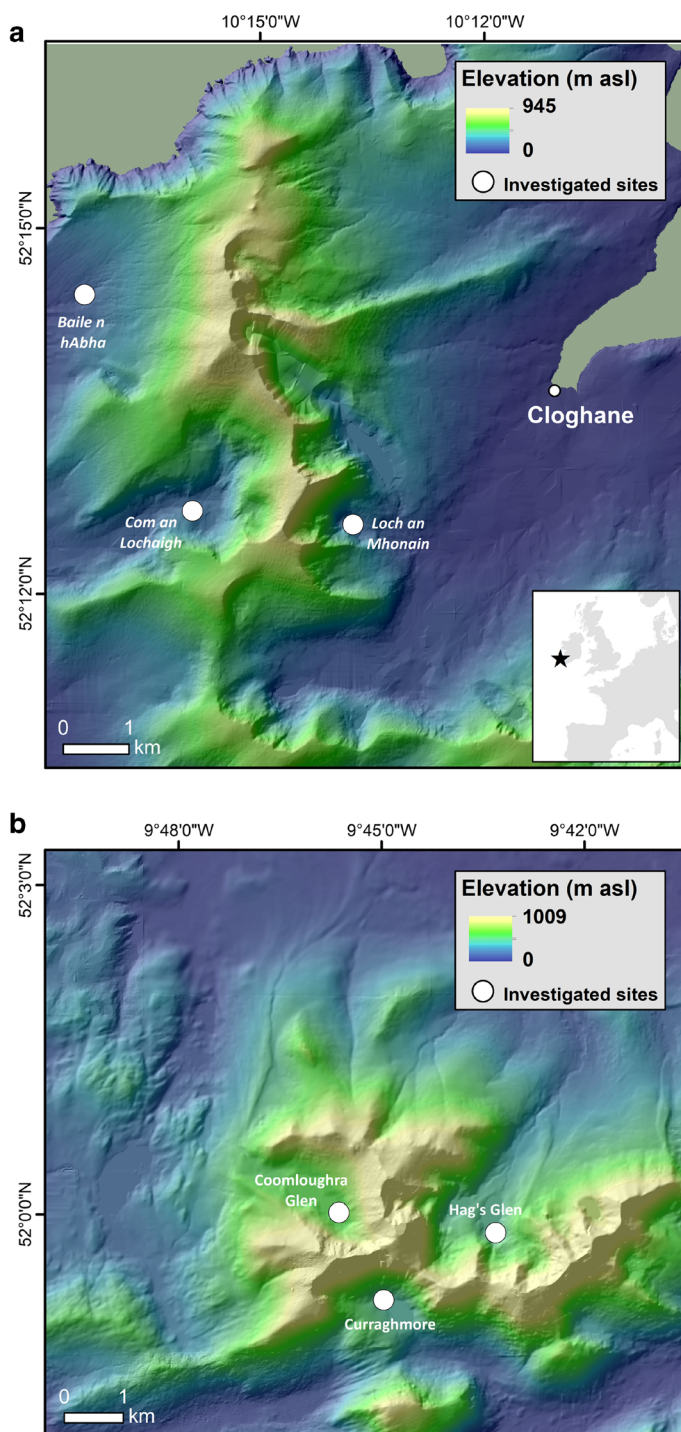
Fig. 1 Digital elevation models (DEMs) of the Brandon Mountain (**a**) and Macgillycuddy's Reeks (**b**) study areas in southwest Ireland

form landscapes dominated by glacial troughs and cirque basins with, locally, around 700 m of incised relief. Slopes and valley floors are mantled by glacial and periglacial landforms which have been partly modified by Holocene fluvial processes. Glacial landforms in the two sites can be grouped into three assemblages associated with distinct cold episodes of the Late Pleistocene: Last Glacial maximum (LGM), a major glacial readvance (probably during Heinrich 1 (16.8 ka), Harrison et al. 2010) and the Younger Dryas (YD) glaciation (12–11 ka). The location and dimensions of talus slopes reflect structural controls, in particular the azimuth of bedding planes and age. Areas outside the limits of YD glaciation were exposed to severe periglacial/permafrost activity and developed large talus slopes (Anderson et al. 2001). Talus slopes developed within the YD limits, i.e. during the Holocene, are poorly developed and much smaller.

Within cirque basins and valley floors are found a well-developed series of alluvial terraces, alluvial fan deposits and debris cones (Anderson et al. 2000, 2004). The alluvial fans and debris cones formed, as a response to the destabilisation of both glacigenic and talus deposits, by mobilisation of debris flows, transitional flows and flood processes. All of the alluvial fans and debris cones lie at the base of gullies eroded into glacigenic sediment-mantled slopes within cirque basins (Anderson et al. 2000). The relief of the slopes above the alluvial fans and cones ranges from 450 to 500 m, and the gradient of the eroded part of the slopes typically varies from 35 to 15°. Erosion reveals that the glacigenic deposits are primarily matrix supported sandy till and are relatively thick, typically 5 m or more. The presence of thick deposits of till is a key control on the formation of alluvial fans at these sites (and shows the importance of antecedent conditions). Debris cones are dominated by debris flow facies. Contrasts in bulk facies assemblages are interpreted as responses to catchment parameters (e.g. Wells and Harvey 1987). In the Macgillycuddy's Reeks, a well-developed alluvial terrace sequence is present in the Gaddagh Valley, inset within a glacial till sheet and decoupled from valley side debris sources (Anderson et al. 2004). In the Brandon Mountain massif, similar alluvial systems are evident. Alluvial terraces, alluvial fan deposits and debris cones are composed of clastic units and interstratified peat horizons. Within the context of the British Isles, the occurrence of peat within these features is rare and hence provides an excellent opportunity to establish a chronological record of Holocene landform development using radiocarbon dating.

The range of geomorphic settings allows Holocene fluvial and slope processes to be investigated in contexts that may have experienced little human landscape modification (high elevation cirque basins) or, by contrast, may have undergone extensive anthropogenic disturbance of vegetation and soil cover and the development of blanket peats (valley floors and lower slopes of rivers draining cirque basins).

