Institution: University of Leeds

Unit of Assessment: UOA7 – Earth Systems and Environmental Sciences

1. Unit context and structure, research and impact strategy

1.1 Summary

The School of Earth and Environment (SEE), University of Leeds (UoL), is a world-leading centre for Earth, Environmental and Sustainability Science of global impact and influence. Highlights demonstrating the breadth and impact of our research since REF2014 include:

- 3,341 research outputs attracting 66,207 citations (99 papers in the top 1% and 876 papers in the top 10% most cited publications worldwide), 2,034 papers in the top 10% of journals¹.
- 67.7% of our papers have an international co-author.
- Athena Swan Silver Award (2019).
- Hosting and co-hosting 7 NERC-, EPSRC- and ESRC-funded centres.
- 68 industry/commercially funded research projects equalling £11.6M.
- Training PGR students and awarding 340 PhDs (Section (S) 2.4), leading three and partnering on four Doctoral Training Programmes/Centres of Doctoral Training.
- Leadership of global and national committees (e.g., IPCC, WMO/UNEP Assessment of Ozone Depletion, Committee on Climate Change (CCC); S4).
- Initiating 2 spinout companies, 8 licences to unique technologies and 3 patent families.
- 36 personal fellowships and 63 personal research prizes/awards.

We completed our most significant programme of strategic growth in any REF period, recruiting and developing 25 tenure-track fellows and 4 international leaders in new areas of endeavour, establishing a thriving and inclusive research environment. Our UOA now comprises 131 staff (127.15 FTE). We invested ~£11M in infrastructure and research facilities (S3.2), including completion of a new wing to the SEE Building (S3.2). We have increased our annual research income from £14.1M (11/12) to £27.2M (19/20), totalling £138M during REF2021, including £95M from RCUK/UKRI and the Royal Society. Our annual total of publications in peer-reviewed journals has risen from 270 (2012) to 494 (2020), with a Field Weighted Citation Impact (FWCI) over twice the subject average (2.1 from 2014-2020)¹.

1.2 Research Structure

To achieve our strategic goal of producing and applying world-leading fundamental science that underpins major interdisciplinary initiatives, we have fostered an environment where disciplinary experts integrate with scientists from other disciplines across seven research themes:

- Atmospheric Science: Delivers fundamental advances in the understanding of climate change, weather forecasting, atmospheric composition, and impacts on our planet and society. We develop advanced computer models of the atmosphere and climate, lead major field campaigns, analyse satellite data in novel ways, perform innovative laboratory experiments, and develop unique approaches to the statistical assessment of uncertainty in weather and climate prediction.
- Physical Climate Change: Explores mechanisms of change in global and regional climates (past, present, future). Observational and numerical modelling-based scientists investigate how natural and anthropogenic forcing and climate variability affect climate and the cryosphere. Areas of expertise include observation and modelling of ice-sheets/sea-ice, ocean and atmospheric circulation, biosphere-climate interactions, radiative forcing, and climate sensitivity.
- Climate Change Mitigation and Adaptation: Addresses the urgent need to accelerate the global response to climate change and to build resilience. We integrate environmental, social science and human geography disciplines and apply quantitative, qualitative, experimental, and modelling approaches in interdisciplinary teams and in collaboration with communities and research users.

¹SciVal bibliometric data (2014-2020) for REF2021-eligible staff (SCOPUS retrieval date 06.01.21). Top Journals from SciVal CiteScore percentiles.



- Energy Pathways: Explores how to deliver a cleaner, more secure, and affordable energy future. Our research focuses on managing the transition to a low-carbon economy, exploring innovative technologies, policies, businesses, and finance models. This knowledge is combined with an understanding of wider impacts on our economy and society to deliver effective change.
- Environmental Processes, Management and Policy: Addresses the functioning of the modern Earth system, including anthropogenic activities of global significance. This is underpinned by laboratory and theoretical approaches advancing our understanding of biogeochemical cycles and processes from the nano-to-global scale. We supply improved practices for ecosystem management, nuclear waste, and pollutant remediation, including the development and implementation of environmental policy by governments and organisations.
- Ancient Environments: Focuses on major events in Earth history through an interdisciplinary
 grouping of geochemists, palaeontologists, and climate modellers. This includes the characterisation
 and drivers of mass extinctions, controls on the chemical evolution of the ocean-atmosphere system
 and links to biological evolution, reconstructing and understanding ecology and biodiversity, and
 understanding the dynamics of past climates.
- **Earth Dynamics:** Examines the structure and evolution of Earth from the core to the surface. We study the generation of Earth's magnetic field, and deformation and lithospheric processes affecting both the continents and oceans, with a strong focus on rheology, geochemistry, fluid-rock interactions, and rates of processes. We apply this knowledge to assess earthquakes, volcanic hazards, space weather, and to understand the evolution of other planets.

1.3. Research and Innovation/Impact (R&I) Support Structure

The breadth of research within SEE, and our management structure (Fig. 1), facilitates a culture of rapid and effective response to new research, innovation and impact (R&I) funding opportunities in collaboration with external partners from design, through translation, to implementation (Fig. 2). The Director of R&I works closely with the Head of School, School Steering Committee and Research Theme Leaders to provide oversight and direction in all matters relating to research (Fig. 1). Since 2014, two Deputy Directors support the achievement of research impact and excellence. Our Research Support Manager helps develop and operationalise our strategic plan, supports our research culture, and oversees funding and fellowship applications. In 2015, we appointed a Research Impact Manager to enhance policy development, partnership building, and business engagement. In 2014, we appointed 3 FTE Research Support Administrators who support Research Theme Leaders, enhance internal communication, facilitate subject-specialist research groups, and increase our agility to respond to funding opportunities. Through research leadership and administrative support, SEE has grown its capacity to support academics in the development of new projects, proposals, collaborations, partnerships, and networking (£1.8M attributable investment since 2014). This R&I Support Team improves policies and procedures to foster a thriving and inclusive research environment. For example, we have established a financially supported outstanding visitor's policy, workload relief for academics preparing large/complex proposals, and transformed our sabbatical policy to allow academics dedicated time for research and wider impact activities (S2.3).

REF2021



Figure 1: School structure/overview of research themes.

Our ambitious and successful approach to building and sustaining partnerships, and to establishing a culture of translating research into impact, is reflected by our nine submitted Impact Case Studies [ICSs 1-9] from 6 out of 7 research themes, and in the examples of wider research engagement (highlighted herein). Our *R&I Support Team* enables our academics to translate their world-class research into economic, societal, and environmental benefits arising from a wide range of impact mechanisms (S4):

- **Policy [ICSs 3|4|7]:** By providing targeted evidence, we have demonstrably influenced policymakers, from local and national government, through to shaping international agendas and approaches.
- **Partnerships [ICSs 1|2|5|6|8]:** We co-design and co-produce research projects with partners from a wide range of sectors to ensure delivery of economic, societal, and environmental benefits.
- Commercial and Business Engagement [ICSs 5|6|8|9]: In collaboration with external partners, our expertise has developed new technologies, improved business performance and decisionmaking, and enhanced practitioner training.

REF2021



Figure 2: Example mechanisms delivering world-leading research, innovation and impact.



1.4 Achievements since REF2014 and Research Theme Strategies

Our research and impact strategy since 2014 has been to realise our potential to address "problembased interdisciplinary research", while simultaneously "developing core expertise". Through our recruitment policy, and the development of new interdisciplinary centres, we have achieved our overarching vision of creating "sustainable long-term research excellence" that can "adapt to changing research agendas", "facilitate a culture of innovation", "build partnerships with stakeholders in industry and the public sector" and enable "long-term investment in individuals and activities to deliver high-impact research."

