Institution: University of Leeds
Unit of Assessment: UoA7 (Earth Systems and Environmental Science)
a. Overview

The School of Earth and Environment (SEE) at the University of Leeds conducts world-leading research of wide societal impact across a broad spectrum of the Earth and environmental sciences. Evidence of the breadth and impact that our research has had since 1/1/2008 includes:

- publishing 1603 ISI-listed research outputs, attracting 15,394 citations[1].
- publishing 62 articles in prestigious journals (*Science* and *Nature* group).
- publishing 66 articles among the top 1% of all cited in geosciences.
- winning £56.8M of research funding, including £36.6M from RCUK & Royal Society.
- hosting the NERC National Centre for Atmospheric Science (NCAS).
- co-hosting the ESRC Centre for Climate Change Economics and Policy (CCCEP).
- leading three scientific themes of the NERC National Centre for Earth Observation (NCEO).
- hosting a cluster of established industry-facing research consortia.
- forming a strategic partnership with the UK Met Office (UKMO).
- providing 5 Lead Authors on all 3 working groups of the 5th IPCC Assessment Report.
- winning 18 personal fellowships and 27 personal prizes or awards for research.
- having staff named in 586 unique news stories about our research.
- being ranked 12th in the world (3rd in UK) by QS for Academic Reputation in Earth Science.

Supporting this success, the period since 2008 has seen a major investment in infrastructure and facilities, including spending £23.5M to unify the School in a new state-of-the-art building for Earth and environmental research. SEE has pursued a vigorous growth strategy over the REF period, focussing on specific research themes. The number of regular academic staff[2] has risen by 26% (from 72 to 91 FTEs), and annual research income has risen at more than twice that rate, by 70% (from £8.3M to £14.1M[3]). At the heart of this strategy is an ambition to increase the quantity of world-leading research outputs and societal impacts. The number of SEE journal papers increased from 209 in 2007 to 270 in 2012. These papers are having much greater impact, with the citation rate increasing from 2.9 to 4.7 cites per paper in the calendar year after publication, compared to a disciplinary average of less than 2.0 cites per paper per year[4].

SEE is structured into four research institutes: Climate and Atmospheric Sciences **(ICAS)**, Geophysics and Tectonics **(IGT)**, Earth Surface Science **(ESSI)** and Sustainability Research **(SRI)**. These institutes provide a breadth of capability sufficient to tackle leading-edge, disciplinary and cross-disciplinary research. Our strategy has focused on seven key research themes facing major interdisciplinary challenges of global scientific and societal importance:

- Atmospheric Science
- Physical Climate Change
- Ancient Environments
- Earth Dynamics
- Environmental Processes & Management
- Adapting to Climate Change
- Energy Pathways

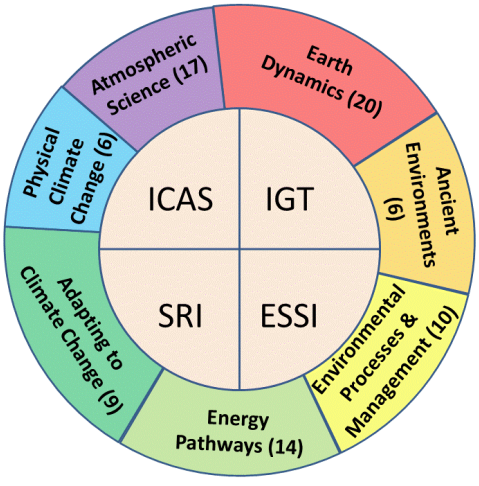

Figure 1. SEE is organised as 4 research institutes (staff in brackets) working on 7 interdisciplinary research themes (see Table 3 for theme data).

[1] ISI Web of Knowledge citation data (Oct/Nov 2013) used as they collate disciplinary centiles (Scopus do not).
[2] On academic "teaching and research" contracts.
[3] Research income data from HESA.
[4] http://www.timeshighereducation.co.uk/415643.article

b. Research Strategy

b1. Achieving our RAE 2008 Strategy

In RAE2008, our strategic aims were "to exploit the opportunities the new School has created" to "consolidate the position of our core areas as international centres of excellence" and to "combine the natural and social sciences in novel and innovative interdisciplinary research". SEE, with considerable University support, has achieved these aims, and has continually refined and updated its strategic goals through annual integrated planning. Our five key priorities in 2008 were to:

i. *Develop our expertise in climate and atmospheric science and palaeoclimate modelling and observation to help predict climate change scenarios and their effects on the Earth system.*

Physical Climate Change has developed into one of our flagship research themes through new appointments (SHEPHERD, SPRACKLEN, BUERMANN), successfully integrating with established researchers (FORSTER, HAYWOOD, CHALLINOR). A new Chair (SHEPHERD) was appointed in 2009, and three other staff (FORSTER, HAYWOOD, CHALLINOR) have been promoted to Chair level. This group has won £7M of research funding during the REF period, has led 3 consortium grants, and has published 155 papers with 7 in *Science* or *Nature*. Climate science is now central to research activities in SEE, strongly interfacing with other themes to develop new scenarios and examine their effects (e.g. CHALLINOR-1).

ii. *Build on our investment in the Sustainability Research Institute (SRI) by developing understanding of the causes and consequences of climate change. We will enhance our policy impacts, for example through our proposal to establish an ESRC Centre for Climate Change Economics and Policy (CCCEP) with LSE.*

SRI has reached critical mass, and is now a research powerhouse. We have appointed 14 new academics (including BARRETT, DESSAI and GUAN, IPCC Lead Authors), and the institute now employs 16 PDRAs and 65 PGR students (up from 3 and 22 in 2007, respectively). These staff underpin our *Adapting to Climate Change* and *Energy Pathways* research themes, from which 20% of our REF outputs and 17% of our research income is derived. The ESRC CCCEP is thriving and has secured funding for an expanded second stage; Leeds authors have led 95 papers, 18 book chapters and 5 books on the causes and consequences of climate change, and the centre provides a successful route to effecting change in UK, European, Chinese and African government policy (e.g. IMPACT CASE STUDIES 1,2)

iii. *Expand our cross-disciplinary research in low-temperature geochemistry, linking nanoscale mineral and biological processes to global biogeochemical cycles.*

We have strengthened the reputation and coherence of our low-temperature geochemistry research through strategic appointments (PEACOCK, POULTON) and with £550k of instrumentation in a purpose-built and newly-staffed (2.0 FTE) *Cohen Laboratory* suite. These investments build on our existing strengths in global elemental cycles and modern environmental perturbations to encompass mechanistic controls on trace metal behaviour (PEACOCK-1) and processes of change occurring through deep geological time (POULTON-1). During the REF period, our low-temperature geochemists have published 230 papers, including 10 in *Science* and *Nature* group journals, and research into fundamental, molecular scale mechanistic reactions at mineral-fluid-life interfaces has attracted £2.5M of income.

