Institution: The University of Edinburgh

Unit of Assessment: Earth Systems and Environmental Sciences (B7)

a. Overview

Who we are: This submission represents the research of the School of GeoSciences. With over 400 academics, researchers and research students, we are the largest grouping of geoscientists in the UK. In our research we explore the factors and forces that shape our world and the environments in which we live. Our mission is to develop a better understanding of the coupled Earth System, that is, the interactions between the Earth's geology, atmosphere, oceans, biosphere and cryosphere, the drivers of variability and change, and the roles and responses of humans in this complex interplay. As indicators of our success in this REF period, we have secured the largest value of NERC grant awards of any HEI Department (£17.3M since August 2008); a total research grant income of £66.7M; the University of Edinburgh 'Geography' and 'Earth and Marine Sciences' were ranked 14th and 16th in the 2013 QS World University Rankings by Subject, and we have 64 papers in the highest impact journals for our field (*Science*, *Nature*-group, and *PNAS*).

Distinctive features: A distinguishing feature of the School is the combination of breadth, relevance and strength of our research. Our research embraces issues relating to equality and vulnerability, development and sustainability, climate and environmental change, energy, food and water security, mitigation of anthropogenic environmental change, natural resources, waste management, and natural disasters. By creating and supporting an intellectual environment that explicitly strives to remove barriers between disciplines, engenders ambition, and encourages internal and external collaboration, we lead in addressing some of the most compelling issues of our time. We address these 'grand challenges' through: interdisciplinary research that builds on strong core disciplines (ecology, environmental sciences, geography, geology, geophysics, meteorology, oceanography); approaches that range from whole-system-scale modelling to process studies and critical analysis; actively fostering collaboration with academic and non-academic stakeholders within and beyond the University, nationally and internationally.

Organisation and structure: Three **Research Institutes** provide strategic direction and research support:

- **Global Change** – examines past, present and future changes in the Earth's surface and near surface environments through measurement, theory, and computational modelling;
- **Earth and Planetary Sciences** – focuses on geology and geophysics relevant to earth dynamics, resources, natural hazards, and the environment;
- **Geography and the Lived Environment** – addresses connections between people, society and the environment using scientific, social scientific, policy and geographical frameworks.

Research Institutes provide thematic focus, help ensure interdisciplinary reach and form the stable management structure upon which the School operates. Each Institute is structured into **Research Groups** of researchers with cognate interests. The membership and foci of Research Groups evolves through time, reflects the dynamic nature of the research environment and ensures that researchers can respond to opportunities. Research Groups have specific thematic priorities and span Research Institutes. A key strength of the School of GeoSciences is its integration into a single organisational unit of research spanning Earth Systems and Environmental Sciences and Geography. In recognition of this continuum, some of our research outputs are cross-referred to UoA C17, Geography, Environmental Studies and Archaeology.

b. Research strategy

B.1 Vision, Strategic Principles and Enabling Structures:

Our vision for the School is that of a world-leading research centre in the geosciences, distinguished by interdisciplinary reach and leadership in addressing 'grand challenge' questions of academic, social and economic importance. To achieve this vision, our strategy has included identifying priority areas for investment; supporting prominent researchers in leading major national and international initiatives; increasing the reach and relevance of our research by developing collaborative partnerships with stakeholders beyond the academy; and recruiting and supporting the best early career researchers (ECR). Here we summarise our high-level successes mapped

against the 'strategic priority areas' we identified in RAE2008. We then provide more detail on achievements by Research Group, identify future strategic priorities, and describe the structures and processes that support the responsive evolution and delivery of strategy.

2008 Priority Research in Global Change: We have expanded our research in climate and earth system observations and modelling, and in associated terrestrial biosphere, cryosphere, marine and landscape evolution research. This highly interdisciplinary research on the nature and drivers of environmental variability and change builds on strategic partnerships made through our leadership of the SAGES (Scottish Alliance for Geosciences Environment and Society) research pooling initiative involving 10 HEIs and an initial (2006) SFC and HEI investment of £22M. Strategic School support through the REF period to ensure continued growth included investment in 15 academic posts (including 11 ECR) and in facilities (£2M).

***Evidence of success**:*

- **Leadership roles** in major research consortia, programmes and initiatives. For example: **IPCC Lead Author** (Hegerl); leadership of **NERC Consortium Grants: ABACUS** (Arctic Biosphere-Atmosphere Coupling; M. Williams), **GAUGE** (Greenhouse gAs Uk and Global Emissions; Palmer) and **GREENHOUSE** (Generating Regional Emissions Estimates with a Novel Hierarchy of Observations and Upscaled Simulation Experiments; M. Williams); **ERC Advanced Fellowship** (Hegerl); **Director** (Crowley, Kerr) of **SAGES** research pool.
- A total of £12M in competitive external research income in the REF period; and 42 papers published in *Science*, *Nature*-group, and *PNAS*.

2008 Priority Area in Earth and Planetary Science: We have expanded research capability and industrial collaboration in areas associated with carbon capture and storage (CCS), hydrocarbon exploration, and earth dynamics. This builds on the Edinburgh Collaborative on Subsurface Science and Engineering (ECOSSE) research pooling initiative (with the British Geological Survey (BGS) and Heriot-Watt University). Strategic support through the review period included investment in 16 academic posts (including 6 ECR) and £1.4M in new equipment and facilities.

Evidence of success:

- We direct (Haszeldine) **Scottish Carbon Capture and Storage** (SCCS; joint with BGS and Heriot-Watt University), which has secured £9.6M in research funding and which has major national and international Knowledge Exchange (KE) and policy dimensions.
- We led the 3.0M€ **EU FP7 Biobased geological CO_2 Storage (CO2SOLSTOCK)** Consortium (Ngwenya, Butler) and we have developed and now lead the **UK BIOCHAR Research Centre**, which has received £1.6M in competitive research funding.
- We co-lead (Wood) the **International Centre for Carbonate Reservoirs** (ICCR) an industrial consortium (with Heriot Watt University) that has received £1.7M in industrial funding, and Curtis leads a new £1M industrial consortium in **Seismic Interferometry**. The industrial consortium **Edinburgh Anisotropy Project**, (EAP, collaborative with BGS, which we lead through Chapman) won the prestigious **Distinguished Achievement Award** (2012) from the Society of Exploration Geophysics. In total, Joint Industry Partnerships (JIPs) have secured £5M in research income.
- **Natural Hazards** research has secured £1.4M in funding from NERC, EU and EPSRC (Main).

2008 Priority Area in Geography and the Lived Environment: We have strengthened capability and leadership in research at the science-society-policy interface, addressing critical questions associated with inequalities, climate and environmental change, land-use, socio-ecological systems, international development and, energy. Strategic support included investment in 18 academic posts (including 6 ECR).