Atmospheric Science

Achievements: In REF2014, our research and impact strategy centred on *"ensuring that understanding of fundamental processes is reflected in weather and climate models",* and to *"strengthen the academic partnership with the Met Office".* To achieve this, we have appointed early-career tenured staff in weather and flood forecasting [BIRCH], volcanic aerosols [ILYINSKAYA], stratospheric aerosol variability [NEELY] and tropical meteorology [SCHWENDIKE].

Success in research funding (e.g., EUCLOUD-MOTION) enabled the first simulation of atmospheric particle formation based on laboratory data (achieved for gas-phase chemistry >40 years ago). This knowledge is crucial for understanding how atmospheric new-particle formation affects climate (e.g., UOA7-411, 795). CHIPPERFIELD/RAP showed that the 1987 UN Montreal Protocol remains effective in the continued recovery of the Ozone layer (UOA7-1318). MURRAY, based on research into climatic effects of atmospheric cloud droplet freezing (e.g., UOA7-1926, 1927), designed novel methods to support cryopreservation applications. Commercialisation of these methods, in partnership with Asymptote Ltd., led to new patents. PARKER led research into the physics of tropical Africa weather/climate, improving weather forecasting methods and operational procedures to inform severe weather warning systems through GCRF African-SWIFT [ICS-1].

The Met Office Academic Partnership (MOAP; S4.1) enhances the integration of our atmospheric science into operational weather and climate models. The partnership has been strengthened through the creation of the University of Leeds-Met Office Strategic (LUMOS) Research Group, and by appointment of JONES, who leads the scientific development of the UK Earth System Model (UKESM), working closely with Met Office-aligned staff in SEE [e.g., BIRCH, FIELD, MARSHAM, PARKER]. CARSLAW and team developed the Global Model of Aerosol Processes, which was embedded into Met Office climate model and UKESM contributing to national climate programmes and projections [ICS-2].

Future Strategy: In concert with the new Priestley International Centre for Climate (hereafter referred to as the Priestley Centre; S1.5), Climate Services will be expanded to comprise atmosphere, weather, and climate solutions. We will address urgent societal, and policy needs around extreme weather/climate events and air pollution, interfacing with University-wide Sustainable and Smart Cities initiatives. A major contribution to the strategic investment in the University Farm, as well as the Global Food & Environment Institute (GFEI; S1.5), is planned. This involves the establishment of a suite of atmospheric observation tools (e.g., radar, lidar, microradiometer) to bring together different in-situ and remote sensing measurements synergising with a broader Critical Zone Observatory.

Physical Climate Change

Achievements: Our REF2014 strategy focused on *"improving understanding of climate change and our contribution to international assessments of climate change and its regional impact"*. In response, we have invested in early-career tenured staff working on large-scale climate dynamics [MAYCOCK], ocean/ice/climate interactions [IVANOVIC], polar Earth Observation [HOGG/MCMILLAN], climate-biosphere feedbacks [RAP], and biosphere-atmosphere interactions and land-use change [C-SCOTT].



MAYCOCK demonstrated that stratospheric ozone representation in climate models has a strong effect on determination of climate sensitivity (UOA7-3117), influencing the development of the latest version of the Met Office climate model. Through leadership in the CryoSat-2 mission, SHEPHERD, HOGG and MCMILLAN showed that polar ice loss between 1992 and 2017 increased mean sea level by 7.6mm (UOA7-2605), receiving widespread international press coverage. Decadal variations in rates of global surface warming have been reassessed to improve confidence in climate change projections over the coming decades (UOA7-1797), providing the foundation for major successes in NERC and EU funding².

Alongside our sustained contributions to IPCC Assessment Reports (S4.3), new developments in statistical climate emulators have enabled complex results from Earth System Models to be tailored to provide evidence-based policy options in response to the Paris climate agreement [ICS-3], and to support policymakers in the development of net-zero targets.

Future Strategy: We will continue to use observations and simulations to assess and quantify the impacts of human activity on the physical climate and Earth system. We will develop new statistical emulator tools to synthesise complex model results and enable comprehensive uncertainty quantification for future changes in Earth system components. We will build on synergies with *Atmospheric Science* and *Climate Change Mitigation and Adaptation* themes, and the Priestley Centre, to apply our fundamental research to solutions for policymakers.

Climate Change Mitigation and Adaptation

Achievements: Our REF2014 strategy focused on *"Exploiting our diverse research on adapting to climate change to provide solutions for global, regional, national and local responses to environmental change and, through the Centre for Climate Change, Economics and Policy (CCCEP), to impact national and international climate policy". To address these goals, we appointed two Met Office Academic Fellows in climate science and decision-making [BRUNO SOARES] and food security and climate impacts [VALADARES-GALDOS], and a Chair in Climate and Health [BERRANG-FORD].*

The theme incorporates research on consumption of resources (UOA7-1212), energy (UOA7-2567), and human development (UOA7-2509). Our global influence has grown through leadership of major international projects (e.g., GCRF-AFRICAP, which is making agriculture in Sub-Saharan Africa more climate resilient and sustainable; S4.1). In 2018, CCCEP entered its 3rd phase, translating its research to advance public and private action on climate change (e.g., research on green growth for the design and delivery of urban climate actions and their integration into related development strategies). Collaborative research with cities across the world is enabling the development of low-carbon and climate-resilient plans (UOA7-1821, 2941; [ICS-4]).

DESSAI initiated the weather, climate, and social science theme of the MOAP (S4.1) and has shaped the UK research agenda as the SPF UK Climate Resilience Champion (UOA7-2633). We also examined climate adaptation in global agricultural systems (e.g., UOA7-638, 1692, 2977). STRINGER examined climate change, desertification, and land degradation links (e.g., UOA7-1693), which resulted in new formal cooperation between IPCC and the United Nations Convention to Combat Desertification.

Future Strategy: We will enhance our ability to understand and engage with human dimensions of climate change. There is a growing need for climate services, and vulnerability and adaptation assessments, as well as solutions-focused research that consider politics, justice and equity of low-carbon and net-zero transitions. This strategy will be underpinned by continued involvement and leadership within the Priestley Centre and GFEI (S1.5).

²Securing Multidisciplinary Understanding and Prediction of Hiatus and Surge Events (SMURPHs; £3M), Constraining Uncertainty of Multi-Decadal Climate Projections (CONSTRAIN; €8M).



Energy Pathways

Achievements: Our REF2014 strategy was to enhance *"research on future Energy Pathways by linking interdisciplinary research on sedimentology/petrophysics/geophysics/geochemistry and energy/economic modelling and advising industry and government on energy policy"*. We have transformed this agenda to tackle how to deliver clean, secure, and affordable low-carbon energy, while meeting rising energy demand. We have appointed outstanding early-career academic staff in geotechnics [PARASKEVOPOULOU], energy demand assessment [AE-OWEN], urban energy system modelling [BALE], energy systems and decision making [ROELICH], low carbon transitions [BUCHS], energy macroeconomics [BROCKWAY], and energy decarbonisation [HALL]. BALE, BROCKWAY, AE-OWEN, ROELICH were awarded prestigious UKRI fellowships.

Our strengthened expertise enabled the determination of global impacts of energy demand. BROCKWAY found that renewable energy-return-on-investment ratios are closer to those of fossil fuels than previously expected (UOA7-2827) and BARRETT determined that the petroleum sector accounted for 56% of total water requirements (UOA7-2511).

Business strategies for the development and viability of subsurface energy resources has been influenced by Joint Industry Projects. HODGSON [ICS-5] led an international consortium of 19 industry partners (Lobe2; Fig. 2) that made major advances in understanding submarine fan stratigraphy with direct industrial applications. Novel laboratory methods to measure low permeability rock properties have been developed by FISHER and commercialised through a spinout company PETRIVA Ltd. [ICS-6].