iv. *Enhance our new Centre for Integrated Petroleum Geosciences (CiPEG), focusing on hydrocarbon exploration and production and related issues of carbon sequestration and carbon accounting/management.*

CiPEG is now established as the University bridge to the petroleum industry. With over 50 affiliated staff, the centre has specialist knowledge on hydrocarbon reservoirs that attracts considerable industrial funding (£9.9M to SEE during the REF period) and delivers high quality research impact (IMPACT CASE STUDIES 5,7,8) and research outputs (MCCAFFREY-1, PEAKALL-1) which broaden and strengthen our multidisciplinary *Energy Pathways* research theme. CiPEG's success is due to our strategic investment of seed funding in staff and facilities such as the *Wolfson Multiphase Flow Laboratory*, and has led to three new academic appointments in applied research (GLOVER, HODGSON, TORVELA).

v. *Strengthen our capacities to understand the causes and consequences of natural hazards such as extreme weather events, earthquakes and volcanoes.*

Our capacity to study hazards has been strengthened through new appointments (HOOPER, KNIPPERTZ, PHILLIPS, and SCHMIDT) and by establishing the HEFCE-funded Climate and Geohazard Services hub to promote the societal impact of our research. Our natural hazards research has attracted over £4M of new funding, including £1M for research on extreme weather and over £1.5M to exploit satellite observations to better understand tectonic and volcanic hazards. Our work in Afar, Ethiopia, and our unique combination of atmospheric and volcanic expertise, have led to high-impact research in the *Earth Dynamics* theme (e.g. WRIGHT-1, SCHMIDT-1). Several staff advise UK Government, including MOBBS and WILSON (now Emeritus), who advised the Chief Scientist during the 2010 Icelandic eruption crisis, SCHMIDT, whose work on fissural eruptions is now included in the UK National Risk Register (IMPACT CASE STUDY 4), and NEUBERG, who advises the UK FCO on the ongoing Montserrat eruption.

b2. A Target Based Evaluation of our Strategy and Current Position

During the REF period, our overarching aim has been to place among the top 3 UK University Schools delivering world-leading research in Earth and environmental science. We have monitored our performance against our main competitors using the following specific, measurable objectives:

i. *Increase the proportion of research classified as world-leading by REF2014*

In RAE2008, 15% of our research outputs were graded world-leading. To improve upon this result, we have focused support and resources on activities that increase the quantity of our highest quality research (see below). We perform a bibliometric analysis on our research outputs to track progress against this target, and this suggests that our efforts have substantially increased the impact of our publications, as judged by their citation rate (Fig. 2).

ii. *Increase research income to a benchmark level of £150k per FTE*

Annual research income has increased by 70% during the REF period (from £8.3M to £14.1M) Part of this is due to a 26% increase in the School size (from 72 to 91 FTEs); however, annual income per FTE has risen also by 34% (from £115k to £154k), hitting our target.

iii. *Increase PGR recruitment with completion rate of > 90%*

PGR recruitment has doubled during the REF period, from an intake of 25 in 2007 to 50 in 2012, increasing the number of students per FTE from 1.5 in 2007/8 to 1.9 in 2012/13. Submission and completion rates have also increased; 97% of students starting in 2007/8 (the most recent data available) submitted their theses within 4 years[5].

iv. *Achieve these goals whilst maintaining a position of financial sustainability*

The School has maintained a position of financial stability during the REF period, enabling our growth. Surplus funds have been invested each year to improve the infrastructure and facilities, and to grow areas of research excellence.

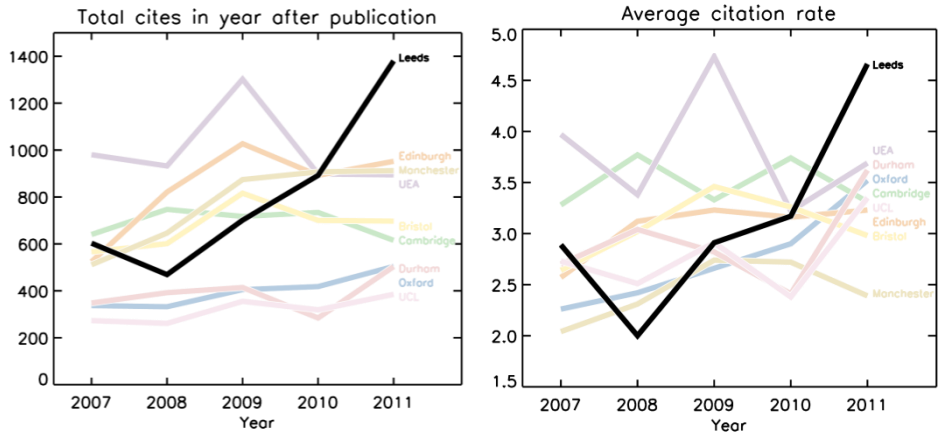

Figure 2. Bibliometric data on research outputs from Leeds and 8 comparable institutions[1]. The citation rate of our papers has grown by 62%, and the total number of citations received by our papers in the year after publication has grown by 128%. These rates are the highest of all institutions in the analysis, who we now outperform in both metrics.

[5] PhD completion rates after taking into account suspensions and extensions.

b3. Research Strategy for 2020

In 2008 our research was concentrated within 4 institutes, each with around 20 academic staff and each divided into 4 disciplinary research groups. For 2020, we have modified this approach to capitalise on our School's potential for problem-based interdisciplinary research, while at the same time developing our core expertise. We have identified 7 interdisciplinary research themes across which our world-leading research is spread (Table 2) and which bridge the work of our 4 institutes (Fig. 1). These themes allow us to focus on global environmental challenges and to capitalise on our disciplinary strengths. Our overarching vision is one of sustainable long-term research excellence, affording us the flexibility to adapt to changing research agendas and to invest in individuals and activities that are able to deliver high-impact research. During the next 7 years, we aim to consolidate our position as a world-leading centre for research in Earth and environmental science, and the vision and strategies we have set to achieve this are outlined below. We will:

i. *Develop our **Atmospheric Science** research to see our understanding of fundamental processes reflected in weather and climate models and a demonstration of their improved capability, in particular in their representation of extreme weather events and aerosol-cloud interaction.* The vision is to increase the realism and fidelity of global and regional atmospheric models, through targeted process-research and observations, guided by uncertainty analyses (MANN-1). Our research spans laboratory studies (CARSLAW-1,MURRAY-1), field campaigns (PARKER-1, BROOKS-1), remote sensing (ARNOLD-1), and modelling (SPRACKLEN-1), and its impact will be enhanced through academic partnerships with the UKMO (which employs 50% of PARKER and 30% of FIELD) and NCAS (which co-funds MANN and FENG to study aerosols and atmospheric chemistry). We will exploit these collaborations to ensure that our research feeds directly into the next generation of Earth system and weather models.