Holocene valley floor deposits are inset within well-developed sequences of LGM and possibly YD glacigenic landforms (Harrison et al. 2010; Barth et al. 2016). Therefore, they offer the opportunity to investigate glacigenic, paraglacial responses and stream-slope coupling mechanisms over the glacial-interglacial transition and the role of Late Pleistocene environmental change and associated geomorphic activity in conditioning and controlling subsequent Holocene valley floor and slope evolution.

In summary, we can show that both regions display similar topographies, geological structure, land use and vegetation histories (Harrison and Mighall 2002), and it has been shown that the large-scale evolution of their geomorphological systems (including their major rivers, valley-side and valley-floor debris assemblages) has responded primarily to rapid and similar shifts in Pleistocene and Holocene climates (Rae et al. 2004; Anderson et al. 2004; Ballantyne et al. 2011).

2 Methods

At both Brandon Mountain and Macgillycuddy's Reeks, late Holocene landform development is represented by a range of depositional valley-side and valley-floor landforms including alluvial fans, debris cones and fluvial terraces (Anderson et al. 2000). The fluvial systems considered here are small (catchments < 7 km^2), and therefore, the time lags of forcing response are likely to be within radiocarbon dating error. Recent river incision through these deposits has exposed sediment units from which we obtained 31 radiocarbon ages on organic materials to date episodes of landform construction (see Tables 1 and 2). The dates are classified as 'change before' dates, which provide a *terminus ante quem* for the episode of landscape change, and 'change after' dates which provide a *terminus post quem* for the landscape change (Macklin et al. 2010).

A number of key morphometric variables influence the response times of the catchments to external forcing, such as climate change. These include size of catchment with smaller catchments likely responding more rapidly to forcing than large ones. In addition, catchments with steeper slopes should be geomorphologically more active and respond more rapidly to forcing in terms of sediment dynamics. Finally, aspect may play an important role in slope dynamics. In SW Ireland, the dominant precipitation comes from the SW-NW quadrants. Slopes facing this direction are expected to collect most precipitation, modulated to some

Table 1 Radiocarbon dates from the Brandon Mountain study areas. All radiocarbon dates were calibrated using CALIB 6.1.1 radiocarbon calibration program and IntCal04 and are expressed using 2 sigma age ranges (to the nearest 5 years) (AD/BC = calendar years; Cal BP = calibrated years before present)

Laboratory no.	Depth (cm)	^{14}C years BP	Cal BC/AD (2σ)	Cal BP (2σ)
Brandon Mountain				
Owenmore				
Poz-18,735	64–63	1255 ± 30	Cal AD 675–865	1085–1280
Poz-17,103	84–83	1875 ± 30	Cal AD 70–225	1725–1880
Poz-18,736	136–135	2520 ± 35	Cal BC 795–540	2490–2745
B-169436	180–176	3260 ± 60	Cal BC 1680–1420	3370–3630
Loch an Mhónáin				
Section 1				
SSSR-6619	33–32	1435 ± 54	Cal AD 435–680	1270–1515
SSSR-6620	35–34	1494 ± 48	Cal AD 430–645	1305–1520
SSSR-6621	45–44	2089 ± 58	Cal BC 355–Cal AD 50	1900–2300
SSSR-6622	58–57	2309 ± 56	Cal BC 535–205	2155–2485
SSSR-6623	68–67	3599 ± 58	Cal BC 2135–1775	3720–4085
SSSR-6624	75–74	3327 ± 55	Cal BC 1745–1465	3415–3695
SSSR-6625	83–82	3846 ± 50	Cal BC 2465–2150	4100–4415
Section 2				
SSSR-6626	45–44	2165 ± 60	Cal BC 370–55	2005–2320
SSSR-6627	55–54	1885 ± 50	Cal AD 15–245	1705–1935
Baile na hAbha				
SRR-6615	12–13	310 ± 55	Cal AD 1455–1795	155–495
SRR-6628	16–17	480 ± 50	Cal AD 1315–1615	335–635
SRR-6616	26–27	1805 ± 60	Cal AD 80–380	1570–1870
AA-40509	30–32	1770 ± 40	Cal AD 135–380	1570–1815
Com an Lochaigh				
AA-40435	25.5–26	810 ± 50	Cal AD 1050–1280	665–900
AA-40436	40–41	895 ± 40	Cal AD 1035–1215	735–915
SRR-6618	52–53	2350 ± 60	Cal BC 750–210	2160–2700

Table 2 Radiocarbon dates from the Macgillycuddy's Reeks study areas. All radiocarbon dates were calibrated using CALIB 6.1.1 radiocarbon calibration program and IntCal04 and are expressed using 2 sigma age ranges (to the nearest 5 years) (AD/BC = calendar years; Cal BP = calibrated years before present)

Laboratory no.	Depth (cm)	^{14}C years BP	Cal BC/AD (2σ)	Cal BP (2σ)
Macgillycuddy's Reeks				
Coomloughra Glen				
SRR-5957	66–67	240 ± 40	Cal AD 1520–1950	0–430
SRR-5958	93–94	235 ± 40	Cal AD 1520–1950	0–430
SRR-5959	122–123	1305 ± 40	Cal AD 650–775	1175–1300
Hags Glen				
Section 6				
SRR-5960	68–69	240 ± 40	Cal AD 1520–1950	0–430
SRR-5961	80–81	450 ± 40	Cal AD 1405–1615	335–545
SRR-5962	84–85	445 ± 45	Cal AD 1405–1625	325–545
SRR-5963	114–115	820 ± 45	Cal AD 1050–1280	670–900
Section 11				
SRR-5964	23–24	835 ± 40	Cal AD 1050–1270	680–900
SRR-5965	28–29	1020 ± 45	Cal AD 895–1155	795–1055
SRR-5966	36–37	1410 ± 45	Cal AD 560–675	1275–1390
SRR-5967	74–75	3360 ± 45	Cal BC 1750–1525	3475–3700
Curraghmore				
Section14				
B-117295	30–31	190 ± 90	Cal AD 1515–1950	0–435
SRR-5955	60–61	705 ± 40	Cal AD 1225–1390	560–725
SRR-5956	72–73	1505 ± 40	Cal AD 430–640	1310–1520

degree by elevation of catchment. Although aspect could theoretically also impact sediment dynamics via vegetation, snow cover and other variables, this is considered of minor relevance because slope lengths are short and watersheds not very high. As a result, we analysed the topographic similarity between the sites using the hypsometry (HI), which is the distribution of land surface area with elevation. The ACME toolset (Spagnolo et al. 2017) was used to extract the various metrics from a 30-m resolution DEM (ASTER G-DEM v.2). Catchments were hand-digitised using a hill-shaded image and 10 m contours extracted from the DEM using standard ArcGIS Spatial Analyst tools.