Several major UKRI Energy Programme Centres now reside in SEE (Centre for Research into Energy Demand Solutions (CREDS); Centre for Industrial Energy, Materials and Products (CIE-MAP); UK Energy Research Centre (UKERC)). The emissions reduction challenge requires a lower-carbon energy system, and we have developed new energy and economic modelling approaches. As part of the UKERC and CIE-MAP centres, BARRETT [ICS-7] has worked closely with DEFRA, BEIS and the CCC, to respond to the needs of policymakers. This has led to a new Leeds-developed UK consumption-based emissions accounting method published as an official Government statistic.

Future Strategy: In 2019, the UoL announced an ambitious plan to reorient its research and teaching away from the fossil fuel sector, going beyond divestment announcements by other UK HEIs. In 2020, we launched a *Geosolutions Centre* to enable progress towards a net-zero future for our campus, nation, and global society. This will leverage our world-leading expertise in subsurface characterization, resource exploration, geoengineering, economics, energy policy, and environmental governance to underpin innovative solutions for future energy generation, resilience, storage, financing, and consumption.

Environmental Processes, Management and Policy

Achievements: In REF2014, we proposed to *"build on our laboratory and theoretical expertise in Environmental Processes and Management to inform practices in subjects of international importance such as nuclear waste remediation and ecosystem services"*. New appointments champion integration of soil, agriculture, and water research [BANWART], and link state-of-the-art experimental biogeochemistry [HOMOKY] to global biogeochemical cycles [MAERZ]. The theme has expanded to encompass environmental policy, thus forming an interdisciplinary team with a common aim of understanding natural and anthropogenic environmental processes, and the application of this knowledge to facilitate policy, organisational and individual behaviour change (e.g., UOA7-2395).

PEACOCK'S ERC Consolidator Grant supports investigations into the role of minerals in the oceanic carbon cycle, and MAERZ leads a NERC large grant quantifying the effect of changing sea-ice cover and water-mass distribution on biogeochemical cycles and ecosystems at the Arctic Ocean seafloor.



BURKE'S research on factors controlling radionuclide transport has informed strategies to manage and monitor radiological contamination at the UK's largest nuclear site.

Two Associate Professor appointments increase expertise in sustainable water and land management and low carbon transitions [BUCHS, MARTIN-ORTEGA; UOA7-3487]. Three Lecturer appointments have grown our research capacity in the socio-politics of food systems, supply chains and resource governance [PADFIELD, PAPARGYROPOULOU, WHITFIELD]. STEINBERGER'S Leverhulme Trust Research Leadership Award reinforces our research excellence in understanding how people globally can achieve a good life within planetary boundaries (e.g., UOA7-2173). YOUNG led an award winning Innovate UK KTP with Asda to influence consumer-shopping habits that reduced food waste leading to benefits for the business, UK consumers and the environment [ICS-8].

Future Strategy: We will build on our collaborations with private and public sectors to advance the environmental economic basis for sustainable resource management, conservation, and restoration practices. New data science approaches will investigate resource use and societal responses to inform policymakers. Integration of indigenous and non-traditional knowledge will reveal novel perspectives on sustainability challenges. We will develop new initiatives to examine risks posed by legacy and new waste generated by transitions to innovative technologies. We will focus on integrating our research on fundamental marine biogeochemical processes into a regional and global multidisciplinary framework.

Ancient Environments

Achievements: Our REF2014 strategy was to "develop integrated process-based models of global biogeochemical cycles, climate and palaeontology to improve understanding of the Earth system during rapid climate change and environmental stress". We have developed palaeobiology as an area of strength through appointments in marine micropaleontology [AZE], macroevolution and macroecology [DUNHILL] and palaeontology and geochemistry [GILL]. Numerical modelling across a range of timescales is embedded in our approach through appointments in palaeoclimate and ice-sheet modelling [HILL] and Earth system evolution modelling [MILLS]. A strategic appointment in sealevel change during critical climate transitions [BARLOW] enabled new linkages with *Energy Pathways*. The group leads large national and international research programmes (e.g., Pliocene Model Intercomparison Project [HAYWOOD] and the Last-Deglaciation working group of the Palaeoclimate Model Intercomparison Project [GREGOIRE, IVANOVIC], which assess drivers of past climate change and uncertainties in simulating palaeoclimate).

The group has made major advances in understanding the causes and consequences of mass extinctions (UOA7-774, 3301). WIGNALL demonstrated that a combination of lethally warm shallow waters and anoxic deep waters caused the Permian-Triassic mass extinction (UOA7-149). The group has secured substantial grant funding (e.g., Biosphere Evolution, Transition and Resilience (BETR) collaboration; NERC/NSF-China). BARLOW was awarded an ERC starting grant using the Last Interglacial to fingerprint sources of ice to better predict future sea-level change and coastal resilience, and GREGOIRE was awarded a UKRI Future Leaders Fellowship aimed at constraining future ice-sheet instabilities and sea level rise projections.

LITTLE studied hydrothermal precipitates pushing back the potential origin of life on Earth by hundreds of millions of years (UOA7-1137). POULTON/NEWTON'S new reconstructions have linked the evolution of Earth's early oxygenation history to the rise of modern nutrient cycles during Earth's Great Oxidation Event (UOA7-343), the early evolution of large complex eukaryotes (UOA7-776), and biological evolution driven by detoxification of shallow waters one billion years ago (UOA7-773). MILLS has developed biogeochemical models providing new insight into the drivers and timing of Earth's oxygenation history (e.g., UOA7-3123, 3124).

Future Strategy: We will supply novel insights into key periods of Earth history documenting environmental and biological change, and as process analogues to inform future projections. We will build on strengths in environmental and palaeobiological reconstruction to spearhead the



development of biogeochemical, ecological and climate models that address mechanistic links between the environment, ecosystem functioning, and biological evolution and extinction.

Earth Dynamics

Achievements: Our REF2014 strategy was to make *"fundamental advances in the observation/modelling of processes shaping the solid Earth, from surface tectonics and volcanism to the dynamics of the core"*. We have strengthened our interdisciplinary expertise in tectonics and deep Earth through the appointment of early-career and senior staff in geodynamics [CRAIG], Earth Observation [ELLIOTT], palaeoseismology/geochronology [GREGORY], microstructure [PIAZOLO] and seismology [NOWACKI]. Volcanological expertise has grown through appointments in Earth Observation [EBMEIER] and geochemistry/petrology [FERGUSON]. New expertise in the application of industrial geophysical technologies to environmental problems [BOOTH] supports investigations into climate change impacts in Antarctica and Greenland. The group provides national and international leadership in Earth Observation and geohazards through the UK NERC Centre for the Observation and Modelling of Earthquakes, Volcanoes and Tectonics (COMET, S1.5/S4.1).

The group have made major advances in the use of satellite geodesy to monitor and respond to natural hazards, through the development of advanced tools and algorithms that can process and model large volumes of data from the Copernicus Sentinel-1 radar constellation (e.g., UOA7-934). The results are having a major impact on understanding of physical processes, including large crustal earthquakes (e.g., UOA7-1882, 3368), caldera collapse mechanisms (UOA7-931), and crust and mantle rheology inferred from earthquake cycle deformation (e.g., UOA7-935, 1883). Our Deep Earth group has advanced understanding of mantle and core dynamics (UOA7-1940, 2074). By harnessing new geomagnetic field observations, LIVERMORE discovered a jet stream within the liquid core providing exciting new insights of the Earths' core (UOA7-1178).

Substantial funding includes National Capability funding to support COMET (2014-2026; WRIGHT), an ERC Consolidator grant (HOOPER; applying artificial intelligence to ground-based and satellite data to forecast volcanic activity), two large NERC grants (one co-led by WRIGHT; utilising Sentinel-1 data for hazard research, the other with institutional lead LIVERMORE; ground impacts of space weather), prestigious early-career fellowships from NERC [DAVIES, EBMEIER, GREGORY, MAGEE] and the Royal Society [CRAIG, ELLIOTT], and investment allowing WRIGHT and HOOPER to launch a spinout company (SatSense Ltd.; Fig. 2 [ICS-9]), which uses Sentinel-1 data for commercial applications. Hazard research in developing countries, supported by GCRF, includes projects on volcanic hazards in Nicaragua [ILYINSKAYA] and seismic hazards in Chile [ELLIOTT]. WRIGHT coordinates Earth Observation activities supporting the Tomorrow's Cities GCRF hub.