ii. *Focus our **Physical Climate Change** research on improving international assessments of the regional impacts of climate change, such as rainfall, crop yield, and sea level rise.* Our vision is to enable meaningful statistical projections in climate models that have had their predictions tested by observations. Our leadership of collaborative research efforts in *Chemistry Climate Model Validation* (CHIPPERFIELD, FORSTER), *Pliocene Model Inter-comparison* (HAYWOOD), and *Ice Sheet Mass Balance Inter-comparison* (SHEPHERD) frame this vision and will take it forwards. It has also been informed by IPCC Lead (CHALLINOR, FORSTER) and Contributing (HAYWOOD) authorship. Work has started with a generation of new climate modelling approaches (CHALLINOR-1, HAYWOOD-3), new theoretical insights (FORSTER-1), and a new framework for exploiting satellite observations of cryosphere change (SHEPHERD-1).

iii. *Exploit our diverse research on **Adapting to Climate Change** to provide solutions for global, regional, national and local responses to environmental change using physically-based evidence and, through CCCEP, to impact on national and international climate policy.* Our vision is to introduce new rigour into adaptation research by approaching the challenge from a complementary physical science perspective. We have started by linking research on *Physical Climate Change* with adaptation case studies in Africa and Asia (e.g. DOUGILL-3; STRINGER-1), and on threats such as global food security (CHALLINOR is a Theme Leader of the *CGIAR Future Earth Partnership)*. The appointment of DESSAI brings a global statistical view of adaptation to climate change, and links physical science with our existing work on governance and economic adaptation (PAAVOLA-2). The impact of our research will be enhanced by the renewed *ESRC* funding of *CCCEP*, and community leadership roles such as the *UK Climate Projection Panel* membership of DESSAI, and the *European Environment Agency's Scientific Committee* membership of PAAVOLA will maximise pathways to impact.

iv. *Expand our **Ancient Environments** research to develop integrated process-based models of global biogeochemical cycles, climate and palaeontology to improve our understanding of the Earth system at times of rapid climate change and of environmental stress.* The vision is to explore intervals of dramatic change, including the great mass extinctions, through multidisciplinary collaboration between palaeontologists, climate modellers, geochemists and volcanologists. Our research has focussed on the development of proxies for marine stressors such as anoxia and extreme temperatures (WIGNALL-1, POULTON-1, NEWTON-1), and we have integrated palaeontological data with numerical simulations of ancient environments (HAYWOOD-

1). New academic research fellows (SCHMIDT, GREGOIRE) will allow us to broaden this approach to include modelling of geotracers and the effects of large-scale volcanism on climate.

v. *Build on our laboratory and theoretical expertise in **Environmental Processes & Management** to inform practices in subjects of international importance such as nuclear waste remediation and ecosystem services.* The vision is to develop a deep understanding of biogeochemical cycles to inform improved ecosystem management. Our investments in the *Cohen* and *Sorby* laboratory facilities have supported initial breakthroughs in the understanding of small-scale geochemical processes (e.g. BENNING-2, PEACOCK-1) and of regional and global scale environmental problems (BOTTRELL-2, KROM-1), and underpin our involvement in wider initiatives such as the *Nuclear Sludge Centre of Expertise* and the EPSRC DIAMOND decommissioning consortium. The strength and impact of our ecosystem service research (PAAVOLA-1, QUINN-1) has been recognised by the appointment of QUINN as a Marks & Spencer NERC KE Fellow. Our overarching aim is to combine each of these approaches to solve environmental problems, such as payment schemes for ecosystem services and nuclear waste.

vi. *Strengthen our **Earth Dynamics** research to make fundamental advances in the observation and modelling of processes shaping the solid Earth, from surface tectonics and volcanism to the dynamics of the core.* Our vision is to understand fundamental processes by building advanced physical models (HOUSEMAN-1 , DAVIES-1) constrained by inter-disciplinary observations from satellite geodesy (WRIGHT-1, HOOPER-2), seismology (STUART-1, NEUBERG-1), geomagnetism (MOUND-1), geochemistry (YARDLEY-1, HARVEY-1), geology (PHILLIPS-3) , and mineral physics (WALKER-1). With the *Climate and Geohazards Services Hub*, this new understanding will be incorporated in state-of-the-science assessments of hazard and risk. The strength in depth within this theme is exemplified by our leadership of interdisciplinary consortia investigating rifting in Afar, global tectonic strain, and the deep roots of the North Anatolian Fault.

vii. *Enhance our research on future **Energy Pathways** by linking interdisciplinary research on sedimentology, petrophysics, geophysics, geochemistry, and energy and economic modelling and, through CCCEP and CiPEG, by advising industry and government on shale gas and carbon sequestration.* The vision is to address contemporary energy challenges through novel interdisciplinary research, to help manage the transition towards a low-carbon energy future. This has been initiated through research on efficient resource extraction, geo-engineering options such as carbon capture and storage (ANGUS, EPSRC Fellow), energy futures (FOXON-1), and on energy demand reduction and energy policy (BARRETT-1). The theme is strengthened by new academic appointments (BARRETT and GUAN, IPCC Lead Authors) now centrally involved in the £18M *UK Energy Research Centre* and the £11M *INDEMAND* consortium. Our leadership of *CCCEP* and *CiPEG* enables impact on stakeholder policies (IMPACT CASE STUDY 1). We will link these centres to our world-leading research on efficient resource recovery through theoretical (PEAKALL-1) and experimental (MCAFFREY-1) approaches, observation of natural flows (PEAKALL-2), and novel geochemical approaches to ore genesis (BANKS-1) to provide a comprehensive view on future energy pathways.