A lower HI indicates a larger proportion of the land surface at lower elevations and vice versa. We also assessed orientation of the sites and other morphometric data.

To demonstrate that the sites all display similarity in current and future climate (and, by analogy, likely similarities in the past climate), we assess how the climate changed during the recent past, and how it is predicted to respond to elevated CO_2, in model simulations from the World Climate Research Program Coordinated Regional Downscaling Experiment (EURO-CORDEX) (Jacob et al. 2014). Climate model output is used because there are no meteorological observations at the field sites.

Gridded observational based datasets would have been preferable, but those available do not provide the resolution necessary to compare our two locations of interest. Three datasets are used; one for the historical period (the twentieth century) and two for the future (the twenty-first century) representing moderate (RCP4.5) and high (RPC8.5) CO_2 concentrations. The simulations use the DMI-HIRHAM5 regional climate model and are driven by ERA-interim boundary conditions for the historical period and the ICHEC-EC EARTH GCM for the future. The data has a sufficiently high spatial resolution (12.5 km) to distinguish between the climates at the Brandon Mountain and Macgillycuddy's Reeks field sites (see Figs. 3, 4 and 5).

Daily 2-m air temperature and precipitation (solid and liquid) are extracted for the Brandon Mountain and Macgillycuddy's Reeks field sites and annual means are plotted.

3 Results

Results of the hypsometric analysis (Fig. 2a–d) show that the three Macgillycuddy's Reeks sites are self-similar and match site 4 from Mt. Brandon with sites 5 and site 6 having slightly lower HIs. Brocklehurst and Whipple (2004) found that for catchments with similar geomorphic/geologic evolution histories, HI values were similar and standard deviations were from 0.02 to 0.04. The standard deviation in HI is 0.04 for all six sites and 0.02 for the five cirque sites (1–5), although we note that the sample size is small. In terms of the HI values, these sites are therefore similar and thus differences in response to forcing between the catchments cannot be a function of hypsometry.

Intuitively, steeper slopes should correlate with catchment responsiveness, i.e. we would expect a steep catchment to react more rapidly to a climate forcing, but there is of course a threshold at which slope angle will preclude sediment cover, so rock slopes and response may be very limited to climate forcing, though all slopes under investigation are sediment mantled. Sites 1 to 4 are all very similar with 5 and 6 having lower mean catchment slope angles (Fig. 2d). The reason for Baile na hAbha is very obvious, i.e. it is not a corrie and Com an Lochaigh is due to the location within a larger multi-bowl cirque system.

Morphometric 'differences' are similarly repeated for all measurements, with one exception, mean elevation, which does demonstrate a clear differentiation between the two regions.
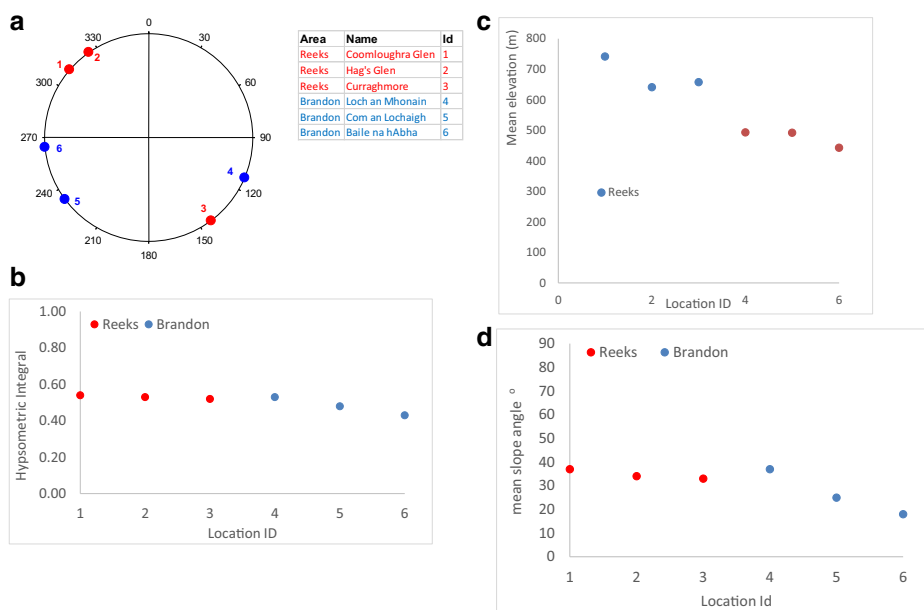