Evidence of Success:

- We built strategically on aspects of SAGES to create the **Edinburgh Centre for Carbon Innovation** (ECCI), a new interdisciplinary and inter-institutional facility at the research-business-policy interface. Led by former SAGES Director, Kerr, the ECCI has received £2.2M in Scottish Government funding to host the **ClimateXChange**, and a **major European Regional Development Fund-supported initiative on green technologies**. Investment of

£10.5M in a custom-refurbished building to host the Centre by the University of Edinburgh (UoE) the Scottish Government and other partners will ensure future sustainability;
- We lead **OPERA (*Op*erationalising *E*uropean *R*esearch *A*pplications)**, a 12.5M€ FP7 European consortium in which research in ecosystems services is being turned into strategic approaches and policy instruments for best-practice management of diverse socio-ecological systems (Rounsevell, Metzger, Patenaude, A. M. Wilson); and we lead the £2.0M **ACES: Abrupt Changes in Ecosystem Services ESPA consortia** (Patenaude, Ryan, Fisher);
- We established and lead **CRESH (Centre for Research on Environment, Society and Health)** as a cross-sectoral research initiative (Pearce, Shortt), with funded research projects on environment and health outcomes in the USA, UK and New Zealand to a total of £1.8M;
- We have established and led the University's **Global Environmental and Society Academy** as part of the University's internationalization strategy (Rounsevell, Reay, A. M. Wilson).

B.2 Research Achievements by Research Institute and Research Group

Here we provide a more detailed breakdown of research foci and exemplar achievements presented by Research Group. These Groups are listed under the most relevant Institute.

Global Change Research Institute

Atmospheric Chemistry & Climate of the Anthropocene *[Bollasina, Doherty, Essery, Hegerl, Palmer, Pumphrey, Stevenson, Tett]*. The Group studies the current climate system and atmospheric composition using data, models and theory. We aim to understand the causes of past climate change to help constrain future climate; changes in the atmospheric composition; and the links between atmospheric chemistry, air pollution, climate forcing, human health and ecosystem impacts. We discovered that human activities have caused changes in extreme precipitation (**Hegerl, *Nature*, 2011**), and that late 20th century weakening of the South Asian Summer Monsoon is related to anthropogenic aerosols (**Bollasina, *Science*, 2011**). Important new constraints on climate sensitivity to CO_2 forcing have been placed using top of atmosphere radiation measurements and modelling (**Tett, *J. Climate*, 2013**). We have quantified emissions of methane to the atmosphere and discovered that emissions in the tropics are driven by changes in the water table depth while changes in the extra-tropics are driven by surface temperature (**Palmer, *Science*, 2010**). The tropospheric forcing of ozone, another greenhouse gas which has impacts on human and ecosystem health, has been attributed to increases in precursor emissions (**Stevenson, Doherty, *Atmos. Chem. Phys.*, 2013**). Future priorities are investigation of the causes of climate change over the last 200 years, including extremes and transient climate response, developing better understanding of the processes behind the hemispheric transport of pollutants, and quantifying the magnitude and uncertainty of emissions of greenhouse gases.

Biosphere *[Dexter, Grace, Graham, Heal, Lehmann, McLeod, Meir, Mencuccini, Mitchard, Moncrieff, Myers-Smith, Nichol, Reay, Ryan, M. Williams]*. The Group's research focuses on terrestrial, freshwater and coastal ecosystems and their interactions with other components of the Earth System. The research is global in reach, and uses fieldwork, genetics, laboratory experimentation, air and space-borne remote sensing, and soil, plant and atmospheric modelling. We have demonstrated the role of historical processes in community assembly (**Dexter**, ***PNAS*, 2012**), and provided new understanding of the evolution of plant defences to herbivores (**Dexter**, ***PNAS*, 2009**). We have made a ground-breaking estimation of tropical forest carbon across the entirety of the tropical land mass (**Mitchard**, ***PNAS*, 2011**); shown how old-growth forests are currently acting as significant global carbon sinks, thereby addressing critical uncertainties in the terrestrial carbon cycle (**Grace, *Nature*, 2008**), and quantified the sensitivity of the Amazon forest carbon sink to intense drought (**Meir, *Science*, 2009**). **McLeod (*New Phytologist*, 2008**) discovered that ultraviolet radiation drives methane emissions from terrestrial plants, and that carbonaceous meteorites could explain atmospheric methane on Mars (***Nature*, 2012**). We have developed a simple model that accurately predicts pan-Arctic terrestrial net exchanges of CO_2 (**Williams, *Phil. Trans. Roy. Soc.*, 2013**). Future priorities are to understand changes in fluxes of nitrogen, methane and carbon between the terrestrial biosphere and the atmosphere.

Cryosphere *[Bingham, Goldberg, Gourmelen, Hein, Hulton, Nienow, Sugden]:* The Group brings together remote sensing, field study and modelling to understand ice sheets, glaciers and their

response to both current and past environmental change. Highlights include: the discovery that increased surface melting on the Greenland Ice Sheet does not lead to an increase in ice discharge as feared, due to hydrology-dynamics coupling (**Nienow, *Nature Geosci*. 2010, 2013, *Nature,* 2011**); development of a new generation of models to quantify the controls on ice-sheet instability in West Antarctica (**Goldberg, *J.Geophys. Res.,* 2009**); insights into the origin and dynamic early history of the Antarctic Ice Sheet (**Sugden, *Nature,* 2009, 2011; Bingham, *Nature*, 2012**); demonstration of tight coupling between dust in Antarctic ice cores and stage of Patagonian glaciation, rather than global climate (**Sugden, *Nature Geosci*., 2009**); and development of a new exposure-dating approach to unravel the history of the earliest glaciations in South America (**Hein, Hulton, *Geology,* 2011**). Future priorities include investigation of the nature and drivers of past and present change in the Antarctic Ice Sheet, and developing a better understanding of the marine and climatic controls on calving glaciers and ice shelves.

Land Surface Dynamics *[Attal, Hein, Kirstein, Mudd, Sinclair, Summerfield]:* The Group examines processes controlling the evolution of landscapes in response to climatic and tectonic forcing using fieldwork, remote sensing, modelling, and dating. We have developed a new model to quantify relationships between sea level change, salt marsh accretion and carbon sequestration and illustrated that salt marshes will decline as sea levels rise (**Mudd, *Geology*, 2009; *Nature*, 2012**). The role of sediment in controlling long-term river erosion has been demonstrated (**Attal, *Geology*, 2008**), and the geomorphic signature of storm events in the Himalaya used to reconstruct extreme precipitation (**Sinclair, *Geology,* 2012**). **Mudd and Attal** (***Science*, 2013**) discovered that hill slope curvature may be used to infer long-term rates of tectonic uplift, and **Sinclair** (***EPSL*, 2008**) discovered that Alpine erosion rates accelerated in response to long-term climate change. Future priorities include developing topographic analysis to constrain tectonic activity, examining the relationship between river flow and sediment load, and investigating the feedback between tectonics, climate and erosion using coupled climate-landscape evolution models.