In addition to these 7 specific research theme targets, we have also identified 3 overarching strategic goals. We will:

viii. *Grow CCCEP into a wider centre of climate science and energy policy.* This expansion will support interdisciplinary research in the Energy Pathways, Adaptation to Climate Change, and Physical Climate Change themes.

ix. *Establish a centre for Earth Observation, building on our leadership within NCEO* (CHIPPERFIELD, SHEPHERD, WRIGHT) *and of the Centre for Polar Observation and Modelling* (SHEPHERD) *and the Centre for Observation and Modelling of Earthquakes and Volcanoes* (WRIGHT)*, and on our links with the UK and European Space Agencies, the UKMO, and NCAS.* The centre will underpin the work of our Atmospheric Science, Physical Climate Change, Adaptation to Climate Change, Earth Dynamics, and Energy Pathways research themes.

x. *Develop our Climate and Geohazard Services hub as a national centre for translating climate and geohazards research into benefits for users in industry, government and non-governmental organisations.* The hub will enhance the non-academic impact of research in our Atmospheric Science, Physical Climate Change, and Earth Dynamics themes.

c. I People, including: Staffing strategy and staff development

c1.1 Staffing Strategy, Including Relationship to Research Strategy and Infrastructure

Our staffing strategy has been a key element of our strategy to deliver world-class research in our areas of strength (Section b). We have grown from 72 (2007/8) to 91 (2012/13) academics, bringing in research-intensive staff at both junior and senior levels, whilst working hard to retain our strongest researchers. To enhance staff support, we have introduced an annual research review and needs analysis exercise which allows us to target resources where they can be most effective. Additionally, we have invested in physical infrastructure (Section d) and in technical and administrative staff to support our key research themes and our core disciplinary expertise. Our current (2010-2015) staffing strategy is to continue with a strong research-led appointment process and to pro-actively support and grow cross-disciplinary research teams. We have also tried to develop a supportive, collegial working environment, with fair and transparent leadership and change-management systems. This dual approach has allowed us to improve our research excellence whilst at the same time pursuing vigorous growth.

c1.2 Recruitment and Retention

Our senior staff appointments have included three flagship Leadership Chairs, jointly-funded by the School and the central University. These chairs have been recruited in research areas that we identified for strategic development and growth: Satellite Geodesy (HOOPER); Geochemical Proxies for Palaeoenvironmental Reconstruction (POULTON); and Climate Modelling (FIELD) - the latter arising through our Academic Partnership with the UKMO. Other senior staff appointments have been aligned to University-wide transformational projects in water (water@leeds, GUAN) and energy (the *Centre for Integrated Energy Research*, TAYLOR and UPHAM) research.

We have introduced a new scheme to recruit rising-stars on Academic Research Fellowships, and our aim is to employ at least one per calendar year. These appointments, made on 5-year probationary contracts, provide early-career researchers with a reduced teaching load and with targeted mentoring as they progress towards becoming fully-independent academics. SCHMIDT and GREGOIRE were the first of these appointments in 2012/13, and the scheme has attracted candidates of extremely high calibre both externally and from within our own crop of PDRAs. In addition to these posts, we have encouraged externally-funded independent fellows to join SEE by offering contracts beyond the length of their existing ones (see Section c1.5).

Retention of key staff has been an important strategy, and the University has been able to react quickly when required to do so. We have successfully retained internationally-leading researchers using Vice Chancellor supported applications to Royal Society Wolfson merit awards (WIGNALL, BENNING, CARSLAW, FORSTER, PARKER) and through 9 internal Chair promotions. In addition, we have been able to recognise exceptional research performance through an annual contribution pay exercise, which allows us to award salary increments and one-off payments to staff at all levels.

c1.3 Career Development Support

The School provides developmental support for research and academic staff at all career stages. Research and academic staff have annual meetings with line-managers as part of the University staff review and development scheme. The purpose of these meetings is to monitor progress, set development plans, and address individual development needs - many of which can be provided by the University's *Staff and Departmental Development Unit,* which runs research-oriented courses on topics such as supervisor training, research ethics, leadership and generating impact.

In addition to these annual personal development meetings, we have established a system for *Research Review & Needs Analysis* (RRNA) where all academic staff meet with the Head of School and Director of Research. The aim of RRNA is to identify how the School can work with each member of academic staff to enhance research performance and opportunity. As an outcome of these meetings a Research Charter has been established, with actions to (i) strengthen research groups to foster areas of excellence; (ii) build links between research groups and teaching teams to promote the participation of students in research activities; (iii) ring-fence School funds to support the generation of world-leading research outputs; and (iv) align sabbaticals to research opportunity. The RRNA process ensures that staff are effectively mentored, that staff with

leadership potential are identified and enrolled on the University's '*Tomorrow's Leaders'* training programme, and that Faculty-level support for preparing and administering research proposals is correctly aligned to staff needs. Following the launch of the RRNA process in 2010/12, follow-up meetings have been held with early career staff in 2011/12 to ensure that the mentoring and research group support systems that have been put in place are working effectively. Each member of academic staff will have an RRNA meeting at least once every 2 years.

To help outstanding PDRAs progress towards academic staff roles, the School has co-funded or fully-funded 7 research fellowships in strategic areas during the REF period, including the first of two Academic Research Fellows (Section c1.2). Other PDRAs with key technical skills have been retained in permanent roles with co-support from the School and our research partners NCAS and NCEO. Staff providing technical and specialist computing support are encouraged to participate in research and contribute towards publications (e.g. MANN-1), and early-career academic staff are provided start-up funds of at least £15k and reduced teaching loads to allow their research to flourish. At the University level, the *Next Generation Researcher Programme* supports staff as they progress from PhD student through early career researcher to research leader.

Opportunities for staff to enhance their research portfolios have also arisen through rationalisation of our teaching. We have made investments in teaching staff and online projects, postgraduate taught programs have been reduced from 14 to 10, and undergraduate taught programs have reduced by 50%. A move to team-teaching has allowed more staff to take sabbaticals and, as identified through the RRNA exercise, sabbaticals are now awarded based on research proposals, ensuring that our established staff have the time to write key papers and develop new projects.

We also invest funds in successful areas of research; we credit the research development accounts of PIs and research institutes with 5% of research income won competitively. These funds can be used to aid existing or new lines of research (e.g. PARKER *Fennec* proposal), or to increase the impact of research through, for example, conference attendance. Funds allocated to research institutes through this scheme are available to support staff with less direct funding.

c1.4 Implementation of the Concordat to Support Researcher Career Development

The University's *Guidance on the Employment of Researchers* describes how the University addresses the Concordat to support the career development of researchers. Within the School, the Concordat is implemented, as outlined above, by ensuring that all researchers have (i) an effective induction to the School and University; (ii) regular probation meetings; (iii) annual staff review meetings, with interim follow-up; (iv) mentoring; (v) a personal development plan and follow-up action; and (vi) access to staff development opportunities.

c1.5 Staff with Personal Research Fellowships Won in Open Competition

Since 2008, the School has hosted 18 independent personal research fellows, thanks in part to our policy of offering longer-term contracts (Section c1.2). These have included prestigious awards from the Royal Society (2), NERC (6), the Leverhulme Trust (3) and 4 other fellowships from the ESRC, Daphne Jackson Trust, AXA, and the Humboldt Foundation. In addition, three staff members have been successful in obtaining Starting Grants from the European Research Council (ERC), and we have actively encouraged independent fellows to move to Leeds.