Future Strategy: To make fundamental advances in understanding dynamic processes that shape the Solid Earth, from the lithosphere to the core. We will build on wide-reaching observational strengths by developing and applying innovative tools for geodesy, seismology, Earth Observation, and geomagnetism, using these to constrain the latest geodynamic models. We will build-on our strength in monitoring earth surface deformation during and after seismic and volcanic crises to enable Civil Protection Authorities to respond rapidly and effectively.

1.5 Strategy for Supporting Interdisciplinarity

We foster interdisciplinary research and impact in different ways (Fig. 2). Our research themes combine disciplines and staff are encouraged to be members of different themes, promoting the exchange of ideas/expertise. We support cross-school and faculty appointments. Six appointments are shared with the School of Geography (SoG) [TILLOTSON, water management; FORD, climate adaptation], Engineering [BALE; ROELICH, energy systems], Leeds Business School [A-TAYLOR, risk/decision-making], and Medicine and Health [BERRANG-FORD, climate and health]. We lead/make major contributions to UoL-wide interdisciplinary themes/research platforms. The Priestley Centre (REF5a), led by FORSTER, brings together expertise across climate change research (including >350 members; £75M active research portfolio). New appointments in Climate



Adaptation [LOWE]/Climate and Health [BERRANG-FORD] have strengthened our Priestley contribution. The GFEI (REF5a) is led by BANWART/WHITFIELD. As part of GFEI, the UoL farm hosts a Critical Zone Observatory integrating agricultural, ecological, biological, social, economic, food and Earth systems research to achieve innovative crop and agricultural practices resilient to human pressures of climate and land use change. GEFI leadership has grown through an appointment in food networks [PAPARGYROPOULOU]. **We host/lead interdisciplinary national research centres, programmes and partnerships** including the NERC National Centre for Atmospheric Research (NCAS; led by MOBBS), COMET (led by WRIGHT), and the Centre for Polar Observation and Modelling (CPOM, led by SHEPHERD). We host the ESRC CCCEP (led by GOULDSON/PAAVOLA) with LSE, three energy research centres (S1.4, *Energy Pathways*), and several large programmes (e.g., GCRF African-SWIFT, GCRF-AFRICAP (S4.1 for evidence of outcomes)).

1.6 Overarching Future Strategy

Our theme-based future strategies contribute to our UOA-wide strategic priority. This is to harness our disciplinary and interdisciplinary strengths, and global partnerships in research, innovation, and impact, to facilitate the transition to a sustainable, resilient, and net-zero future, and the achievement of UN Sustainable Development Goals. We will:

- Actively reorient our geosciences research towards global challenges, including net-zero energy systems, sustainable use of strategic resources, and infrastructure resilience to geohazards in a changing climate.
- Enhance our internationally leading expertise on climate and atmospheric science boosting weather and climate prediction capabilities around the world, improving our provision of climate services and solutions.
- Maintain our internationally leading expertise on climate action, net-zero economy and society, whole energy systems and nature-based solutions for sustainability, developing synergies/opportunities in sustainable/resilient food systems and agriculture.

1.7 Research Integrity, Safe Research Environment, Open Access & Data Stewardship

We adhere to the UoL Research Integrity Policy: (i) *Honesty* in research, (ii) *Rigour* in performing research and using appropriate methods, (iii) *Transparency and open communication* including declaring conflicts of interest, (iv) *Care and respect* for all participants in, and subjects of, research.

To promote a collegiate and open research environment, we ensure representation at all levels in School decision-making (Fig. 1; S2). All researchers adhere to School guidance on co-authorship of publications, defining anticipated author contributions and best practice in ensuring appropriate and fair levels of inclusion. Following UoL processes, all staff complete a Risk Review before applying for external research funding. Where required, these initiate ethical, health and safety risk assessments. The appropriateness and need for governance structures alongside the financial viability of projects are assessed. All research grant applications include a Data Management Plan complying with University/funder policies. Data and code underpinning research outputs are made available following publication either via the lead author or uploaded onto internal (Research Data Leeds) or external data repositories (e.g., BADC, BODC, NSIDC, Pangea), or dedicated project websites³. We use archives (e.g., GitHub) to store computer codes that underpin our research and impact (e.g., UOA7-2983 [ICS-3]) enabling the reproducibility of our science.

We strive to ensure that research outputs and data exceed HEFCE's Open Access (OA) requirements and provide training in OA publishing. We use the University's Symplectic system to upload Author Accepted Manuscripts within 3 months of acceptance rather than publication. >99% of our in-scope REF2021 outputs are OA compliant, 31% are Gold OA, and are available on the <u>White Rose Research Online (WRRO)</u> repository. The WRRO has recorded >887,000 and >137,000 downloads of our papers and PhD e-theses respectively (sample period 31.07.13-31.07.20). This compares to ~45,000 and ~10,000 for REF2014. Downloads have occurred from 211 sovereign

³~30% of our REF2021 papers record data/code deposits.



nations and dependencies (compared to 177 for REF2014). We promote the use of preprint servers (e.g., EarthArXiv, PhysArXiv, PaleorXiv) so a wider audience can access our research prior to publication. ORCID iD, used by staff, aids cross referencing. SEE academics serve as editors on 25 OA Journals.

2. People

2.1 Staff Overview

Table 1: Number of staff/career stage by primary research theme association (FTE)⁴.

	Atmospheric Science	Physical Climate Change	Climate Change Mitigation & Adaptation	Energy Pathways	Environmental Processes, Management & Policy	Ancient Environments	Earth Dynamics	Total
Professor	8.3	3.2	6.6	10.85	5.8	3.0	3.0	40.8
Associate Professor	5.0	2.8	4.0	3.8	11.8	7.7	11.0	46.1
Lecturer	2.0	3.0	0	5.8	5.0	1.0	5.0	21.8
UAF (Tenure-track)	0	2.0	2.0	2.0	2.0	1.0	3.0	12.0
Research Fellow (Permanent)	0	0	0	0	0.5	0	1.0	1.5
Research Fellow (Tenure-track)	0	0	0	0	0	0	2.0	2.0
Research Fellow (Fixed term)	0	0	1.0	1.0	0	0	1.0	3.0
Total	15.3	11.0	13.6	23.45	25.1	12.7	26.0	127.15

SEE has grown from 91 (2012/13) to 127.15 FTE (131 by headcount) REF-eligible staff (2019/20), 98% have permanent/tenured contracts. Our vitality is enhanced by diversity in experience (Table 1), gender and nationality (Fig. 3). Of 131 academic staff, 31 are international. In 2019/20, our PDRA community totalled 134.25 FTE. Our unit benefits from support provided by 17.1 FTE laboratory staff and 19.7 FTE research administrators.



Figure 3: (a) Gender, (b) nationality of UOA staff.

⁴32% of staff sit across research themes. For all tables/figures, staff are listed by primary research theme.



2.2 Recruitment and Retention (Sustainability)

Our appointments support SEE's Research, Innovation, and Impact strategy. Of our REF-eligible staff, 48 were recruited, or took up their REF-eligible role, during REF2021 (33% appointed internationally (Table 2; Fig. 4)). 44% of recruited staff are female, reflecting our commitment to improve the overall gender balance of our staff-base.

Position	No. of Staff	Gen	International	
		Male	Female	
Professor	4	3	1	2
Associate Professor	4	1	3	3
Lecturer	13	9	4	7
UAF (Tenure-track)	18	8	10	4
Research Fellow				
(Permanent)	1	0	1	0
Research Fellow				
(Tenure-track)	5	3	2	0
Research Fellow (Fixed				
term)	3	3	0	0
Total	48	27	21	16

Table 2: Number of REF2021-eligible staff appointed during REF2021.