Oceans and Past Climate *[Bird, Cowie, Darling, Ganeshram, Geibert, Henley, Jung, Kroon, Pichevin, Thomas, Tudhope].* The Group investigates the nature, mechanisms and drivers of past and present climate and environmental variability and change, using fieldwork, geochemistry, experimentation and modelling. Highlights include quantification of the timing and rates of rapid sea level rise during deglaciations (**Thomas**, ***Science*, 2009, *Nature*, 2012**); revealing the sensitivity of ENSO to global climate change over the past 22ky (**Ganeshram, Pichevin, Tudhope, *Nature Commun*., 2013**); improved understanding of the role of nutrient cycling and atmospheric CO_2 on orbital time scales (**Geibert, *Nature*, 2011**); identification of an enhanced biological pump drawing down CO_2 in the last glacial (**Pichevin, Ganeshram, *Nature*, 2009**); and discovery that the Atlantic deep circulation was reversed during the last glaciation (**Thomas, *Nature*, 2010**). We used genetic evidence to reveal that some foraminifera may have survived mass extinction events by bridging the planktic-benthic divide (**Darling, *PNAS,* 2008);** and we identified and quantified recent decline in the growth rate of tropical corals due to climate change (**Tudhope, *Coral Reefs,* 2009).** Future priorities are to use novel geochemical proxies to improve understanding of processes controlling carbon and nutrient cycling in the world's oceans (past and present), and, using combined palaeodata-climate modelling approaches, to better constrain estimate of future climate variability and change.

Earth and Planetary Sciences Research Institute

Earth Dynamics, Evolution and Environment *[Bromiley, Brusatte, Butler, de Hoog, Fitton, Fusseis, Harley, Hayward, Kroon, Ngwenya, Nichol, Odling, Robertson, Saunders, Tait, Wood]:* The Group explores the dynamic nature of the Earth in terms of its tectonic and magmatic history and the evolution of life. Highlights include discovery that change in carbonate skeletal mineralogy through time is controlled by global seawater chemistry and atmospheric CO_2 interacting with ecological function (**Wood, *Geology*, 2009**); that the rise of dinosaurs was gradual prior to mass extinctions thus allowing evolutionary radiations (**Brusatte, *Science*, 2008**), yet some dinosaur groups experienced long-term declines in the 10-15 million years prior to their final extinction at the end of the Cretaceous (**Brusatte, *Nature Commun.,* 2012**). We produced the first 3D image showing the distribution of melt in partially molten peridotites (**Fusseis, *Science*, 2011**); showed that rare earth elements in zircons can be used to evaluate the conditions and timing of their crystallisation from melts deep in orogenic belts (**Harley, *J. Petrol.*, 2010**); demonstrated how the

complete range of Fe isotope compositions measured from natural pyrite throughout Earth's history can be produced inorganically without recourse to microbial processes as previously assumed (**Butler, *Science*, 2011**); and developed the 'granular fluid pump' model to explain how fluids are transferred through the mid-crust (later shown to apply also to lower-crust) (**Fusseis, *Nature*, 2009**). Future priorities include low temperature fluid-rock interactions, tracking contaminants using trace element or isotopic sensors to estimate the spatio-temporal evolution of fluid-rock interactions in both man-made (nuclear waste geological disposal facilities, CCS sub-surface systems, mines) and natural systems, and studying the long-term interaction between global environmental change and the evolutionary dynamics of both terrestrial and marine life.

Solid Earth Geophysics and Natural Hazards *[Bell, Calder, Cayzer, Chapman, Craven, Curtis, Hinton, Komabayashi, Main, Naylor, Olsen, Saunders, Stevenson, Tait, Whaler, W. Williams, Wright, Ziolkowski]:* The Group's research focuses on estimating and interpreting the Earth's internal physical properties; investigating the physics of Earth dynamics and processes such as earthquake triggering, mineral magnetization, continental rifting, and flow in the Earth's outer core; and developing and testing robust statistical, probabilistic and forecasting methods for hazards such as earthquakes and volcanic eruptions. Highlights include finding the physical process underlying the inter-event time distribution of naturally-induced earthquakes (**Naylor, *Phys. Rev. Let.*, 2009**), showing how earthquakes themselves can be used as seismometers (like microphones) deep in the Earth, recording seismograms from other earthquakes (**Curtis, *Nat. Geosci.*, 2009**), and demonstrating the ability to link petrologically-constrained timescales of magmatic processes to timescales of active geophysical volcano monitoring networks (**Saunders, *Science*, 2012**). We have used magnetotellurics to show a substantial magma reservoir in the mantle (where it 'should' be over-buoyant) beneath a Quaternary magmatic segment in Afar, Ethiopia (**Whaler, *Nature Geosci.*, 2013**), and our magnetic mineralogy research has been applied in the design of magnetic recording media, and in understanding magnetotactic bacterial biomineralisation (**W. Williams, *Nat. Nanotech.*, 2008**). Future priorities include developing and applying new models to better define probability and uncertainty in seismic hazard analysis, to re-draw the UK Seismic Hazard Map, and to quantify probabilistic forecast quality for natural hazards in real-time applications. New methods of analysis will be applied to data from a constellation of new near-Earth orbiting magnetometry satellites to model mantle electrical conductivity and test theories of core dynamics (e.g., **Olsen, *Nature Geosci.*, 2008**).

Geological Resources and Waste Storage *[Butler, Chapman, Curtis, Fusseis, Gilfillan, Harley, Haszeldine, Ngwenya, Sohi, Wilkinson, Wood, Wright, Ziolkowski]:* The Group develops research methods and strategies to locate, characterise and monitor: geological reservoirs of resources such as oil, gas, water and geothermal heat; sites for geological storage of waste; and transport and fate of pollutants. Research highlights include demonstrating that the key mechanism for storing CO_2 in natural reservoirs over millions of years is dissolution into reservoir formation water and that formation of new solid minerals is not a significant mechanism (**Gilfillan, *Nature*, 2009)**; a tested and practical workflow and technology for assessing the potential for CO_2 storage of large subsurface aquifers (**Haszeldine, *Science*, 2009**); and an assessment of long-term mud-rock CO_2 sealing capabilities (**Wilkinson, *Geology*, 2013**). Development of interferometric wave theory **Curtis (*Phys. Rev. E,* 2010)** led to a new class of nonlinear subsurface imaging methods being transferred to industry; and, a unification of previously-distinct theories of anisotropic poroelasticity improved fluid & fracture property estimates from seismic data (**Chapman, *Geophysics*, 2009**). Future research priorities are in the areas of reservoir quality and subsurface imaging.