Fig. 2 a Orientation of the study sites. Catchments 3 and 4 are from the precipitation 'lee side' and are hypsometrically similar to catchments 1. If aspect was a controlling factor it would be expected that 3 and 4 should behave concomitantly and different from 1, 2, 5, and 6. **b** Hypsometry (HI) of the study sites in the Macgillycuddy's Reeks and Brandon Mountains. Area ID also included. **c** Catchment slope angles in the Macgillycuddy's Reeks and Brandon Mountain study sites. ID as Figure S10. **d** Mean elevation in the study sites
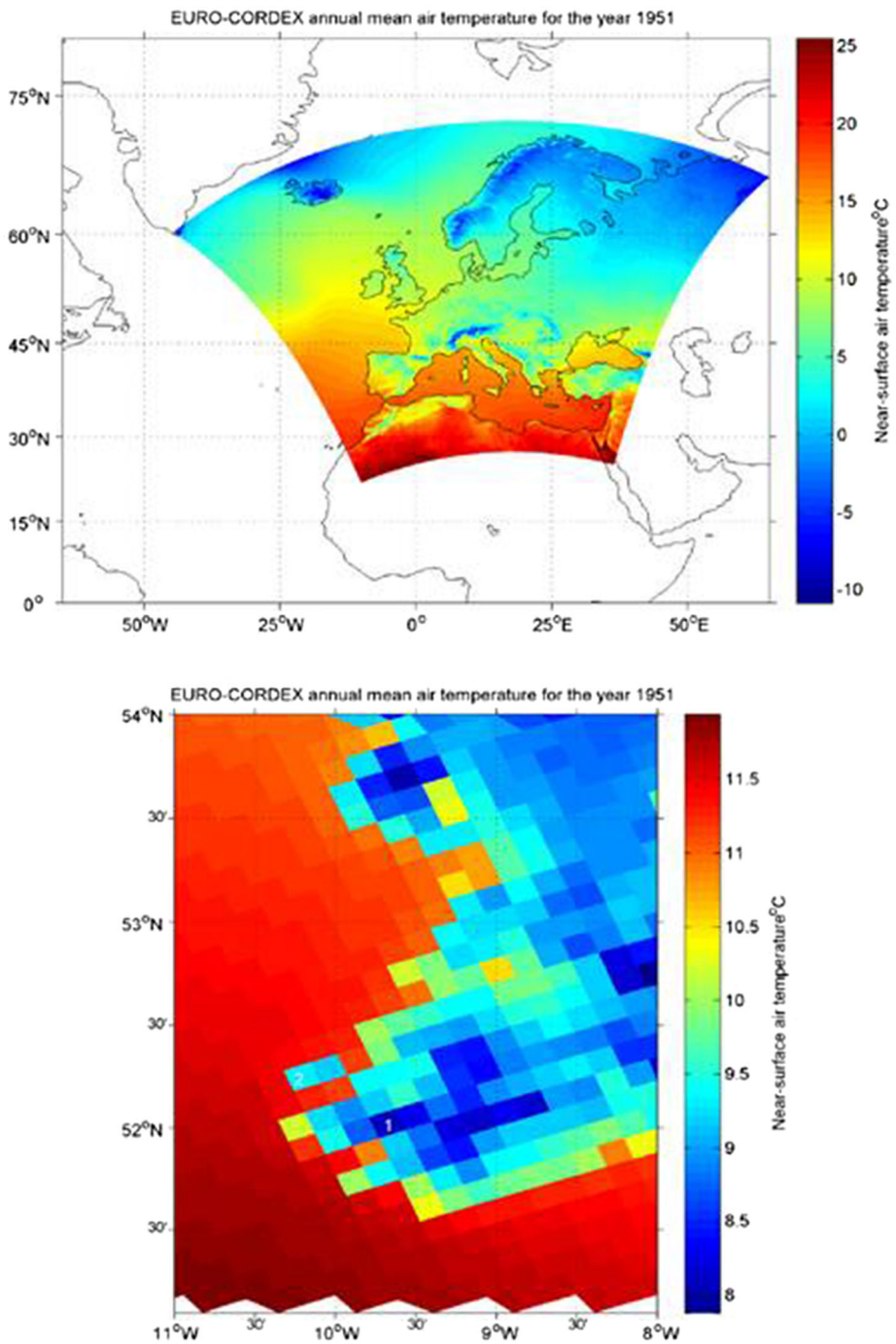
Fig. 3 EURO-CORDEX regional climate model domain (top) and the location of field sites (bottom) where (1) is the Macgillycuddy's Reeks and (2) is the Brandon Mountain

Intuitively, higher elevation catchments would be expected to react more readily than lower elevation but this response is not seen, as demonstrated in the analysis below.

The modelled temperature at Brandon Mountain is approximately 1.2 °C higher than the Macgillycuddy's Reeks due to the warming influence of the Atlantic Ocean (Fig. 3). Under elevated CO_2 concentrations the modelled climate of both sites shows an increase in temperature and a minor reduction in precipitation that is similar in magnitude and statistically significant (see trend values tabulated in Tables 3 and 4). The model shows a projected temperature increase of 0.01 °C year^{-1} and 0.03 °C year^{-1} for RCP4.5 and RCP8.5 respectively and a precipitation reduction of approximately 3–3.6 mm year^{-1}. During the historical period, it gives a warming of 0.01 °C year^{-1} and no statistically significant trend in precipitation at either site (see Figs. 3, 4 and 5 and Tables 3 and 4).

A probability analysis of the data shows that warmer days are more frequent in the modelled future and the distribution of rainfall on wet days is broader, i.e. there is an increased frequency of both wetter and dryer days (see Fig. 3). Both sites experience similar precipitation intensities under elevated CO_2 and over the historical period. Figure 6 shows very little variation between the two sites in the average number of days in a year with light precipitation (5–20 mm day^{-1}) and moderate/heavy precipitation (> 20 mm day^{-1}). The similarity between the two sites in the means and the distributions (standard deviations) of daily temperatures and precipitation indicates that they experience very similar climates. That this is true for both historic and future simulations implies that their climates are closely aligned even as wider climate varies. This provides a good basis for expecting our two mountain massifs to have been similar climatologically throughout the mid to late Holocene. Note, however, that our argument is not that the climate model provides an accurate simulation of historic or future climate in these regions but merely that under the modelled global climate system, the local climates are similar and vary together. One might therefore expect other models, and, indeed reality, to exhibit the same consistency in behaviour between these sites even if the absolute values of climatic variables and their distributions are quite different.

Despite these topographic, geological, geomorphological and climatic similarities between the two massifs, our results demonstrate a strong differentiated response of regional fluvial systems to late Holocene climate change. Figure 7 shows periods of development of depositional valley-side and valley-floor landforms from nine sites in the two massifs. Only two sites (sites 1, 7), one from each massif, show evidence of geomorphological activity with the evolution of landforms (fluvial incision or deposition) between 4500 and 3500 cal BP. Between 2500 and 1700 cal BP, periods of activity occur at four sites on Brandon Mountain (sites 1–3, 5) but there is no evidence of landform evolution in the Macgillycuddy's Reeks. Further, geomorphological activity took place at four sites in Brandon Mountain after 1700 cal BP, including two where fluvial incision or deposition were long lasting, > 1000 years based on nonoverlapping radiocarbon ages. A major phase of landform evolution commenced in the

Table 3 Table of annual near-surface temperature trends and p values to indicate statistical significance

	Brandon Mountain		Macgillycuddy's Reeks	
	Air temperature trend (°C year^{-1})	p value	Air temperature trend (°C year^{-1})	p value
Historical period	0.0094	0.0041	0.0103	0.0031
RCP 4.5	0.0143	0	0.0147	0
RCP 8.5	0.0306	0	0.0319	0