c1.6 International Staff Appointments, International Recruitment and Visiting Scholars

SEE has a long-standing record of international research collaboration, strengthening our ability to recruit overseas staff and to attract scholarly visits. During the REF period, we have recruited 52 international research staff, including 2 at Chair level and 9 on other academic grades. We regularly host international scholars at all levels, from visiting students to sabbatical visits of senior academics. Altogether, we have hosted 118 visitors from 35 countries during the REF period, and the international nature of our research is exemplified by the wide diversity of nationalities from which co-authors of our published research are drawn (Fig. 3). We have retained links with staff leaving to take up international Chair positions (HUBACEK- MARYLAND; TERMANSEN- AARHUS; FRASER- GUELPH) through joint PhD supervision, and through international research programs – activities that enhance our external profile and our ability to recruit international staff. As a consequence of this diversity, the School has developed an internationalisation strategy with the

express purpose of maximising the potential for new opportunities. This strategy is informed by the global reach of our existing collaborations (Fig. 3), and aims to promote international research activities through coordination and by raising the School's international profile.

c1.7 How SEE Supports Equalities and Diversity

The Head of School takes responsibility for our equality and diversity policy. SEE holds the Athena SWAN Bronze award, and we are working to achieve Silver status. Holders of leadership and management positions receive training to ensure that they recognise and value diversity in making appointments, and can support all staff to make their best possible contribution towards the School. This training helps ensure that flexible working practices and part-time work are supported, as well as career beaks not being discriminated against in recruitment and/or promotion decisions.

c. II. Research students

c2.1 Research Students Overview

Since 2008 SEE has doubled the number of postgraduate research (PGR) students. PhD student numbers have risen from 105 in 2007/8, to 227 today. Our students produce high quality research, co-authoring 21% of all papers and 11% of papers we are submitting to REF. Graduating students are in high demand both in the academic sector as well as in a wide range of industrial, governmental and non-governmental organisations. Of those who graduated during the REF period, 73% have gone on to careers in research, and 39% are now working outside the EU.

Some of our students have been outstanding. TIM ANDREWS published 5 first author publications during his PhD (one returned in REF, FORSTER-3). ANJA SCHMIDT produced a well-received interdisciplinary *PNAS* paper (SCHMIDT-1), 2 other papers, and won the Springer 2012 PhD prize. IAN HAMLING published 6 papers, including a first-author paper in *Nature Geoscience* (2 returned in REF, WRIGHT-1,3). KUISHANG FENG published 4 papers, 2 as first author (2 returned in REF, BARRETT-3,4). A visiting student, YADONG SUN, published 2 papers in *Science* from his time at Leeds that are both returned in REF (WIGNALL-1, BOTTRELL-1).

c2.2 PGR Recruitment: Approaches to Recruitment, and Any Discipline-Specific Issues

Over the REF period, we have increased the quality of proposed PhD projects, we have strengthened student recruitment, and we have diversified sources of PhD project funding. For example, the 2012 intake of 50 students included 14 NERC grants, 3 ESRC and one EPSRC grant, 9 international government or Commonwealth grants, 9 University Research Scholarships, 9 industry funded grants, 5 self-funded students, and a handful of grants from different sources (e.g. Marie Curie ITN networks and the Leverhulme Trust). One quarter (12) of these PhD projects were CASE awards: 5 with the UKMO, 2 with the Natural History Museum, one each with CEH, BGS, StatOil and Arup. We have hosted several Marie Curie ITNs during the REF period (e.g. CLOUD, CLOUD-TRAIN, IMVUL), and we have been successful at recruiting students through highly-competitive University scholarships. We now routinely peer-review proposed PhD projects for research quality, impact and training before selecting and advertised nationally and internationally, and all students are recruited based on their academic ability and experience after a personal interview at Leeds. Student selection for NERC DTC awards is based entirely on merit.

c2.3 PGR Student Training and Support Mechanisms

The school has structured support and training for its large intake of students. Training plans are established during the first month and renewed annually, students are all jointly supervised, and it is a requirement that they receive at least 10 formal supervisor meetings annually. Details of these meetings are recorded online in our *Postgraduate Development Record* (PDR), introduced in 2011. Targeted training is organised at School, Faculty and University levels. Important generic skills are learned in publication master classes, by demonstrating on UG and MSc courses, and through student participation in the annual University-wide PGR conference.

The Postgraduate Research Tutor takes overall responsibility for supporting PhD student training. They ensure that supervisors are given the necessary training, organise a buddy system for incoming students, and make sure that PGR students are represented on School committees and are embedded within research groups. Since 2009, our PGR tutors have also run monthly drop-in

sessions to discuss individual needs. Interdisciplinary and offsite training opportunities will increase with the recent success of our bid to host and lead a NERC Doctoral Training Partnership, where opportunities exist with 48 linked partners encompassing all NERC-facing science.

These mechanisms work: the School has a 97% thesis submission rate (including suspensions and extensions, as of Feb 2012, students starting in 2007/8), with a steady increase from 79% for students commencing between Nov 2002 and Oct 2003 to today's high[5].

c2.4 PGR Student Progress Monitoring

The School uses "health check" meetings to monitor the progress of PGR students at months 6, 12, 24 and 33 of their projects. Transfer to full PhD status takes place at the 12-month meeting. To apply rigour to this process, both health-check and transfer meetings are overseen by a "Transfer Chair", an experienced senior member of staff. All meeting documents and those from supervisory meetings are stored on the PDR system and checked at the start of registration each year.

c2.5 Level of Support in the School for PGR

As well as the pastoral support outlined above, the School provides financial support to PGR, including (i) awarding annual prizes for the highest quality student-led journal paper (£500 per prize and up to 5 awarded per year); (ii) contributing 50% support in grants to highly competitive and/or industry-funded schemes (around 2 awards per year, supporting BGS applications and UKMO staff); (iii) support for 4 members of staff to undertake part-time PhDs; and (iv) research grant allocations or stipend contributions for ten students funded through a variety of funding bodies (e.g. Commonwealth Council, Mexican Government).

d. Income, infrastructure and facilities

d1. Evidence of Current and Planned Investments in Infrastructure and Facilities

During the REF period, the University and School have invested significant funds in our research environment, infrastructure and facilities. A £23.5M Capital Building project, completed in December 2009, unified all of the School's research and teaching spaces within a purpose-built, state-of-the-art building. The School committed £2M of its own strategic funds to the project, with the remainder from University and HEFCE. The co-location of our diverse research interests within a single building and the provision of communal social space have fostered an environment in which interdisciplinary and collaborative research can flourish. As part of the building project our analytical geochemistry facilities have been co-located in a dedicated wing, equipped to the highest international standards. The School has, meanwhile, continued to expand, to the extent that neighbouring space is now being refurbished to accommodate our sustained growth. The School has committed £100k to this latest building project, which has a total value of £1M.