Geography and the Lived Environment Research Institute

Human Geography *[Bondi, Brady, Cupples, Ellis, Ginn, Hasty, Ioris, Johnston, Laurier, Lovell, MacDonald, Morris, Pearce, Penrose, Ruwanpura, Shortt, Slater, Swanton, M. Wilson, Withers]*: The Group structures its activities around four thematic priorities: 'Materialising Geographies', 'Lived Geographies', 'Just Geographies' and 'Nature's Geographies'. The Group's work addresses one or more of these themes in different geographical contexts, employing a variety of methodologies, often in interdisciplinary ways. We have examined in new ways the geographies of uneven resource disposition in advanced economies and the global south; explored and explained differentials in health, wealth, and well-being; and illuminated in historical and comparative context questions concerning nature, the environment, and the geography of science. Research highlights

include: a major new interdisciplinary synthesis of environmental philosophy and aesthetics (**Brady, *The Sublime in Modern Philosophy: Aesthetics, Ethics and Nature*, 2013**) which offers innovative critical appraisal of a leading conceptual category (the sublime/sublimity) in philosophy, environmental interpretation and aesthetics; establishing new perspectives in the relations between environment and socio-spatial inequalities in health and well-being (**Pearce, *Annals Ass. Amer. Geogrs*., 2010; *Prog. Human Geog*., 2012; *Trans. Inst. Brit. Geogrs*., 2010)**; establishing connections between the science of geography and the geographies of science in historical and institutional context in a work which challenges profoundly the received wisdom of the last 25 years (**Withers, *Geography and Science in Britain 1831–1933*, 2010**); recasting connections between gentrification and displacement (**Slater, *City*, 2009**); and demonstrating how climate change is catalysing new forms of technology and policy innovation (**Lovell, *Env. Plan. C*., 2009**). Future priorities include investigating the links between environment, health, politics, and human behaviour; new ways of understanding urban marginality in comparative international context, and questions of access to resources (e.g., health care, clean water, housing, food); work on the aesthetics of nature and environment; and historical geographies of science and metrology.

Environment and Society *[Dugmore, Fisher, Lovell, Mackaness, Metzger, Newton, Panagiotakopulu, Patenaude, Reay, Rounsevell, Shackley, Van der Horst, Woodhouse].* The Group focuses upon environment-society relationships, including assessment of the consequences of environmental change for human livelihoods, and analysis of past human-environment interactions. The Group's activities are structured around four thematic priorities: understanding processes of socio-ecological and socio-technical systems; environmental governance (including carbon, energy, land-use); ecosystem services; and earth observation and spatial analysis. We are distinctive in our temporal reach – undertaking novel conceptual and empirical research on major transitions in the past (Dugmore, Newton), present (Lovell, Shackley, van der Horst), and future (Metzger, Rounsevell, Reay) – and across different spatial scales (households, communities, cities, and continents). We work in conjunction with policy, industry, and third sector organisations to illuminate policy: the co-creation of data and knowledge with stakeholders is integral to our work. Research highlights include: creating a new environmental stratification model as the basis to national, European, and global ecological modelling (**Metzger, *Glob. Ecol. and Biogeog*., 2013**); demonstrating the importance and uncertainties of nitrous oxide in greenhouse gas accounting (**Reay, *Nature Climate Change*, 2012**); advancing futures analysis and socio-ecological systems modelling (**Rounsevell, *Lands. Ecol*., 2009; *Global Env. Change*, 2013**); developing novel measures of land surface resilience and tools to anticipate threshold change (**Dugmore, *PNAS*, 2012a, 2012b; *Holocene*, 2013**); developing new insights about climate change and energy including the reasons for conflict over onshore wind farms (**Van der Horst, *Land Use Pol*., 2010**); explaining environmental change and socio-economic continuity and collapse in Greenland and the Mediterranean (**Panagiotakopolu, *Boreas*, 2013; *Naturwissenschaften*, 2013**). Future priorities include: using large globally-relevant data sets to better understand processes of change, innovation and transition; new ways of using and displaying information such as visual analytics; developing novel empirically-rich understandings of environmental resilience and security; and providing new insights into the catalysts for major socio-ecological and socio-technical system transitions.

B.3 Future Strategy

We have identified the following areas as strategic priorities for future investment. These all build from areas where we have a core of existing research excellence and address fundamental and applied research that is central to 'grand challenge' questions facing society. They build not only on the interdisciplinary framework within the School but also within the University (e.g., collaborations with the Schools of Engineering, Informatics, Business, Social and Political Science, Physics and Astronomy, Chemistry, and Law), and beyond. Each has a strong international component through collaborations and strategic partnerships. (Contributing Research Institutes in brackets; GC = Global Change; EPS = Earth and Planetary Sciences; and GLE = Geography and the Lived Environment).

- **Earth System Modelling and Prediction (GC):** We will enhance our existing investments in the modelling of complex earth systems by the improved integration of observations (e.g., remote sensing) and modelling, and by further coupling of climate, biosphere, ice and

landscape evolution models, focusing on feedbacks and uncertainties in future prediction.

- **Ecosystems and Ecosystems Services (GC, GLE):** We will develop our expertise in landscape-scale terrestrial ecology, in particular on atmosphere-biosphere-climate feedbacks and research at the science-social science-policy interfaces to address questions on sustainability, ecosystem services and food security. We will develop a Centre for Integrated Forest Science that will draw in partner organisations to build critical mass and facilitate growth of this research at the fundamental-applied boundary.
- **Natural Hazards (EPS; GC, GLE):** We will grow our research on natural hazards including seismic, volcanic, and extreme weather and climate. We will develop interdisciplinary research that ranges from the physics of the processes through to the risks, hazards, societal and economic impacts, the policy relevance, as well as the social and political processes affecting societal resilience. To facilitate this work we will create a Centre for Natural Hazards Research with other academic and non-academic partners.
- **Energy Resources and Waste Storage (EPS; GLE):** We will build on our research collaborations with engineers, business, policy makers and the finance industry around energy futures, including carbon sequestration, unconventional hydrocarbon exploration and production (e.g., shale gas), exploration geophysics, and the low carbon economy. To help achieve this, we will develop an Edinburgh Industrial Geoscience identity and will further expand collaborations internationally.
- **Marine (GC; GLE):** We will expand our research capability in marine science and policy relevant to current and future climate change by targeting investment in facilities and strategic development of partnerships with other research organisations and with policy makers.
- **Human-Environment Interaction (GLE):** We are significantly expanding our work on the geographies of health, well-being and urban justice, including, immediately post REF, leading the Scottish Longitudinal Studies Centre and the new ESRC Administrative Data Research Centre. We will address the philosophical bases to the human understanding of environment and nature, and build on our recent work to promote new understanding of the politics of nature and natural resources in advanced economies and in the Global South.
- **Big Data (GC, EPS, GLE):** All of the aforementioned priority areas have Big Data requirements and opportunities. We will build on our exceptional foundation in the School and University by further investing in infrastructure, academic posts and academic, government and industry collaborations to provide a transformative capability for the wider research community.

B.4 Structures and processes to deliver a vibrant and responsive research strategy

To support the evolution and delivery of strategy, we have established structures and processes that maximise the benefits of our large and interdisciplinary research environment. A stable ***Research Institute management structure*** provides support for the evolution and development of Research Groups that bridge disciplines and which are responsive to opportunities. Research Institutes participate in an annual planning exercise to assess progress against stated goals, and identify opportunities and plans for the next 1-2 and 2-10 years. This ensures that good ideas evolve dynamically into a rolling School plan that identifies immediate priorities and long-term strategies. ***Support for identifying and realising new research opportunities*** is delivered through the combined services of the School Research Organisation (Director of Research, administrative support and School funding), the School's Business Development Executive (BDE) and Edinburgh Research and Innovation (ERI), the University's central body overseeing research, innovation and technology transfer. Support includes improving research proposals through internal peer review; workshops on funding opportunities and grant writing; fostering of relationships between funders and researchers; scoping workshops; and seed-funding for new activity. ***Funding for research, facilities and infrastructure*** is provided through the School (see 'D' below). An ***academic staff Workload Model*** provides transparency in balancing teaching, research, administration, knowledge exchange and wider academic leadership.