Table 4 Table of annual precipitation trends and associated *p* values

	Brandon Mountain		Macgillycuddy's Reeks	
	Precipitation trend (mm year⁻¹)	*p* value	Precipitation trend (mm year⁻¹)	*p* value
Historical period	1.0596	0.6206	1.6163	0.4262
RCP 4.5	− 3.0502	0.0036	− 3.1293	0.0032
RCP 8.5	− 3.6664	0.0007	− 3.4407	0.0013

Macgillycuddy's Reeks from 1300 cal BP and in the last 500 years. Thus, although both study areas have been exposed to the same climate regime, the geomorphological response to this forcing has varied considerably. In the Macgillycuddy's Reeks, all sites experienced geomorphic activity during the last 1000 years with only one site (site 7) showing stability in the last 500 years. In contrast, at Brandon Mountain, there was little geomorphological activity during this period and none related to the most recent aggradation phase (phase 5 in Fig. 7). Before 1500 cal BP, the Macgillycuddy's Reeks appear to have been relatively insensitive to climate events, whereas Brandon Mountain records all aggradation phases (1–4) except for the most recent. In summary, both massifs have responded to short-term climate changes over the last 4500 years that are considered to have been uniform across the region, but these climate changes have resulted in highly differentiated and nonlinear landscape responses. Unlike other
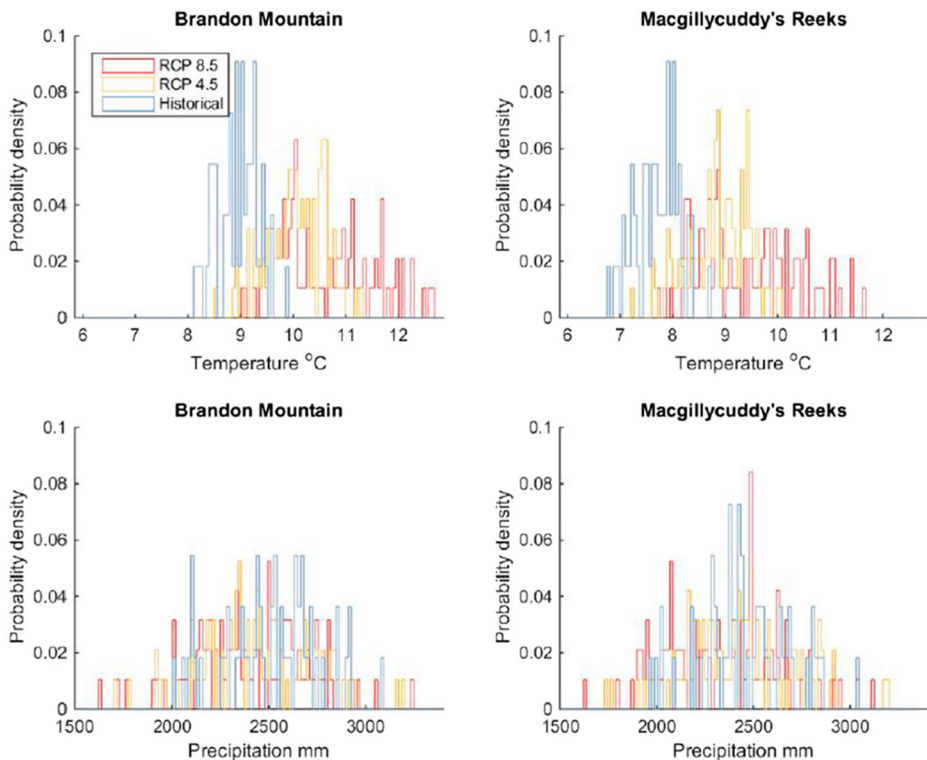

Fig. 4 Probability density for annual mean precipitation and temperature for the historical and future climate change scenarios. The probability density is defined as the number of temperature or precipitation values in a bin divided by the total number of observations. The sum of the bar heights are equal to one
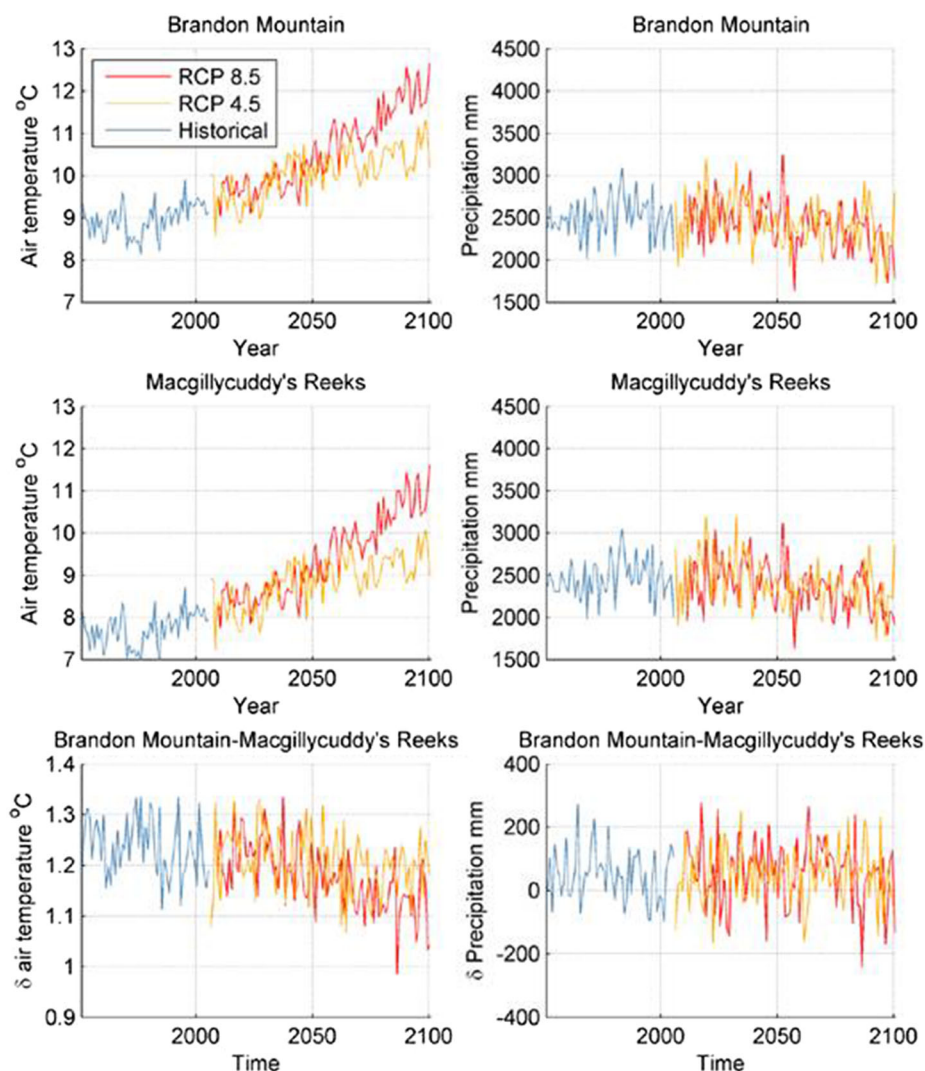
Fig. 5 Time series of the annual near-surface air temperature and precipitation at Brandon Mountain and the Macgillycuddy's Reeks for the EURO-CORDEX datasets. The bottom figures show the temperature and precipitation differences between the two sites