The School's financial stability has allowed us to invest an additional £500k in 2012/13 and to earmark a further £1.2M through to 2017 in infrastructure and facilities, for which the University typically provides matching funds. The strategic facilities and technical staffing needs required to support research excellence are under constant review, with the main criterion being the potential for enhancement of world-leading research.

d2. Provision and Operation of Specialist Infrastructure and Facilities

The new and refurbished SEE building enables the School to meet its needs for world-class research and excellence in learning and teaching. The new facilities include purpose-built laboratory suites, flexible teaching space, computing suites, and a range of formal and informal meeting spaces designed to facilitate the sharing of ideas.

The *Cohen Laboratory*, opened in spring 2010, provides a co-located suite of purpose-built laboratories for multidisciplinary biogeochemical research, including hydrogeochemistry, mineral synthesis and reactions, geomicrobiology, isotope geochemistry and trace metal analysis of environmental samples. The labs have supported extensive research within the *Environmental Processes & Management* theme including 189 research papers that have emerged since the facility was established, and 39 that we are returning to REF (e.g. BENNING-1, BENNING-3, BURKE-1). A wide range of biogeochemical research takes place within the suite, including stable isotope geochemistry, marine and freshwater geochemistry, environmental mineralogy and radiochemistry.

The facility also provides support to all researchers requiring geochemical analysis within the School, particularly within the *Ancient Environments* theme.

The *Sorby Environmental Fluid Dynamics Laboratory* hosts an array of equipment to study flow properties and fluid concentrations, and predominantly supports research within our *Energy Pathways* theme. The lab also has NERC recognised facility status, and allows a wide inter-disciplinary community to conduct experiments on sedimentary processes, ecohydraulics, carbon sequestration, and nuclear waste remediation. Within SEE, the Sorby lab has been integral to our applied research on turbidites (IMPACT CASE STUDY-7) and has supported more than 40 papers during the REF period, 8 of which are returned to REF (e.g. PEAKALL-3, PEAKALL-4, MCCAFFREY-4).

The *Wolfson Multiphase Flow Laboratory* is part of the University-wide and SEE-hosted Centre for integrated Petroleum Engineering and Geoscience. It was established in 2006 and has been upgraded during the REF period through a £300k grant from the Royal Society Wolfson Laboratory refurbishment fund and matched-funding from the University. The laboratory enables the multi-phase flow properties of fault rocks to be determined, aiding the prediction of petroleum flow in the subsurface leading to research of societal impact (IMPACT CASE STUDY-5 and IMPACT CASE STUDY-8). The lab supports work within our *Energy Pathways* research theme, including projects on the petrophysical properties of tight gas sandstones, and our current focus is on measuring the properties of shales in both top seals and shale gas reservoirs. Altogether, more than 40 industrial reports and 8 academic research papers have emerged from the lab during the REF period.

Researchers within the *Physical Climate, Atmospheric Science,* and *Earth Dynamics* themes benefit from University-wide facilities such as High Performance Computing (HPC) and dedicated School computer clusters which have supported several of our most significant model-based analyses (e.g. HAYWOOD-1, CHIPPERFIELD-1, HOUSEMAN-1, MOUND-1). On the strength of this research, Leeds will host a new 5056 core supercomputer for the N8 universities funded by EPSRC via a stakeholder model. *Atmospheric Science* has also benefited from SEE and NCAS investment in dedicated laboratory facilities, including a new laser lab which has supported key breakthroughs on ice nucleation (MURRAY-1, DOBBIE-1) and aerosols (BROOKS-1, MCQUAID-1).

In addition, we have also invested a further £2.5M in equipment during the REF period, including a £1.1M electron optics suite, a £0.6M towable Doppler radar system for research on extreme weather, and a £130k aqueous ICP-MS. The electron optics suite includes an electron microprobe and a SEM, both optimised for geological applications. The facility is being widely used by colleagues from industry and from UK HEIs including Bristol, Cambridge, Durham, and the OU, and has supported work appearing in 40 papers (e.g. YARDLEY-1, MORGAN-3) since 2009.

d3. Research Funding Portfolio and Future Plans

Our research is aligned to the strategic priorities of UK Research Councils. We have a strong track record of attracting NERC funds, and our research income from the ESRC and EPSRC energy themes has also grown (Table 1). The inherent risks of relying on RCUK funding are recognised, and this has motivated our strategy of growing research income from other sources. As a result, over the REF period, non-RCUK funds have grown from £3.2M in 2008/2009 to £4.9M in 2012/2013, including €1M from the European Space Agency (ESA). In addition, SEE researchers have benefited from £3.7M of income in kind since 2008, arising from the use of NERC facilities including aircraft, geophysical equipment, and laboratory analyses. Future plans are increasingly focussed on larger interdisciplinary projects aligned to our research themes (see Section b3).

Table 1. Research income during REF period. SEE has been increasingly successful at attracting funding, with annual income rising by 70% from £8.3M to £14.1M, and income per FTE rising 34% from £115k/FTE in 2007/8 to £154k/FTE in 2011/12.

Funding Source	Funding
BIS Research Councils, Royal Society	£36.6
EU government bodies	£5.6
UK industry, commerce and public corporations	£5.0
Non-UK industry, commerce & public corporations	£5.0
UK central government bodies & local authorities	£1.5
UK and EU-based charities	£0.6
Other sources	£2.5
TOTAL	**£56.8**

d4. Consultancy and Professional Services

Staff are encouraged to perform up to 30 days of consultancy work per year, with Head of School permission. This work heightens the reputation, diversity, and impact of our research. For example, several staff (CHIPPERFIELD, FORSTER, SHEPHERD) have performed consultancy work for ESA, leading to 9 new research awards from this sponsor during the REF period and to SHEPHERD's role as Lead Scientist for the CryoSat mission. Similarly, FORSTER'S professional service for the Airport Commission increases the impact of SEE research on government policy. Since 2013 staff are required to channel consultancy work though the Faculty Research Office, ensuring a consistent level of legal protection and that consultancy does not impair our core research.

e. Collaboration and contribution to the discipline or research base

e1. Overview of Collaborations and Community Roles

During the REF period, SEE researchers have been involved in 537 separately-funded national and international research collaborations across academia, the public sector, and industry, interacting with a wide range of stakeholders and leading to high-quality blue-sky and applied research outputs (see Table 2). These projects include 23 consortia[6] , 7 of which have been led by us. Our researchers sat on 109 separate advisory panels including 13 for branches of UK government and 3 UK Research Council executive boards, gave 69 keynote lectures, and chaired 97 sessions at international or national conferences. In addition, SEE staff acted as chief editors for 7 journals and editors for 61 others, and we have provided 26 members of Research Council Peer Review Colleges. The research of our staff has been externally recognised through the award of 18 personal or ERC fellowships and 27 prestigious awards or prizes, through the selection of 5 of our staff as Lead Authors of the IPCC 5th Assessment Report on Climate Change, and through 586 news stories reporting our research. Some other indicators of esteem are set out below.