c. People

C.1. Staffing Strategy and Staff Development

Relationship between Research Strategy and Staffing Strategy: Our overall strategy is to appoint outstanding academic scholars who enhance research capacity. A distinguishing feature of our strategy for recruiting new staff is that we require individuals not only to excel in their own

discipline, but also to have a demonstrable capacity and enthusiasm for communicating and working beyond disciplinary boundaries. In this way, we seek to build on our advantage of being an integrated School to enhance leadership of interdisciplinary research. Decisions about subject areas for investment in new staff are made by the School Policy and Resources Committee (SPARC), informed by our vision and strategic plans (B.4 above). Decisions about the level of new appointments are made with consideration of the desirability of recruiting early career researchers to develop the next generation of world-class academics, and the need to appoint senior staff in order to give 'weight' to an established or emerging research area. We have made 49 academic appointments in the period, including 23 ECR, with 8 five-year tenure-track Chancellor's Fellows awarded through a competitive University-wide scheme. The expectation is that these Chancellor's Fellows will transfer to open-ended teaching and research contracts. As a consequence, we have an academic population with 23% ECR and 45% under 45 years old. The University is making available a further 50 Chancellor's Fellowships early in 2014, representing an on-going commitment, outside of REF, to be the UK's leading institution supporting the development of early career academic staff. We anticipate 2-3 further appointments as our competitive share of these additional Fellows. In sum, our staffing strategy represents a major investment in the future vibrancy of the subject area, both locally and nationally.

Academic Staff Development: All academic staff (including Research Fellows) elect to become a member of a Research Institute. Their direct line manager is the Head of Research Institute (HoRI). The main mechanisms and processes for staff development in supporting research are: ***Induction and Mentoring***: All new academic staff and Fellows are provided with Induction within the School (offered through the Research Institutes), and University-wide (offered through the Institute for Academic Development, IAD). Each new staff member is allocated an academic Mentor, who provides guidance over the development of a successful academic portfolio of work and skills. ***Line Management and Annual Progress Review***: All staff have an Annual Review with their HoRI or Head of School at which achievements over the past year are reviewed, and targets for the coming years agreed. For Research Fellows, there is a major review one year before the end of the Fellowship, attended by two HoRI and the Head of School, where the progress of the Fellow is assessed, and where the School considers whether the Fellow's skills, achievements and trajectories match the ambitions and opportunities for the School. On this basis, a decision is taken on whether to offer the Fellow an open-ended academic contract. ***Personal Development and Training Opportunities***: All staff are encouraged to participate in personal development opportunities offered by the University (via the IAD), and by external agencies including RCUK. These include courses and training opportunities on managing research staff, managing research budgets, PhD student supervision, outreach and dealing with the media. Senior staff attend Leadership programmes run by the University. ***Access to Specialist Space and Research Facilities***: All staff have access to our extensive laboratories and analytical facilities (see 'D' below). Many Facilities are run as Small Research Facilities (SRF) and are funded through this route. However, the School provides support for staff for proof-of-concept work to allow development of external funding proposals. ***Supporting Graduate Students***: All academic staff and research Fellows are encouraged to supervise PhD students (see C.2 below). We give ECR priority in allocation of studentships, always ensuring wider academic support and identifying the best interests of the student. ***Sabbaticals***: Academic staff are eligible to apply for one semester of paid sabbatical leave for every four years of service.

Research Staff Development: The School's Research Training and Development (RTD) Section has responsibility for the management and support of research staff development. The RTD works in close collaboration with the School's long-standing Research Staff Organisation (RSO), a self-managing network of post-doctoral staff. This shared commitment helps the School implement the principles of the 'Concordat to Support the Career Development of Researchers'. Distinguishing features of the support offered by the RSO is the allocation of a 'buddy' for all new research staff, a School and College environment that encourages researchers to participate in interdisciplinary events, seminars and discussions, and a wide range of courses offered through the IAD.

Personal Research Fellowships: We have won 22 prestigious personal fellowships: three EC Marie Curie Fellows (Belcher, Pothuri, Stoy); seven NERC Fellows (Gilfillan, Hastie, Henley, Kettle, Kirstein, Mitchard, Reay); one NERC Advanced Research Fellow (Darling); four Royal Society of Edinburgh Fellows (Krasa, Naylor, Stevenson, Walcott); a Newton Fellow (Guerrieri); a Daphne

Jackson Fellow (Bird); a Royal Academy of Engineering Research Chair (Ziolkowski); a Leverhulme Visiting Professor (Olsen); a Leverhulme Trust Major Research Fellowship (Withers; 2011-2013); a European Research Council (ERC) Starter Fellowship (Pearce, 2011-2016); and, an ERC Advanced Fellowship (Hegerl, 2013-2018). In addition we gained major visiting fellowships: an Australian Research Council Future Fellowship (Meir, 2012-2014; held at ANU); the Laurence S. Rockefeller Visiting Faculty Fellowship at Princeton University's Center for Human Values (Brady, 2011-2012); a Leverhulme Trust Study Abroad Fellowship at City University of New York (Dugmore, 2012-2013); and Fitch Laboratory Senior Visiting Fellow at the British School at Athens (Panagiotakopulu, 2010-2011).

International staff appointments and international visitors: Of the School's academic and research staff, 20% are non-UK nationals. Recruitment within the REF period has brought in academic staff from 16 different countries. We have research collaborations (evidenced through shared grants and publications) with colleagues from over 40 countries, which, as would be expected, results in a vibrant stream of short- and long-term visiting researchers.

Equality and Diversity: The School embeds equality, inclusion and diversity throughout its activities. The Head of School chairs the School Equality and Diversity (E&D) Committee and a senior academic (Ganeshram) is the E&D Officer, serving on the College E&D Committee (Chaired by the Head of College). The University was awarded the HR Excellence in Research Award in 2010 for its role in implementing the 'Concordat to Support the Career Development of Researchers': this is implemented in the School by the RSO. E&D Training is available to all staff and researchers through the University's Human Resources (HR), and attendance is mandatory for chairs of all appointment panels. The School has achieved Athena Swan bronze status (2013), and is committed to achieving Silver. The School promotes family-friendly working policies by supporting requests for part-time working (6 requests; all granted) and 14 periods of maternity leave during which sabbatical leave still accrued.

C.2. Research Students

Overall management of our postgraduate community is the responsibility of Research Training and Development (RTD) within the School. RTD is led by a senior academic (Heal) and supported by 2.5 full-time support and administrative staff. RTD is responsible for ensuring effective student supervision, and delivery of the School's postgraduate research recruitment, training, progress monitoring, and Quality Assurance.