studies, ours here has enabled comparison of response of adjacent systems, not individual systems in isolation, which means we can compare their responses over time and identify when they respond in phase and when in antiphase.

4 Discussion

These results suggest that autogenic feedbacks are significant in determining landform responses to climate forcing; nonlinear behaviour and 'initial condition-like' sensitivity are important in their evolution. External forcing by climate does not always have the ability to

determine uniform geomorphological responses across apparently 'uniform' landscapes, irrespective of the scale of forcing or of system lags (Phillips 2010), though the larger and the more sustained the forcing is, the more likely the whole system is to respond. Additionally, the magnitude of change may be less important than a process shift (e.g. changes in cryogenic weathering driving changes in vegetation dynamics and fluvial incision may be caused by modest climate shifts). Together, these factors imply that regional predictions of landscape response to sustained climate change and/or individual high-magnitude weather events are likely to be very difficult to make for some landscapes and require a probabilistic geomorphological framework (Church 2003) that includes sensitivity to initial conditions, one which is complementary to that found in some climate projections (Corti et al. 2015). This provides challenges to those attempting to develop adaptation strategies where landscape change may be an integral factor determining the climate response of ecological, agricultural, and societal systems. We have shown how a regional-scale landscape has responded to a common past climate change, and this gives us insight into the challenges in describing how it may respond in the future under forcings that are likely of higher magnitude than those experienced throughout the Holocene. The scale of analysis of landscape responses is also pertinent, because adaption policy and management take place at similar spatial scales and so will require geomorphological analyses at these scales.

We show good correlation between periods of wetter climate and UK Holocene flooding episodes (Fig. 7). This strongly suggests that while short-term climate change is the major control on fluvial and alluvial landform development, our two adjacent mountain sites have responded differently. In other words, while the broad-scale picture of fluvial change shows
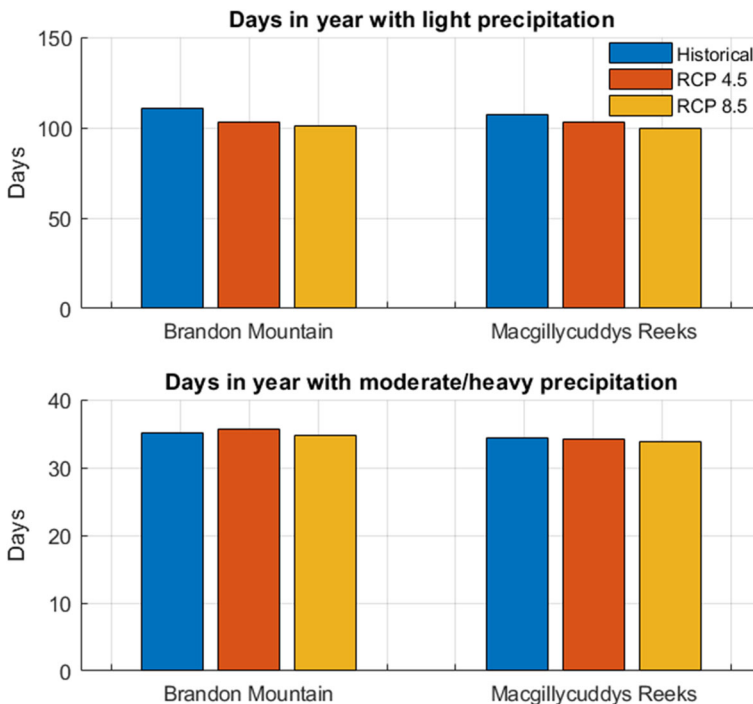