A balance of staff at different career stages is required for long-term sustainability, leadership succession planning and to fulfil our responsibility to the sustainability of science (Table 1). We introduced a rising stars tenure-track fellowship scheme which was subsequently mirrored by a University-level initiative (250 Great Minds Fellowship scheme recruiting University Academic Fellows (UAF)). 20 of our early-career academics were part of the UAF scheme during REF2021, with several initially recruited on fixed-term fellowships (e.g., NERC IRF, Royal Society URF). PhD students and PDRAs with exceptional potential have been supported to win independent research and tenure-track fellowships [e.g., CRAIG, HALL, HOGG, AE-OWEN, C-SCOTT], and have been appointed as Lecturers [BRAMHAM, PAPARGYROPOULOU]. Lecturers and research fellows comprise 83% of our academic staff recruitment.







On average each year since 2014, 3 REF-eligible staff have taken up positions at other organisations. All have retained active research collaborations with staff in our UOA. From an average REF-eligible staff-base of 120 during the REF2021-cycle our annual retention rate is 97.5% (excluding retirements). We have retained several internationally leading researchers using Vice-Chancellor supported applications to Royal Society Wolfson Research Merit Awards⁵.

2.3 Staff Support, Development, Recognition Strategy

Supporting Researcher Career Development: We are committed to providing a thriving and inclusive working research environment, with opportunities for professional and personal development (see REF5a). We ensure best practice in researcher recruitment and researcher assessment as outlined in the San Francisco Declaration of Research Assessment (DORA) and Leiden Manifesto (responsible use of research metrics). We are a signatory to the Concordat to Support the Career Development of Researchers, which is implemented through (i) induction to SEE and UoL; (ii) probation meetings; (iii) annual staff review meetings (SRDS); (iv) mentoring; (v) personal development plans; and (vi) access to staff development opportunities (Organisational Development and Professional Learning, OD&PL). In addition to SRDS, we hold biennial Academic Meetings between staff and the Head of School, Director of R&I and Director of Student Education to ensure that mentoring/support is effective, and to identify leadership opportunities.

Our staff are supported at all career-stages. All staff and research students are embedded within research themes (S1) supporting collegiality and peer-to-peer mentoring. Financial rewards are distributed to Principal Investigators of successful grant applications to help them initiate new research and impact projects (5% of overheads), and to our research themes as a community resource to support academic activity, irrespective of current grant status (5% of overheads). Staff benefit from a workload allocation of 20% pro-rata for core research, and time required to deliver wider impact is recognised within our workload model.

We support progression of tenure-track fellows to independent academics through reduced teaching loads, targeted mentoring and training, and funding start-up packages (sensitive to the differential costs of an individual's research). An Early-Career Academic (ECA) forum facilitates discussion of issues such as probation objectives, funding opportunities, and enables ECAs to communicate with academic leaders and central UoL services. ECAs have representation in all SEE decision-making bodies, including the EDI Committee (S2.5). Emeritus academic staff remain active members of SEE, providing expertise and mentoring for more junior staff [e.g., STUART, WILSON, YARDLEY].

PDRAs have the same support and training opportunities as other academic staff, and are encouraged to contribute to teaching and to build their professional skills portfolio. PDRAs are included on the UoL's redeployment list automatically, and future career plans are discussed in meetings with HR and Deputy Head of School six months prior to contract completion. As part of our Athena Swan commitment (S2.5), we have appointed a member of staff as PDRA champion to represent the community within UoL management structures. PDRA representatives attend Research Theme and Faculty R&I Committee meetings.

SEE has a research, scholarship and study leave policy, allowing staff (including part-time staff) a period away from normal duties to focus on research, translation to impact, new teaching materials, and to enhance research collaboration (S4.1). Sabbaticals are available through three streams: (1) offered to all academic staff every 3 years; (2) discretionary in terms of timing; and (3) offered to academic staff who have completed long-term administrative/leadership roles.

Facilitating Knowledge Exchange (KE) and Research Impact: Our research strategy includes "*enabling staff to become embedded in external organisations or to host non-academics in the School*". The *R&I Support Team* provide specialist assistance for KE-based grant applications (incl.

⁵CARSLAW, CHIPPERFIELD, PARKER, PEACOCK, POULTON, SHEPHERD, STRINGER, WIGNALL, WRIGHT



Cheney fellowships (funded by a Leeds Alumni to develop global partnerships), KE Fellowships)). EPSRC and ESRC Impact Accelerator Accounts and the NERC Yorkshire Integrated Catchment Solutions Programme (iCASP) facilitates secondment activity with external organisations and KE partnerships. Secondment destinations have included BEIS [C-SCOTT], Born in Bradford [Research Scientist PRINGLE] and Yorkshire Water [PDRA RICHARDSON]. The MOAP secondment scheme enables SEE to host Met Office staff, including Science Managers from International Climate Services and Volcanic and Chemical Dispersion Groups. Incoming secondments have included Leeds City Council's (LCC) Head of Sustainable Energy and Climate Change, Environment Agency (EA) staff and JBA Consulting.

Focused support mechanisms (S1.3) have increased staff engagement in the development of research impact across SEE, engendering a culture that encourages and champions research translation activity alongside publications and research income (S4). Specific support mechanisms include consultation on impact pathways, staff workload allowances, an impact development budget (e.g., enabling CHIPPERFIELD to present at the United Nations on increased CFC-11 emissions, PARKER to employ a copyeditor for the Forecaster's Handbook, AM-OWEN to present at an Arup low carbon retrofit meeting), and administrative staff time to assist with engagement activities. Staff access professional impact training via OD&PL, including policy engagement workshops with UK Parliament and Government departments. Support for commercialisation and public engagement activities occurs in partnership with R&I Services (RIS).

Promotion and Recognition: We follow a clear and transparent promotion process for all academic staff, with multiple routes towards promotion (e.g., R&I, Student Education, Academic Leadership; see REF5a). The importance of research translation and impact activity is recognised in promotion criteria, including leadership of collaboration/partnerships, and engagement activities that maximise socio-economic benefits. Since 2014, 52 academic staff have been promoted (40.3% female: 59.6% male; Table 2), including 21 promotions for staff recruited during REF2021, demonstrating our commitment to staff development (Table 3). 12 of 32 promotions to Associate Professor come from our tenure-track research fellow cohort. 16 promotions have been awarded to research support and technical staff during REF2021.

Promotion stage		Gende		
	Staff Promoted	Male	Female	International
Professor	12	7	5	3
Associate Professor	32	18	14	5
Lecturer/Senior Research Fellow	8	6	2	1

 Table 3: Number/nature of promotions during REF2021.

Staff achievements are also recognised/rewarded financially following UoL's policy on rewards and recognition. In 2019/20, 28 staff (including research, teaching, laboratory/technical and administrative) were rewarded in this way.



2.4 Postgraduate Research (PGR) Students

Research Students Overview: During REF2021, we supervised 340 UoL PGRs (Fig. 5) to completion (295.19 PGR FTE directly attributable to supervisors in SEE; Fig. 5d). 283 PGRs were registered in SEE, 57 PGRs received their degree from a different UoL school (e.g., SoG, Civil Engineering, Chemical and Process Engineering) demonstrating the interdisciplinarity of the cohort. The average completion rate (within 7-years) for PGRs commencing study between 2007/08 and 2013/14 is 87.7%.

Our PGRs produce high quality research, authoring 390 papers during REF2021 and are authors on 20% of papers submitted to REF2021 (65 papers in total, 38 with the PGR as 1st author). AE-OWEN, now a tenure track fellow, was the UoL outstanding PGR of the Year in 2014. Our students participate in KE and wider impact activities (e.g., BEIS policy placement [SCHLICH-DAVIES]).