PGR recruitment and funding: The School increased its postgraduate research student intake from a total of c.50 starters/year during the period 2001-2008 to 57/year in 2011, and expects to move to an annual intake of 60/year by 2015. On average 34% of the starters during the REF period took their first degree outside the UK and 40% were female. The School receives studentships through: NERC (89 studentships over the review period); via its formal involvement in EPSRC DTC (15 studentships); the AHRC (via CDA and CDP competition; 3 studentships); and, the ESRC Scottish DTC (23 studentships). From 2014 we will lead in an 18-students/year NERC DTP, and partner in the AHRC Doctoral Programme Scotland. We have diversified our funding sources, in part through providing part-scholarships that lever other funds. This element of support has grown from a total of £162K (2008-09) to £206K in 2010-2011. The School has secured 25 studentships through industry support in this way in the last 4 years. Other notable sources of PhD funding derive from leadership of Scottish research pooling initiatives (SAGES and ECOSSE; 12 funded PhD students over the REF period); the Scottish Power Academic Alliance (SPAA) between industry and academia (4 funded PhD students); competitive studentships, such as CASE studentships, CONACYT, China Open Scholarships (12 funded PhD studentships); and Donor (including alumni) support in the form of bursaries (over £250K over the review period).

Supervision, training and support mechanisms: Each student has two supervisors and an 'advisor' who can provide independent advice and whose formal role is to chair the Confirmation Panel which determines progress to Year 2. Supervisors attend University training courses on supervising research students. Supervision is carried out through a series of regular meetings (normally five per semester). Formal training is delivered through compulsory training in research skills, through attendance at seminars, submission of research skills assessed essays and through the delivery of a peer- and staff-assessed oral presentation in Year 1 and poster presentation in Year 2 to the Annual Postgraduate Conference. All students undertake, as a minimum, a 10-day

programme of professional development training per year (involving research training in paper writing, poster presentation, formal speaking to academic and non-academic audiences, etc.). Human Geography PGR students are required to attend the residential Advanced Research Training for Postgraduate Human Geographers, research training which involves the five-institution consortium that makes up the Human Geography Pathway within the ESRC Scottish DTC.

Progress monitoring: Formal monitoring of student progress takes place in months 9, 12, 24 and 29 of a full time PhD (with equivalent moments of review for part-time students). The timings of formal review reflect, respectively, first full review and Confirmation Panel; annual review and upgrade (to MPhil/PhD status); detailed appraisal and two-year review; and final formal review and discussion of the student's 'Intention to Submit' form. For the Month 9 Confirmation Panel, Year 1 postgraduate students are required to bring together a Literature Review, the presentation to the Annual Postgraduate Conference, and a programme for future work as a 10,000 word report.

Graduate School and the Academic Community: The School has an active GradSchool, a self-organised student body that stages events including an annual 3-day graduate conference and away-days funded by School and industry sponsorship. All PGR students are encouraged to participate fully in the academic life of the School, including contributing to Research Institute and Research Group seminars. Students also organise sessions at major international meetings (e.g., RGS-IBG AC 2012, AAG 2011, 2012, ICHG 2012).

Excellence in the PGR community: In addition to the School securing competitive studentships, we have outstanding students who secure their own funding in open competition, for example one via the Foundation for Urban and Regional Research, three Helen Wallis Fellowships (British Library) and J B Harley Fellowships in the History of Cartography. Students are encouraged to publish in leading outlets before they graduate, examples of which include work in *Science, Progress in Human Geography*, and *Imago Mundi* during the REF period. Cook (supervisor: Shackley) secured a highly-competitive Royal Society of Edinburgh Business Fellowship (2011-2012). Three students secured placements in the Parliamentary Office for Science and Technology (POST) (Meacham, Street, Ryan: supervisor: Williams). Other achievements include: Guilband (supervisor: Butler) Geological Society of London President's award; Bartholomew (supervisor: Nienow) Royal Society Dudley Stamp Memorial Award 2008; Soto (supervisor: M. Williams) UNESCO-L'Oreal Fellowships for young women in science 2010; best paper/poster prizes at American Geophysical Union, British Hydrological Society; Association of American Geographers.

d. Income, infrastructure and facilities

D.1. Research Income

Income and sources during REF2014 period: Two goals identified in RAE2008 were to increase research grant income and to diversify the sources of funding. Both goals have been achieved. The average research income/year during the RAE2008 period was £5M/annum: the average income for the REF2014 period was £13.3M/annum (range £11.3M-£14.5M/annum). As a result of increasing our funding from Government, EU and, to a lesser extent, industry, we have moved from a ~50% reliance on RCUK (especially NERC) income at the start of the REF period, to one where RCUK makes up ~30% of research award value for 2012/13. This overall success and diversity of research income has been achieved against the downturn in the global financial climate since 2007.

Future research funding strategy and plans: We are well placed to continue to increase and diversify the sources of our research income by focusing on selected areas where there are opportunities for growth in consonance with our research vision, strategy, and expertise:

***RCUK**:* We have scope to increase our competitiveness through the development and leadership of high-quality consortia proposals given the close alignment of our research foci and priorities with those of NERC, EPSRC, ESRC (and on 'Science and Culture' in AHRC). In particular, there are opportunities for enhanced funding success in ecosystem and climate science, natural hazards, and energy-related research. Support for these initiatives is coordinated by the Director of Research and the Research Organisation, and includes financial and administrative support.
Government funding: A significant success during the REF period has been our increased collaboration with Government, securing funding for major projects and initiatives such as SCCS and ECCI (e.g., £2M SRDF grant for SCCS and £2.2M government funding for ClimateXChange,

and see 'B' and above). Building upon these established strong and productive relationships, we will target current and future funding streams both to address fundamental and applied research questions at the science-policy interface, and to support knowledge exchange and impact. ***Europe:*** We aim to increase funding from Europe, for example through Framework Programmes which align with our research foci, and through the ERC. To achieve this, we will provide enhanced support for colleagues to develop networks and proposals (as for RCUK), and by explicitly drawing upon colleagues with expertise and proven success in this funding context (e.g., Rounsevell, Metzger, Pearce, Hegerl). ***Industry:*** We have opportunities to increase funding from industry to support research to aid the transition to a low carbon economy (carbon capture and storage, exploration geophysics, carbonate reservoirs, and unconventional hydrocarbons such as shale gas), and in natural hazards (seismic, volcanic, weather and climate). To support this endeavour, the School has provided support for a full-time Business Development Executive (BDE) to build relationships, identify opportunities, and help prepare bids and contracts. Further BDE staff have been recruited through SCCS and ECCI (see 'B' above) to identify and realise further such opportunities. All BDE work closely with ERI in the University. We are establishing an Industry Advisory Board to help develop our strategic approach to securing industry funding for pure and applied research. ***Consultancies and Professional Services:*** Academic staff are supported to undertake consultancies up to a maximum of 60 days/year. These consultancies, which span from policy advice to technical projects, build relationships, and contribute to wealth creation and knowledge exchange. The total contract value of consultancies and professional services undertaken during the REF period was £2.8M. A proportion of consultancy funding flows back to the School to support research and KE.