Fig. 6 The average number of days in the year with light (5–20 mm day^{-1}) and moderate/heavy (> 200 mm day^{-1}) precipitation for the historical and future climate change scenarios
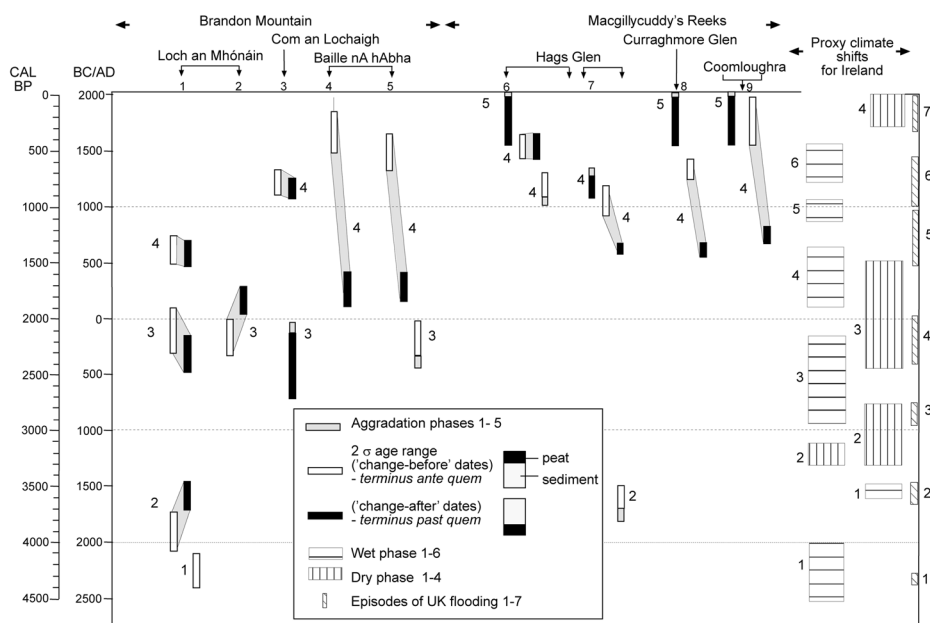
Fig. 7 Phases of geomorphic activity on Brandon Mountain sites 1 and 2 (Loch an Mhónáin), site 3 (Com an Lochaigh) and sites 4 and 5 (Baille nA hAbha) and in the Macgillycuddy's Reeks sites 6 and 7 (Hags Glen), site 8 (Curraghmore Glen) and site 9 (Coomloughra), south-west Ireland (from Anderson et al. 2000). Peat immediately above and below each minerogenic layer associated with a Holocene landform was radiocarbon-dated to ascertain the timing of the deposition of the sediment to infer geomorphological instability. The age of each minerogenic layer is plotted using the two sigma calibrated age ranges of the radiocarbon dates using Calib 6.0 (Reimer et al. 2009, 2013). 'Change-before' dates are where the sample age provides a *terminus ante quem* for the change (open blocks) and 'change-after' dates (shaded blocks) where the sample age provides a *terminus post quem* for the observed sedimentological change (Macklin et al. 2010). Proxy climate records were reconstructed from ombrotrophic (rain-fed only) peat bogs across Ireland based upon changes in plant macrofossils. The timing of wet and/or dry shifts/phases used to infer a climate shift is also shown; composite wet shifts for Britain and Ireland and from individual bogs (Mongan, Abberknockmoy (Barber et al. 2003), wet and dry shifts/phases from Owenmore (new data, this study), dry phases reconstructed from testate amoebae-derived water table reconstructions from ombotrophic peatlands in Northern Ireland (Swindles et al. 2010). Black boxes represent major UK Holocene flood episodes (Macklin et al. 2012)

a climate driver, at the small scale (where adaptation planning and Regional Climate Modelling is focused), the picture is much more complex.

5 Conclusions

We have demonstrated here that river catchment responses to external forcing may be highly spatially and temporally variable and that event-scale forcings result in highly nonlinear and localised responses dependent on catchment properties. It is likely then that in certain contexts, geomorphological responses to climate change are nonlinear, highly sensitive to antecedent conditions, autogenic properties and processes and the processes that amplify, dampen or filter feedbacks. It is also likely the case that different landscape settings (e.g. rivers, paraglacial mountains, coastlines) exhibit different sensitivities to forcing by ongoing climate change than others. Higher sensitivity is likely to result in both higher-magnitude and less predictable

responses. We argue that to provide decision-relevant information to adaptation planners, there is a need to consider the wide range of plausible landscape responses to future weather and climate events. While this can be guided by understanding those processes in the present and the past, it cannot necessarily be deterministically, or even probabilistically (Church 2003), constrained by them. We suggest that the current research focus has led to an information gap between geomorphologists and policy makers. Recognising that both aleatory and epistemic uncertainty exists in geomorphology and evaluating such geomorphological uncertainties would help geomorphologists better guide adaptation planning.

References

Anderson E, Harrison S et al (2000) Holocene alluvial fan development in the Macgillycuddy's Reeks, southwest Ireland. Geol Soc Am Bull 112:1834–1849

Anderson E et al (2001) A Late-Glacial protalus rampart in the Macgillycuddy's Reeks, south-west Ireland. Irish J Earth Sci 19:43–50

Anderson E, Harrison S et al (2004) Late Quaternary river terrace development in the Macgillycuddy's Reeks, southwest Ireland. Quat Sci Rev 23:1785–1801

Ballantyne CK et al (2011) Periglacial trimlines and the extent of the Kerry-Cork Ice Cap, SW Ireland. *Quat Sci Rev* 30:3834–3845

Barber KE, Chambers FM et al (2003) Holocene palaeoclimates from peat stratigraphy: macrofossil proxy climate records from three oceanic raised bogs in England and Ireland. Quat Sci Rev 22:521–539

Barth AM, Clark PU, Clark J, McCabe AM, Caffee M (2016) Last Glacial Maximum cirque glaciation in Ireland and implications for reconstructions of the Irish Ice Sheet. Quat Sci Rev 141:85–93

Benda L, Dunne T (1997) Stochastic forcing of sediment routing and storage in channel networks. Water Res Res 33:2865–2880

Brocklehurst SH. Whipple KX (2004) Hypsometry of glaciated landscapes. Earth Surf Process Landf 29(7):907–926

Burrows MT, Schoeman DS et al (2011) The pace of shifting climate in marine and terrestrial ecosystems. Science 334:652–655

Church M (2003) What is a geomorphological prediction. In: Wilcock PR, Iverseon RM, Prediction in Geomorphology. AGU, 183–194

Collins M, Booth BB et al (2011) Climate model errors, feedbacks and forcings: a comparison of perturbed physics and multi-model ensembles. Clim Dyn 36:1737–1766

Corti S, Palmer T et al (2015) Impact of initial conditions versus external forcing in decadal climate predictions: a sensitivity experiment. J Climate **28**:11, 4454–11, 4470

Coulthard TJ, Lewin J et al (2005) Modelling differential and complex catchment response to environmental change. Geomorphology 69:224–241

Daron JD, Stainforth DA (2013) On predicting climate under climate change. Environ Res Lett 8:034021

Deser C, Knutti R, Solomon S, Phillips AS (2012) Communication of the role of natural variability in future North American climate. Nat Clim Chang 2:775–779. https://doi.org/10.1038/nclimate1562

Harrison S, Mighall T (2002) *The Quaternary of Southwest Ireland*. Quaternary Research Association, Cambridge, 156pp