Figure 5: PGR (a) gender, (b) nationality, (c) funding source and (d) total number (FTE) of students graduating annually. Information in (a-c) shown for PGRs registered in SEE only, and (d) shows all PGRs with a SEE-supervisor.

SEE led the SPHERES NERC DTP, and its continuation PANORAMA⁶. We also lead the NERC/UK Space Agency SENSE CDT with the University of Edinburgh, NOC, and BAS. We are pathway leaders in the ESRC White Rose CDT, an ESRC CDT in Data Analytics and Society (hosted by the Leeds Institute of Data Analytics), the EPSRC Fluid Dynamics CDT, and the EPSRC Bioenergy CDT⁷. Strategic partnerships with organisations such as the Met Office have led to enhanced student recruitment via NERC-CASE studentships.

PGR Recruitment, Monitoring, Training, Support, Careers: PGR projects are openly advertised (e.g., UoL website, findaphd.com). Our CDTs/DTP run social media campaigns ahead of recruitment rounds aimed at underrepresented groups, highlighting the opportunity to those who may consider

⁶SPHERES/PANORAMA: 82 studentships in our UOA (30.6 funded by the School/UoL). ⁷Since 2014, DTPs/CDTs have enabled 106 studentships within our UOA.



this career path less frequently. Staff involved in shortlisting/interviewing candidates receive EDI and unconscious bias training. Candidate shortlisting follows a quantitative assessment against predefined criteria, aiming to identify student potential independent of their background. Our NERC DTP uses multiple 2-to-1 interviews to reduce interview bias and give PGRs from diverse backgrounds/cognitive diversity the best chance to succeed. DTP/CDT panels refer to a question catalogue with defined scoring criteria.

Upon joining SEE, PGRs join research themes and DTP/CDT cohorts to foster a sense of belonging. Students are co-located in multi-occupancy offices, each with an allocated desk and new computer. Students have a formal induction, including social events, to raise awareness of important policies and processes and to build a sense of belonging. The Leeds Doctoral College (REF5a) brings all support services and opportunities available to PGRs together. On a local level, supervisors and SEE PGR Tutors (PGRTs, both male and female), are available to respond to queries and direct PGRs to appropriate resources and help. There is one PGRT for every 30 PGR students, and they support students through regularly advertised drop-in sessions.

PGRs have access to SEE-specific training activities (e.g., programming for environmental scientists, publications masterclasses) and OD&PL training. DTP/CDT cohorts have access to additional training and development activities, including careers and leadership, communication & policy, and data & analytics. Training events are offered to the entire PhD cohort whenever resources permit. DTPs/CDTs offer opportunities for students to interact with DTP/CDT partners both within and outside academia. SEE seminar series are an important aspect of training and PGRs are expected to attend and present at research theme seminars. All PGRs (regardless of their source of funding) are given a Research Training Support Grant to attend national and international conferences to share research, increase visibility, and enhance career prospects. PGRs have been recognised at conferences such as the American Geophysical Union (AGU) for their outstanding research contributions.⁸

SEE operates a co-supervision model, ensuring that each PGR student has access to a minimum of two supervisors. PGR representatives are included in School and Faculty committees (e.g., Research Theme Committee meetings, Faculty Graduate School meetings) and are a vital conduit for information flow to and from the PGR community. We use formal 'health-check' meetings to monitor the progress of PGR students at months 6, 12, 24 and 33 of their studentships. Transfer to full PhD status takes place at the 12-month meeting. To ensure rigour, transfers are performed by independent assessors, including an experienced Transfer Chair. Transfer outcomes are decided by assessors not supervisors. The UoL system, GRAD (Graduate Record of Achievement and Development), records all PGR engagement in an auditable way. All full-time PGRs are expected to have at least 10 formal meetings per annum with their supervisors, with many having weekly meetings to ensure satisfactory progress and checks on wellbeing.

PGRs undertake internships and placements (required and funded by CDTs/DTPs) governed through Faculty Graduate School policy in companies (e.g., BP) and organisations (e.g., Red Cross, British Geological Survey, EA), and to further their skills (e.g., participation in Antarctic field surveys). SEE pioneered the alternative thesis format, which includes manuscripts as published in peer-reviewed literature. The first UoL student following this route was based in SEE (HOWELL graduated 2016). PGR publication is celebrated by our annual PGR publications prize. Prize-winning PGR papers submitted to REF2021 include UOA7-2431, 2506, 3124.

Completed graduate students have gone into a variety of exciting careers in research and education (e.g., NASA Jet Propulsion Laboratory, UC Berkeley, ETH Zurich, Yale University, Met Office), government (e.g., BEIS, Ministry of Environment & Climate Affairs – Oman) and industry (e.g., World Bank of Carbon).

⁸Six AGU Outstanding Student Presentation prizes.



2.5 Supporting Equality and Staff Wellbeing

Equality, Diversity, and Inclusion (EDI): SEE supports the UoL EDI policy ("*Everyone included everyone involved*"). This commitment is reinforced through the Leeds Gender Framework, which oversees UoL's involvement with Athena SWAN (REF5a). SEE actively participates in the Faculty EDI Committee that meets termly, cascading good practice through the School and shaping new policies through the School-level EDI Committee (Fig. 1). The Faculty of Environment holds a silver Athena SWAN award (awarded November 2019), building on a bronze award (April 2016). The Athena SWAN award recognises good practice within SEE, such as supporting staff to work flexibly⁹. SEE policy on supporting staff returning from family leave, or with caring responsibilities, provides a range of additional support options. These include rebalanced workload, continuation of back-fill arrangements for a fixed period, funds to support re-connection linked to work activity (e.g., financial support for childcare arrangements to enable academic conference attendance and paid childcare to enable keeping-in-touch days). This policy goes beyond standard UoL expectations, with associated costs met by SEE.

All staff complete an online EDI training module and have access to unconscious bias training. Female staff are encouraged to engage with several training programmes (Springboard and Aurora (REF5a)). Springboard aims to build confidence and assertiveness. Aurora fosters leadership skills for female staff in both academic and professional roles. Recent participants of the programme have progressed to campus leadership roles (e.g., Chair of Women at Leeds Network [GILL]). STRINGER participated in the Homeward Bound Project Expedition to Antarctica for women in climate leadership.

EDI and REF: Our REF core team, outputs and impact review groups were balanced by gender and disciplinary background, including interdisciplinary experts. Outputs were internally reviewed by multiple staff to reduce score bias. The submitted output portfolio was based on a statistical model that included output grades without reference to staff names, to reduce the potential for output selection bias. Staff members on review groups and REF core team, who assessed the portfolio of outputs and impact case studies, received enhanced EDI training to ensure the submitted portfolio represents an appropriate diversity from male/female staff, from staff at different career stages, and from full- and part-time staff (Table 1). Analysis of the average distribution of outputs per staff member demonstrates our REF processes have not led to bias in the representation of staff with disclosed protected characteristics.

Staff Wellbeing: OD&PL (REF5a) offers resilience training sessions covering a broad range of topics including, mindfulness, working with stress and emotion, and understanding and managing anxiety. This is supported by the Staff Counselling and Psychological Support Service. Staff networks are available for all staff: Women at Leeds, Leeds 11 (to support BAME staff), the LGBTQ+ network, Muslim staff network and Staff Mental Health & Disability network. Women at Leeds offer monthly events for female staff on campus. Staff who are also carers can make one-to-one appointments with Carers Leeds, who provide practical advice and support. Carers can apply for 5 days paid leave in addition to existing annual leave allowance (increased to 10 days during the COVID-19 pandemic). Staff wellbeing is monitored through SRDS meetings, academic meetings with School management, and through mentoring practices.