D.2. Infrastructure and Facilities

The School of GeoSciences is exceptionally well-equipped with facilities to support research, including hosting and managing three NERC Facilities (NERC funding of £0.8M/year) and two further NERC-recognised Facilities for the benefit of the wider community. In addition to the IT, sample preparation labs, standard geochemistry (e.g., XRF, XRD) facilities and field equipment that would be expected in any well-found geoscience research University, the School houses, or through formal collaborative arrangements, has access to the following major facilities:

In-House Geochemical Facilities: The ***Edinburgh Materials and Micro-Analysis Centre*** (EMMAC) provides integrated facilities for the application of microbeam analytical techniques to material analysis. The facilities are concerned with micron-scale investigations of the chemical composition, atomic structure and surface texture of both natural (mineral) and synthetic materials. Analytical techniques and instruments available include Ion Microprobe Analysis (SIMS) - Cameca ims 4f, Cameca ims; Electron Microprobe (EPMA) - Cameca SX100; and Scanning Electron Microscope (SEM) - Phillips XL30CP, with analytical (PGT) and electron diffraction (HKL) attachments to be upgraded to a FEG-SEM in 2013/2014. The combined SIMS, EMPA and SEM facilities in the School of Geosciences form the core of a National Facility funded by NERC. This NERC Ion Microprobe Facility received the top grading, for the third consecutive time, in the most recent assessment of NERC facilities, and has underpinned over 110 publications in the REF period. The ***Cosmogenic Nuclide Facility*** produces samples for the measurement of cosmogenic isotopes by accelerator mass spectrometry (AMS) and noble gas mass spectrometry. Most activity focuses on ^{10}Be and ^{26}Al AMS targets from quartz samples, and ^{36}Cl from whole-rock and mineral separates to date land-surfaces and quantify rates of earth surface processes. This facility produced the data for high-impact outputs including **Sugden, *Nature Geosci*., 2009** and **Hein, *EPSL*, 2011**. The ***Electron Microprobe facility*** specialises in tephrachronology and a range of dating, geological and geo-archaeological applications. The ***Stable Isotope Mass Spectrometry facility*** has two SIRMS providing C, O and N-isotope analyses of sub-milligram samples of carbonates and C, N and S-isotope analysis of organic matter, mostly for environmental, palaeoclimate and palaeo-oceanographic research, including, for example, **Tudhope, *Nature Geosci*, 2008; Ganeshram, Pichevin, Tudhope, *Nature Commun*., 2013.** Our ***Organic Geochemistry Facility*** houses analytical capabilities for extraction, separation, identification and quantification of a wide range of natural compounds and contaminants in diverse sample types, including waters, soils and sediments and include GC, GC-MS, HPLC, TPH, PAH, and DOC/DINtrace-level Dissolved Organic carbon and Nitrogen analysis. The ***ICP-OES*** and

associated clean sample preparation facilities enable the group to reconstruct past sea surface temperatures (Mg/Ca) and ocean bioproductivity (e.g. **Ganeshram, Pichevin, Tudhope, *Nature Comm.*, 2013**; **Pichevin, *Nature*, 2009**; **Geibert, *Global BioGeo. Cycles*, 2010**). We will install a new **MC-ICP-MS** facility in late 2014.

SUERC (The Scottish Universities Environmental Research Centre) is a collaborative facility operated jointly by the University of Edinburgh and the University of Glasgow and situated at East Kilbride. It hosts geochemical analytical facilities for earth and environmental research, including five NERC Facilities: the Argon Isotope Facility, the Isotope Community Support Facility, the Life Science Mass Spectrometry Facility, the Cosmogenic Isotope Analysis Facility with two NEC accelerator mass spectrometers, and the NERC Radiocarbon Facility (Environment). GeoSciences staff and students collaborate extensively with SUERC researchers in the development and application of geochemistry to Earth and environmental research projects.

Geophysical Equipment Facility and Field Spectroscopy Facility: The School hosts and manages the national NERC Geophysical Equipment Facility and the NERC Field Spectroscopy Facility. These facilities specialise in support for GPS, GPR, geomagnetism, laser scanning, field portable spectro-radiometers, sun photometers and an FTIR spectrometer to support a wide range of earth, environmental and ecological applications in NERC-funded science. Both facilities received excellent scores (4.63/5 and 5/5) in the most recent evaluation of NERC Facilities, and in the REF period have underpinned >185 research papers.

Experimental Geoscience Facilities: We have a range of facilities to support high-P and high-T research including in-house blast-proof labs, a high-resolution CAT scanner, and a range of ultra-high-pressure and temperature facilities in the collaborative Centre for Science at Extreme Conditions (CSEC; housed in the School of Physics and Astronomy).

Airborne Geoscience: The School owns and operates a Diamond HK36 TTC-ECO aircraft to help us explore the lower atmosphere and atmosphere-Earth interactions. Equipment includes a Hyspex VNIR1600 hyperspectral imager and Picarro G2301-m CH_4, CO_2 and H_2O Flight Ready gas analyser. This is a NERC Recognised Facility (since 2012).

Field Equipment and Workshop: Specialist field equipment includes two LICOR 6400 photosynthesis systems to measure leaf and ecosystem level fluxes of CO_2 and water, a LICOR LAI-2000 plant canopy analyser to quantify the density of plant canopies, and their spatial variability and a Li8100 automated soil respiration system which is used to provide high quality field data on CO_2 flux from soil. The School also has a well-equipped mechanical workshop with specialist design-and-build technical support for field, laboratory and analytical equipment.

Other Specialist Research Facilities: The School has a video-editing and recording suite for use in ethnographic research and qualitative methods research training in human geography.

Computing and IT: Computing and IT support for research is integrated across the School through a suite of Linux servers providing large-scale storage, back-up, database and IT resources. Academic and research staff have access to the University's exceptional high-performance computing services (e.g., the Edinburgh Parallel Computing Centre, EPCC, which manages the national facility HECToR). Desktop/laptop access is through networked systems, and specialist software is widely available. IT services in the School is supported by 9 dedicated support staff. We have a specialist Computing Officer to support Earth System Modelling including the running of IPCC-class climate models.

Library facilities: The University Library is one of the largest research libraries in the UK (*c*.3.5M printed items, *c*.22K e.journal serials), and hosts the Centre for Research Collections and 'EDINA', the UK's JISC Data Centre. Specialist access is provided to online historical journals and data archives. The city of Edinburgh is widely recognised for its research library facilities and institutions: the copyright National Library of Scotland, the National Records of Scotland, National Museums Scotland to name only a few.

D.3. Recent and Future Investments in Infrastructure and Facilities

Recent investment: The School has invested over £3.7M in new and upgraded research facilities over the REF period. Highlights include investments in a new Biochar research facility (£463K);

airborne sensors for terrestrial ecology research (£150K); FEG-SEM to support Earth, environmental and material science applications (£350K); design and build of a large-volume GREAT Cell for CO_2 sequestration, and natural hazards research (£410K); greenhouse gas measurement field and laboratory equipment (£386K); trace element and stable isotope mass spectrometers for environmental and palaeo-environmental research (£932K); and upgrade of geochemistry clean and sample preparation laboratories and cold stores (£236K). In many cases, the School sum shown was used to match funds from other sources (RCUK; industry; donors). A further infrastructure investment of £10.5M (from the University, Scottish Government, donors and other sources) was made for the newly refurbished ECCI building.