Harrison S, Glasser N, Anderson E, Ivy-Ochs S, Kubik PW (2010) Late Pleistocene mountain glacier response to North Atlantic climate change in southwest Ireland. Quat Sci Rev 29:948–3955

Hawkins E, Sutton R (2009) The potential to narrow uncertainty in regional climate predictions. Bull Amer Meteorol Soc 90:1095–1107

Hawkins E, Smith R, Gregory J Stainforth DA (2015) Irreducible uncertainty in near-term climate projections. Clim Dyn 1–13. doi:https://doi.org/10.1007/s00382-015-2806-8

Jacob D, Petersen J, Eggert B, Alias A, Christensen OB, Bouwer LM, Braun A, Colette A, Déqué M, Georgievski G, Georgopoulou E (2014) EURO-CORDEX: new high-resolution climate change projections for European impact research. Reg Environ Chang 14(2):563–578

Jenkins G, Murphy J, Sexton D, Lowe J, Jones P (2009) UK Climate Projections. Briefing Report. Department for Environment, Food and Rural Affairs (DEFRA), London

Knight J, Harrison S (2011) Evaluating the impacts of global warming on geomorphological systems. Ambio 41:206–210

Knight J, Harrison S (2013) The impacts of climate change on terrestrial Earth surface systems. Nat Clim Chang 3:24–29

Knutti R (2008) Should we believe model predictions of future climate change? Philos Trans R Soc 366:4647–4664

Knutti R, Sedláček J (2012) Robustness and uncertainties in the new CMIP5 climate model projections. Nat Clim Chang 3:369–373

Lague D, Hovius N et al. (2005) Discharge, discharge variability, and the bedrock channel profile. J Geophys Res 110(F4). doi:https://doi.org/10.1029/2004JF000259

Lane SN (2013) 21st century climate change: where has all the geomorphology gone? Earth Surf Process Landf 38(1):106–110

Lowe J, Bernie D, Bett P, Bricheno L, Brown SJ, Calvert D, et al. (2018) UKCP18 Science Overview report November 2018. Met Office Hadley Centre

Macklin MG, Jones AF et al (2010) River response to rapid Holocene environmental change: evidence and explanation in British catchments. Quat Sci Rev 29:1555–1576

Macklin MG, Fuller IC et al (2012) New Zealand and UK Holocene flooding demonstrates interhemispheric climate asynchrony. Geology 40:775–778

Maslin M, Austin P (2012) Uncertainty: climate models at their limit? Nature 486:183–184

Oppenheimer M, Little CM, Cooke RM (2016) Expert judgement and uncertainty quantification for climate change. *Nat Clim Chang* 6(5):445

Phillips JD (2010) Amplifiers, filters and geomorphic responses to climate change in Kentucky rivers. Clim Chang 103:571–595

Rae A, Harrison S et al (2004) Periglacial trimlines and former nunataks of the Last Glacial Maximum (LGM) in the vicinity of the gap of Dunloe, southwest Ireland. J Quat Sci 19:87–97

Ramankutty N, Gibbs HK et al (2006) Challenges to estimating carbon emissions from tropical deforestation. Glob Chang Biol 13:51–66

Reimer, P.J, Baillie, M.G.L. et al. (2009) Quaternary Isotope Laboratory, Radiocarbon Calibration Program, University of Washington. http://radiocarbon.pa.qub.ac.uk/calib/calib.html

Reimer PJ, Bard E, Bayliss A, Beck JW, Blackwell PG et al (2013) IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon 55:1869–1887

Schumm SA (1979) Geomorphic thresholds: the concept and its applications. *Trans. Inst. Brit. Geogr*, NS 4:485–515

Smith LA (2002) What might we learn from climate forecasts? Proc Nat Acad Sci U S A 99(Supp 1):2487–2249

Spagnolo M, Pellitero R, Barr ID, Ely JC, Pellicer XM, Rea BR (2017) ACME, a GIS tool for automated cirque metric extraction. Geomorphology 278:280–286

Spencer T, Naylor L, Lane S, Darby S, Macklin M, Magilligan F, Möller I (2017) Stormy geomorphology: an introduction to the special issue. Earth Surf Process Landf 42(1):238–241

Stainforth DA, Smith LA (2012) Clarify the limits of climate models. Nature 489:208

Stainforth DA, Allen MR et al (2007) Confidence and uncertainty and decision-support relevance in climate predictions. Phil Trans Roy Soc A 365:2145–2161

Swindles G, Blundell A et al (2010) A 4500-year proxy climate record from peatlands in the North of Ireland: the identification of widespread summer 'drought' phases. Quat Sci Rev 29:1577–1589

Wells SG, Harvey AM (1987) Sedimentologic and geomorphic variations in storm-generated alluvial fans, Howgill Fells, northwest England. Geol Soc Am Bull 98:182–198

Wise RM, Fazey I, Smith MS, Park SE, Eakin HC, Van Garderen EA, Campbell B (2014) Reconceptualising adaptation to climate change as part of pathways of change and response. Glob Environ Chang 28:325–336

Xie SP, Deser C et al (2015) Towards predictive understanding of regional climate change. Nat Clim Change 5(10):921

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Affiliations

Stephan Harrison[1] · Tim Mighall[2] · David A. Stainforth[3] · Philip Allen[4] · Mark Macklin[5] · Edward Anderson[6] · Jasper Knight[7] · Dmitri Mauquoy[2] · David Passmore[8] · Brice Rea[2] · Matteo Spagnolo[2] · Sarah Shannon[9]

[1]   College of Life and Environmental Sciences, Exeter University, Penryn TR109EZ, UK

[2]   School of Geosciences, University of Aberdeen University, Aberdeen AB24 3FX, UK

[3]   Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science, London, UK

[4]   Department of Geography, Frostburg State University, Frostburg, MD, USA

[5]   School of Geography, College of Science, University of Lincoln, Lincoln LN6 7TS, UK

[6]   Stockton Riverside College, Harvard Avenue, Stockton-On-Tees, Durham, UK

[7]   School of Geography, Archaeology and Environmental Studies, University of the Witwatersrand, Johannesburg, South Africa

[8]   Department of Geography, University of Toronto Mississauga, Mississauga, Ontario, Canada

[9]   School of Geographical Sciences, University of Bristol, Bristol BS8 1TH, UK