3. Income, infrastructure and facilities

3.1 Research Funding Portfolio and Future Plans

We have increased our research income since REF2014 (Fig. 6). In 2019/20, we had >350 active research grants and a research income of £27.2M (93% growth since 2011/12 (£14.1M)). During REF2021 (2013/14-2019/20), we secured 20 competitive grants with an award value >£1M

⁹UoL flexible/remote working policy (REF5a) extended to all staff (full-time, part-time, fixed term).



(including 3 led by early-career researchers). In 2019/20, our income/FTE was £214k, compared with £154k in 2011/12.

Our research is aligned to the strategic priorities of UKRI. The breadth of our research enables agility and responsiveness to interdisciplinary and challenge-led opportunities with high potential to generate impact (e.g., GCRF-AFRICAP (£8M)¹⁰, iCASP (£4.8M), GCRF African-SWIFT (£7.97M), [ICS-1]; Fig. 2; S4.1). We have an outstanding track record of NERC funding, securing >£74M in research income during REF2021 from over 360 projects. Aggregate data (2015/16-2019/20) demonstrates that UoL received more NERC funding that any other institution. Our research income from EPSRC is significant (£9.2M), reflecting our success in the energy sector¹¹ and leadership roles in large centres (S4.1). Staff lead two EU Horizon 2020 projects¹² and we have been awarded 4 Starter/Consolidator Grants by the ERC increasing our funding from EU Government (£14.9M). Our non-UKRI/non-EU Government research income totalled £27.9M, reflecting over 150 different sources, including £3.3M from the Met Office and £2.9M from the European Space Agency (ESA). We have demonstrated leadership in long-term (+10 years) industrial consortia, and since 2014 have engaged with ~45 companies through collaborative Joint Industry Projects (JIPs, e.g., Lobe, FRG-ERG, PETGAS), securing £9.5M in research income and influencing business decision-making and practitioner training.



Figure 6: HESA research income for REF2014/REF2021. 5-year data enables direct comparison to the REF2014 Environment Statement.

Our research culture supports preparation of grant applications, which is crucial given the dynamic funding landscape. We provide time through targeted workload relief for staff leading large grant proposals. Our research structure provides bespoke support through a central R&I Development Manager (RIDM) and by the *R&I Support Team*, who provide tailored advice on proposal design/development and planning impact pathways (S1.3), and our Faculty Research Office (FRO) for grant costing. We use our research themes, alongside University-wide initiatives (e.g., GFEI, Priestley Centre), to support the transition from idea generation to proposal development around curiosity-driven and impact-oriented research. Formal and informal internal peer-review are engrained in our operation, including grant-writing courses, cross-theme and cross-faculty review

¹⁰Total award value per programme from UKRI Gateway to Research Website.

¹¹EPSRC Fellowships [BALE, BROCKWAY, HALL, AE-OWEN, ROELICH]

¹²EU Horizon 2020 projects CRESCENDO and CONSTRAIN.



panels, and mock interviews. Since 2019, we have opened our review panels to observers to build even greater confidence in review processes.

Future income success relies on continued support for academics to maximise their individual potential, on retaining leadership of key centres (Fig. 2), exploiting our unique research breadth to face interdisciplinary grand challenges, and capitalising on our internal and external collaborations/partnerships. We will encourage staff to continue to develop world-leading research to face responsive/directed calls, and to engage in actively shaping the UK's research agenda through proposing strategic priorities and highlight topics, and by championing specific areas to decision makers¹³.

3.2 Evidence of Investments (Infrastructure and Facilities)

During REF2021 we made significant investments in our physical research environment (infrastructure and facilities). A £23.5M Capital Building project, completed in 2009, unified SEE's research and teaching within a purpose built, state-of-the-art building. To accommodate subsequent growth, a £7.3M project provided a new wing inaugurated as the Priestley Building (June 2019; Fig. 7), with four floors of offices and meeting rooms housing the Priestley Centre, and academics and PGRs across our research themes. Co-location of diverse expertise fosters an environment in which interdisciplinary and collaborative research flourishes. NCAS (hosted by SEE) moved their HQ at UoL to the newly refurbished Fairbairn House (£392k investment), alongside the creation of a new annex for the <u>Atmospheric Measurement and Observation Facility (AMOF)</u>. The physical footprint of SEE has expanded by ~20%.



Figure 7: New Priestley Building collaboration spaces (left & right) and external building connecting to the original SEE building (centre).

3.3 Provision/Operation of Specialist Infrastructure and Facilities

The SEE building was purpose-built to provide world-class capability in research and teaching, which includes a range of state-of-the-art laboratory and computing suites. During REF2021, we have maintained and expanded existing laboratory suites, developed a range of new specialist laboratories, and contributed >£1M to a major enhancement of UoL High Performance Computing (HPC) that provides free access for staff and PGR students.

Our Cohen Laboratory provides a suite of facilities for multidisciplinary (bio)geochemical and isotopic analyses of rocks, soils, sediments, and water. *Cohen* has underpinned development and application of new techniques for reconstructing and understanding modern (e.g., UOA7-1353) and ancient (e.g., UOA7-343) environmental conditions, and attracts ~10-20 international research visitors per year. Expanded capability includes the addition of a new ICP Aqueous Analysis Facility (supported by a dedicated technical specialist; £197k equipment investment) and the purchase of a new stable isotope mass spectrometer and preparation system, which specifically allows the analysis of samples at the scale of individual microfossils (£408k investment). The facility has supported a major expansion of geochemical research outputs within the *Ancient Environments* and *Environmental Processes, Management and Policy* themes, including 370 research outputs since REF2014. *Cohen* supports research with the National Nuclear Laboratory to inform risk management at UK nuclear

¹³E.g., DESSAI Champion for <u>UK Climate Resilience Programme</u>



sites. Major research programmes based on these facilities include ERC MinOrg, NERC Locked Up and two of the three NERC BETR directed international programmes.

The Sorby Environmental Fluid Dynamics Laboratory (SEFDL), a NERC-recognised facility, hosts equipment to study the properties and fluid concentrations of geophysical flows, and supports research within our Energy Pathways and Ancient Environments themes, with expertise in sediment-laden currents (UOA7-488) and particle image velocimetry (PIV). The SEFDL is a key component of the EPSRC CDT in Fluid Dynamics and the Leeds Institute for Fluid Dynamics. Capital investment during REF2021 (>£1M (EPSRC (£227k), NERC (£493k), Industry (£115k), UoL (£187k))) includes the addition of Volumetric Particle Image Velocimetry and 3D Laser Doppler Anemometry systems. These allow collection of high spatial and temporal resolution velocity data to investigate complex turbulent flow fields. The breadth of equipment allows an interdisciplinary community to conduct experiments on particulate transport processes, remediation, and high-resolution analysis of particle characterisation, including supporting >30 PhD students during REF2021, and applied research with Speedo on swimwear development [PEAKALL].

The *Wolfson Multiphase Flow Laboratory* measures petrophysical properties of porous media, particularly low permeability rocks, and supports our *Energy Pathways* theme (e.g., UOA7-1221, 1903). The laboratory is integral to research conducted through multiple JIPs, and has led to a new spinout company PETRIVA Ltd. [ICS-6]. Capital purchases include a GE Brivo 385 medical-type CT-scanner (£200k) and a stressed mercury injection porosimeter (£200k). The hosting of long-term academic visitors from Brazil, Canada, and India illustrates the international profile of *Wolfson*.

The *Cosmogenic Laboratory*, operational in 2014, processes samples for measuring chlorine-36 on an ICP-AMS (Inductively Coupled Plasma Accelerator Mass Spectrometer). It is the only facility in the UK applying cosmogenic isotopes to active faulting and has been used to determine the rates and patterns of slip due to earthquakes in Abruzzo, Italy (L'Aquila earthquake 2009). These data underpinned GREGORY'S NERC Independent Research Fellowship. Key publications include UOA7-2697.