Table 2. Research income and awards, impact of scientific outputs, community roles, and news stories naming SEE staff within our seven research themes during the REF period[7].

		Awards			REF Papers				Community roles			
Research Theme	**Staff**	**Research income (£M)[9]**	**Fellowships[10]**	**Prizes[11]**	**# Papers**	**% in top 1%[12]**	**% in top 10%[12]**	**% in top 20%[12]**	**Keynotes**	**Editorships**	**Peer Review College**	**Unique News Stories[8]**
Ancient Environments	5.5	1.6	3.0	1.5	18	28	58	78	5	7.5	2	44
Physical Climate Change	5.8	3.9	1.0	1.8	21	52	81	84	6.3	4.0	2	268
Energy Pathways	14	7.5	2.5	7.8	55	7	41	64	12	10	2.5	88
Adapting to Climate Change	8.8	2.4	2.0	0.8	26	17	51	58	6.3	12	1.5	11
Environ. Proc. & Management	9.8	5.1	1.5	4.8	37	13	64	71	16	12	5.5	52
Earth Dynamics	20	11	5.8	5.0	76	5	41	55	17	8.5	5.5	47
Atmospheric Science	17	25	2.3	5.3	70	15	61	64	7.0	13	7.0	74
Total	**82**	**57**	**18**	**27**	**304**	**14**	**53**	**64**	**70**	**68**	**26**	**586**

[6] NERC (6), EPSRC (1), ESRC (3), EU (3), ESA (10).

[7] Non-integer numbers due to partial membership of research themes or <100% FTE roles; data rounded to 2 sig. fig.

[8] Nexis media search on 21.11.2013.

[9] Research expenditure per calendar year, based on Leeds HESA data.

[10] NERC (6), ERC (3), Leverhulme (3), Royal Society (2), EPSRC, AXA, Humboldt , Daphne Jackson.

[11] Wolfson Research Merit (Benning, Carslaw, Forster, Parker, Wignall), Philip Leverhulme Prize (Guan, Haywood, Stringer), Max Hey Medal (Morgan, Walker), IPPR Northern Light (Gouldson), Leontief Prize & JEST Top Policy Paper (Guan), Goldring Award (Hodgson), Hochstetter Lecturer (Manville), LF Richardson Prize & EMS YSA (Marsham), Core Chemical Engineering Award (Peakall), Bullerwell Lectureship (Rost), ANZ Academy of Management (Russell), Springer Thesis Prize (Schmidt), Coke Medal, Humboldt Award & MDA Distinguished Lecturer (Yardley).

[12] Citations relative to geosciences disciplinary percentiles, Web of Knowledge.

e2. Contribution to the Discipline or Research Base

We support the wider Earth and environmental science community through membership of national and international advisory boards, by playing an active role in organising and participating in scientific meetings, and as editors of peer reviewed journals. During the REF period, 26 SEE staff have sat on NERC and EPSRC Peer Review Colleges. We have also advised 13 NERC strategic committees[13], 3 UK Parliamentary Select Committees[14], 4 UK DEFRA advisory groups[15], and numerous other branches of government including the Strategic Advice to Government in Emergencies Group, the UK DECC, the Cabinet Office Effusive Volcanic Eruption Advisory Group, the UK Government Climate and Development Knowledge Network Roster of Experts, the UK Energy Research Council knowledge transfer network, the UK Committee for Climate Change and the ESRC-EPSRC Energy and Communities Programme. SEE staff have also advised the UKMO, the UK Aviation Commission, 3 overseas governments[16] and 10 international organisations including the European Environment Agency, the Council of Europe, the China Council for International Cooperation on Environment and Development, the International Energy Agency, the European Space Agency, the World Meteorological Organisation Commission for Climatology, the UN's Convention to Combat Desertification and Taskforce on Hemispheric Transport of Air Pollutants, the Global Seismic Network, and the IPCC. In addition to these roles, SEE staff have led 8 international collaborative research projects[17] and have provided scientific advice to 14 others via their steering committees[18], and have advised various review panels of 6 international research sponsors[19]. Our staff helped organise 97 scientific symposia including Goldschmidt conferences and Royal Society discussion meetings, and have given 450 invited talks including 70 keynote addresses[20]. We actively support the scientific peer reviewed literature; BENNING is principal editor of *Geochemical Perspectives*, CARSLAW is executive editor of *Atmospheric Chemistry and Physics*, GOULDSON is editor of *Environmental Policy and Governance*, NEUBERG is editor in chief of the *Journal of Volcanology and Geothermal Research*, PARKER is chief editor of the *Quarterly Journal of the Royal Meteorological Society*, WIGNALL is managing editor of *Earth Science Reviews*, WILSON (now emeritus) is executive editor of the *Journal of Petrology*, YARDLEY is chief editor of *Geofluids* and, altogether, SEE staff edit 61 other journals[20].