Future Investment in New Estate: The School estate is spread across two campuses and three major buildings. This physical separation inhibits us from realising our full potential, so we have developed plans to locate the whole School in a single site, in buildings designed specifically to support our world-class geoscience, geographical, and interdisciplinary research. The University supports this vision. An architect design team will be appointed in early 2014 and we envisage achieving our goal with complete new-build (~£80M) on the King's Building campus by 2018.

e. Collaboration or contribution to the discipline or research base

E.1. Support for and Exemplars of Research Collaborations and Interdisciplinary Research

We take interdisciplinarity to be a desired aim, a great strength and an abiding challenge. We support and promote interdisciplinary and collaborative research in several ways:

- Our Research Institutes are themselves interdisciplinary; we have 5 interdisciplinary research seminar series and School-wide meetings offering a total of 117 formal events per annum; and cross-Institute membership of Research Groups is encouraged;
- The College of Science and Engineering promotes interdisciplinary research through funding workshops and 'sandpits' on emerging interdisciplinary research horizons that span the University;
- Our School Research Organisation, BDE and the University's ERI work to identify research opportunities and potential partners for large bids for collaborative research projects;
- The School (D.3, above) provides matching funds to support new interdisciplinary ventures.

Exemplars of interdisciplinary research collaborations include the following:
Research Pooling: We have significant leadership roles in the development and implementation of the SAGES and ECOSSE Research Pooling initiatives (see 'B.1' above). These initiatives are highly interdisciplinary, and, in the case of SAGES, incorporate ten HEI. We contribute to these initiatives as Directors, Theme Leaders and Co-Chairs of the Executive Committees. In both cases, the School provided substantial matched funding (via funded posts and equipment). Through this leadership and strategic investment, we have helped ensure that the clear benefits of research pooling continue beyond the initial SFC funding (both are entering a new post SFC-funding phase). We joined the new Marine Science and Technology Scotland (MASTS) pooling initiative in 2012 to further facilitate collaboration.

Leadership roles and contribution to major national and international initiatives: We are active participants in national Centres (e.g., NCAS, NCEO); participate and hold leadership roles in international research programmes such as IODP, IGBP, WCRP; are involved in developing international earth-observing satellite missions (e.g., through ESA, Japanese Space Agency; NOAA); participate in and lead major consortia (e.g., leadership of: SCCS; OPERA; ACES; CO2SOLSTOCK; EAP; ICCR; GREENHOUSE, ABACUS, GUAGE, see B.1, pages 2 and 3).

Human Geography Collaboration: We have established CRESH; delivered six research symposia in the review period (involving HEI and non-HEI) on greenspaces; military geographies; environment and health; forestry, risk and governance; art and the environment; high-rise living; led a Leverhulme Trust International Network (2008-2011) and an AHRC-funded conference on 'Travel, Writing, and Literatures of Exploration, c.1750-c.1850 (April 2010) following major AHRC grants. Our work here connects with scholars in philosophy, aesthetics, history, history of science, medical practice, psychotherapy, ethnomethodology, and sociology.

E.2. Collaboration with research users

We collaborate extensively with research users to shape new research agendas (which feed into our strategy and vision). For example, through the Scottish Power Academic Alliance, we work with the sponsors not only to conduct the research, but also to identify new opportunities and future directions. The combination of the threat of damaging impacts of climate change with the potential for reducing atmospheric CO_2 emissions via CCS in the North Sea drove our strategic investment in research around CCS in consultation with the Scottish Government. We have expanded science and technology-focused research to embrace research on health and environmental risks, economics and public perceptions of CCS to provide outputs in forms relevant to policy making. We host the ClimateXChange initiative (via ECCI) to provide policy-makers with information required to make decisions and identify future policy and funding priorities.

E.3. Leadership in the Academic Community

International leadership: We lead research initiatives with scholars in 41 different countries in 152 different institutions. We have in the review period given 80 plenary or keynote lectures to scholarly meetings in 22 countries, not including the UK. Whaler serves as president of the International Association for Geomagnetism and Aeronomy (2011-2015); Heal is President of the International Commission on Water Quality (2013-); Brady served as President of the International Society for Environmental Ethics (2010-2013); and Hegerl and Rounsevell are IPCC Lead Authors for the 5th Assessment Report.

National and International advisory board membership: Exemplars include: Hegerl - Member of US National Academies/National Research Council's Climate Research Committee (to 2009), member of Scientific Advisory Boards of the UK Met Office Hadley Centre, the CLISAP Centre for Excellence, Hamburg, and the Alfred Wegener Centre for Climate and Global Change, and PI for the International Detection and Attribution Group; Kroon - Chair IODP Proposal Evaluation Panel; Palmer - ESA Science Review Panel for Climate Change Experiments on the International Space Station; M. Williams - ESA BIOMASS mission advisory group (2008-2013; BIOMASS selected for launch 2020); Sugden - Chair, Royal Society of Edinburgh 'Facing up to Climate Change' Enquiry (2011); Whaler - Chair International Review Panel of Danish Space Science (2008); Main - UK representative on the International Commission for Earthquake Forecasting (2010-2011); Lovell - convenor, Carbon Capture initiative within InCluESEV, the RCUK Energy Programme's 'Interdisciplinary Cluster on Energy Systems, Equity and Vulnerability' (2008-2011); Metzger - coordinator of IALEUK, the UK landscape ecology network bridging science, policy and practice; Rounsevell - Chair, European Research Council Research Grant Panel, 'Environment, Space and Population'; Harley - Chair, Royal Society of Edinburgh Expert Panel "Scotland's Higher Activity Radioactive Waste Policy: a response to the Scottish Government" (2010).

Election to membership/ fellowship of learned societies and notable prizes: Exemplars, that span career stage, include: Hegerl - elected Fellow of the Royal Society of Edinburgh (2013) and Wolfson Royal Society Research Merit Award (2014-2019); Nichol (2011) and Bromiley (2013) - elected Fellows of the Royal Society of Edinburgh Young Academy; Haszeldine - OBE 'for services to climate change technologies' (2012) and William Smith Medal of the Geological Society (2011); Withers - Centenary Research Medal of the Royal Scottish Geographical Society (2008), Saltire Society Research Book of the Year Award (2012), and Founder's Gold Medal of the Royal Geographical Society for 'world-leading research in cultural and historical geography' (2012); Sugden - the Seligman Crystal of the International Glaciological Society (2012) and RSGS Research Medal (2011); Whaler - Price Medal of the Royal Astronomical Society (2013); Dugmore - co-recipient of the Gordon Wiley Prize from the American Anthropological Association (2010); Chapman - the EAGE Distinguished Lecturer Award (2009) and share of SEG Distinguished Achievement award for EAP (2012); Wright – RSE/BP Hutton Award for Energy Innovation (2011); Grace - Marsh Award for Climate Change Research (2009); Hegerl - NOAA Outstanding Scientific Paper Award for Oceanic and Atmospheric Research, (2008); Palmer - Philip Leverhulme Prize (2008), Zeldovich Medal (2010), and Wolfson Royal Society Research Merit Award (2013-2018); Main – EGU Louis Néel Medal (2014); Mudd - EGU Arne Richter Award for Outstanding Young Scientists (2013); Bollasina - AGU James R. Holton Junior Scientist Award (2013).