We provide leadership within the academic and industrial sectors through high-level community roles, and the research of our staff has been recognised with external honours. In academia, CHIPPERFIELD, SHEPHERD, and WRIGHT are theme leaders of the National Centre for Earth Observation, GOULDSON is co-director of the Centre for Climate Change Economics and Policy, GUBBINS (now emeritus) is chair of the NSF Computational Infrastructure for Geodynamics Committee, MOBBS is Director of the National Centre for Atmospheric Science, SHEPHERD is Director of the Centre for Polar Observation and Modelling, WRIGHT is Director of the Centre for Observation and Modelling of Earthquakes and Tectonics, and WILSON (now emeritus) served as a member of NERC Council. In industry, FAIRHEAD is President of GETECH Ltd, FISHER is a member of the committee overseeing decommissioning of the North Sea Brent Platform, KNIPPERTZ is advisor to the AXA Research Fund, YARDLEY is Remuneration Committee member for RDR Ltd, and YOUNG is a member of the ASDA Sustainability Advisory Group and an environmental advisor to the Carpet Foundation Board. Our staff also play active roles within learned societies; BENNING is Vice President of the *European Association of Geochemistry*, PEACOCK is Council Member of the

[13] NEB, NCAS Board, NCEO Board (3), NIGF and HPC Steering Committees, PRC Services Review Group, expert groups on Cirrus for GEWEX, Macronutrient Cycles, Sustainable Supply of Mineral Resources, and Ice Sheets, a review panel for UK Aircraft Provision, a Sustainable Agriculture Taskforce, and a Minerals and Mining Think Tank.
[14] Energy and Climate Change (2), and Environmental Audit.
[15] Carbon Accounting Standards, UK Climate Projections, Environmental Regulation, Social Sciences.
[16] Greek Ministry of Education, Armenian Ministry of Energy, Quality Assurance Netherlands Universities.
[17] POLMIP, SPARC/ICAG AC&C, IMBIE, PLIOMIP, IAVCEI commissions on Volcanogenic Sediments and Volcano Seismology, AEROCOM aerosol microphysics, ESC Working Group on Earthquakes & Volcanoes.
[18] DesertNet, EU Cost 722, Global Soil Week, IAVCEI-CTS, IGAC , IGEO-Supersites, iGov, MIAVITA, NDACC, PMIP, RACEWIN , SCAR ACE, SPARC/CCMVal , TabMEP.
[19] German Helmholtz Society, Chinese Academy of Sciences, NSF, Australian Research Council, Danish Council for Scientific Research, French National Centre for Scientific Research.
[20] Full list available at http://www.see.leeds.ac.uk/ref_esteem

Mineralogical Society of Great Britain and Ireland, STEINBERGER is Council Member of the *International Society for Industrial Ecology*, WIGNALL is President of the *Yorkshire Geological Society*, YARDLEY is Past-President of the *European Association of Geochemistry,* and our staff sit on advisory boards of 15 other societies[21]. Four SEE staff have been elected to prestigious positions within learned societies[22], 19 have won 27 prizes or awards for research excellence[11], and 16 have won personal research fellowships.

e3. Collaborations

Our research collaborations (Fig. 3) have grown through strategic investments in facilities and in integrative, including partnerships with the NCAS and the UKMO, co-funding of the CCCEP, the Centre for Low Carbon Futures, and the Nuclear Sludge Centre of Expertise, pump-priming of the CiPEG and Climate and Geohazard Services, and upgrades to our world-class research facilities including the Wolfson Multiphase Flow Laboratory, the Cohen Laboratory Suite, and the Sorby Environmental Fluid Dynamics Laboratory. These activities and many other smaller investments have supported new important and exciting collaborations, examples of which include the design of a weather forecasting handbook for meteorologists in Africa (PARKER), working in partnership with authorities in China to develop low carbon cities (IMPACT CASE STUDY 1), long-term involvement in the CERN CLOUD project to determine the role cosmic rays play in climate change (CARSLAW-1), and a collaboration with the aerospace industry to develop a new satellite mission concept to detect tectonic strain. Much of our research is interdisciplinary, reflecting the design of our School, and is collaborative by its nature. For example, we have combined climate and social science to assess food security (CHALLINOR-2), and we have studied the health effects of volcanic eruptions (SCHMIDT-1), integrating atmospheric science, volcanism and epidemiology.

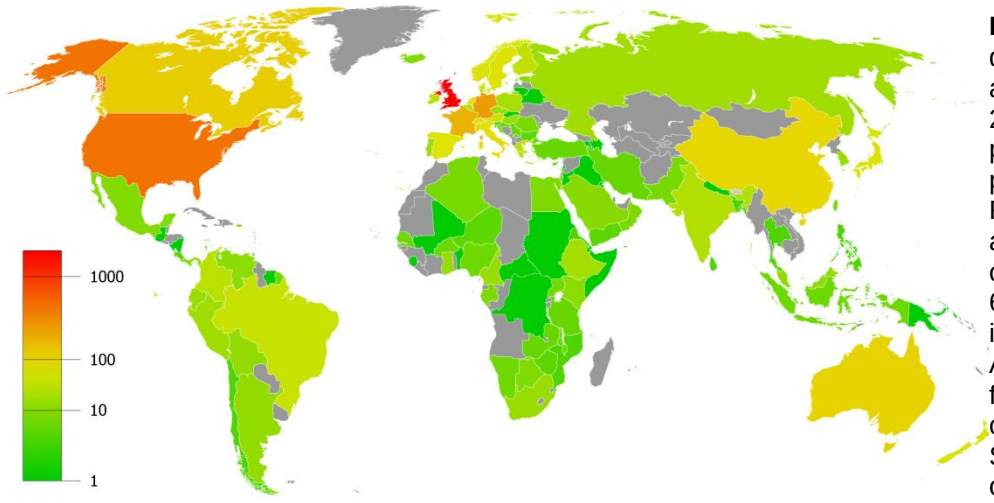

Figure 3. Global distribution of co-authors on SEE papers 2008-2013. Of the papers we have published during the REF period, 85% have a co-author from outside of Leeds and 60% have an international co-author. Altogether, academics from 118 different countries are listed in Scopus as co-authors on SEE papers.

We are careful to make sure that our successful collaborations inform our research strategy. For example, the extensive links between CCCEP, our IPCC authors and the UK Government (DECC and DEFRA) have been used to identify future research directions, framing, for example, the second-stage of CCCEP and our leadership of the EPSRC/NERC-funded Integrated Assessment of Geo-engineering Proposals consortium. Within our *Atmospheric Science* research theme, the scaling up of local observations to inform climate models grew out of national collaborations, especially our partnership with the UKMO, and now helps to inform UK strategy for next generation chemistry-aerosol modelling, boundary layer modelling and weather forecasting. Elsewhere, the interdisciplinary and cross-sector work of our *Centre for integrated Petroleum Engineering and Geoscience* informs future research areas, underpinning new projects on tight sands and shale gas reservoirs. These projects, in turn, inform the strategic priorities of our research themes.

[21] British Sedimentological Research Group, European Association of Geochemistry, European Mineralogical Union, European Society for Ecological Economics, Geochemical Society, Geological Society, International Association of Geodesy, Mineralogical Society of Great Britain and Ireland, Palaeontological Association, Royal Society, Royal Meteorological Society, Society of Exploration Geophysicists, Society of Petroleum Engineers, Chinese Academy of Sciences, Finnish Academy of Science.

[22] Gubbins (FRS, EGU Hon. Member), Hooper (Senior Member, IEEE), Houseman (AGU; IASPEI), Russell (AMO-NEE).