The *Ice Nucleation Laboratory*, housing a unique range of bespoke equipment, enables experiments to characterise, quantify and understand atmospheric ice nucleating aerosol particles (e.g., UOA7-1365), and supports our *Atmospheric Science* research theme. The facility includes a Portable Ice Nucleation Experiment Instrument (PINE), which is being commercialised and developed through MURRAY'S ERC Consolidator Grant. Our new Mobile Weather Radar measures areal precipitation, radial winds, and polarisation parameters. The new platform commissioned directly for use by the EA and the Scottish Environment Protection Agency enables longer-term deployments to support nowcasting of convective storm events in Scotland and Cumbria.

SEE houses a variety of smaller, specialised laboratory facilities, including a *Micropalaeontology Laboratory* and *Experimental Petrology Laboratory* that are new developments during REF2021. In addition, our *Electron Microscopy Facility* underpins research across a wide range of disciplines, and includes an electron microprobe and two scanning electron microscopes optimised for geological applications.

Researchers within SEE benefit from University-wide Advanced Research Computing (ARC) facilities. ARC HPC (ARC1-4), alongside dedicated SEE computer clusters, have supported significant model-based analyses (e.g., UOA7-2880, 4427, 4468) and impact case studies [e.g., ICS-1|2|9]. UoL hosted the <u>N8 (HPC) shared facility Polaris</u> (2013-2018) and invested in the new ARC3 (2017) and ARC4 (2019) facilities (totalling 12,000 cores). Since 2016, we have provided School-level technical and scientific support for research computing that enables internationally leading research. The *Centre for Environmental Modelling and Computation* (CEMAC) significantly accelerates our high impact research in environmental modelling and computation, helping SEE train a new generation of scientists in the latest scientific computing, data processing and visualisation techniques. CEMAC support includes a Technical Director, three software development scientists and five science domain experts (supporting research across multiple SEE research themes). Since



its launch in June 2016, CEMAC staff have supported >40 publications (e.g., UOA7-797, 2431, 4468) and 48 projects (value totalling £32M).

3.4 Operational and Scholarly Infrastructure

Alongside the *R&I Support Team* (S1.3), technical staff are a vital part of our operational infrastructure. To maintain our extensive laboratory facilities, SEE is supported by 17.1 FTE laboratory managers and technical staff. As part of our ongoing review of facilities, we established a Facilities Working Group to provide peer-to-peer professional support for laboratory staff, a formal collective voice for this staff-base, and structured input into both the long-term facilities strategy and the overarching School aims. In 2019, a technician in *SEDFL* (BROWN) was appointed as SEE collead for EDI, a demonstration of the extension of our commitment to both academic and technical staff.

SEE is supported by four University libraries (REF5a) holding >2 million titles. Library facilities have received ~£50M in investment during REF2021. They provide access to >1000 relevant peer-reviewed journals.

3.5 In-kind benefits and UK Research Facilities

SEE researchers have benefited from >£4.1M of income in-kind during REF2021 using UKRI facilities, including aircraft, geophysical equipment, and laboratory analyses. Our researchers access major research facilities (e.g., Diamond Light Source, NERC ship time, ESRF, HPC), which underpin >100 research grants. Research led by a PGR student [DUNNE] was enabled using the CERN CLOUD Chamber (Cosmics Leaving Outdoor Droplets; UOA7-411). Alongside UoL HPC, national/regional/Met Office/NCAS supercomputing facilities have been utilised extensively (e.g., Archer, Polaris, Monsoon and Jasmin) with simulations underpinning several REF outputs (e.g., UOA7-2072, 2984).

SEE and UoL host several national facilities (e.g., *SEDFL*, S3.3). Our NCAS partnership includes leasing and operating a UKRI-owned aircraft (BAe-146), which provides the world-leading national Facility for Airborne Atmospheric Measurement (FAAM). This is used by the UK atmospheric research community on campaigns around the world. NCAS staff within SEE are responsible for deploying and managing NCAS's suite of mobile instrumentation as part of AMOF.

4. Collaboration and contribution to the research base, economy and society

4.1 Collaborations, Leadership and Partnerships

Our researchers lead a diverse range of centres and programmes (Fig. 2), aligned to our research and impact strategy, which support regional, national, and international collaborations and partnerships, and result in socio-economic benefits. Our collaborations are operationalised by administrative support teams, and facilitated by the *R&I Support Team* (S1.3) and University-level themes and platforms (REF5a).

Centres, Programmes and Networks

The **ESRC CCCEP** centre [PAAVOLA, GOULDSON], jointly hosted with LSE, entered its second phase in 2013 and third phase in 2018. CCCEP's mission is to advance public and private action on climate change through rigorous, innovative research, and engages with governments and international organisations to influence policy. Research on climate compatible developments [STRINGER, DOUGILL] brought together stakeholders in sustainable land management in South Africa, informing national policy and the UN Development Programme, and strengthening ongoing collaborations with the African Climate and Development Initiative (University of Cape Town). Green growth (Phase 2),



low-carbon climate resilient cities and industrial strategies (Phase 3) research themes have informed national and international city planning [ICS-4]. Local action is further facilitated through the CCCEPaligned **ESRC P-CAN network** (2019-2023). P-CAN has expanded links with researchers (QU Belfast, University of Edinburgh) and public, private and third sector decision-makers to translate climate policy into community change through initiation of a Leeds city climate commission; a concept replicated in Belfast and Edinburgh. 25 low carbon plans have been delivered to local authorities and local enterprise partnerships.

NERC Yorkshire iCASP (2017-2023) [HODGSON, MARTIN-ORTEGA] is a regional impact programme shared with SoG. It generates economic, policy and environmental benefits through integrated catchment solutions that address flooding, water resource and land management issues. The programme is co-delivered with a wide range of partners, including Yorkshire Water, EA, LCC, environmental consultancies, the Universities of Sheffield and York, and NCAS. A cohort of Impact Translation Fellows lead projects at the researcher/user interface. Engagement is evidenced by 11 secondments to and from UoL. iCASP has built a strong regional presence, with co-design workshops and an annual networking event ('Confluence'), with several MPs and 159 organisations attending. By July 2020, iCASP had created 23 jobs, supported organisations in securing £6.9M of funding, and informed 9 regional and 4 national strategies.

A sustained portfolio of **UK energy systems, demand** and **transition** research includes leadership of the **CIE-MAP** centre (BARRETT, 2015-2018), thematic leadership in **UKERC** Phase 3 and 4 (P-TAYLOR, BARRETT, 2014–2024) and **CREDS** (BARRETT, BUCHS, 2018-2023). As part of the UKRI Energy Programme, the centres bring together leading Universities to deliver interdisciplinary research that positions the UK to meet its energy and environmental targets. The centres' researchers at Leeds have engaged with UK government and industry partners and produced working papers and policy briefings. Through CIE-MAP, BARRETT worked with BEIS and DEFRA to develop policy relevant analysis and models, which led to changes to government indicators [see ICS-7]. CIE-MAP engaged with the construction sector to inform industry guidance prepared by the UK Green Building Council and the Green Construction Board. Following UK legislation to adopt net-zero targets, the CREDS materials and products theme has continued to identify opportunities for energy efficiency in UK industry, working closely with the CCC. In addition, Leeds CREDS researchers released recommendations on reducing household carbon footprints in May 2020 [PDRA IVANOVA] featured in a BBC article.

The **Future Climate for Africa Programme** (FCFA; 2015-2022) is funded jointly by NERC and the UK Foreign Commonwealth and Development Office. FCFA has brought together >200 researchers from >20 countries to improve understanding of climate variability and change across Africa through the implementation of 5 consortia programmes. SEE leads the East Africa-focused HyCRISTAL [MARSHAM] and manages major work streams for South and Central Africa-focused UMFULA [DESSAI, DOUGILL, STRINGER], West Africa-focused AMMA-2050 [PARKER, CHALLINOR] and IMPALA [BIRCH, FORSTER, MARSHAM, PARKER]. HyCRISTAL, supported by the East African Community of 6 nations, produced hydrological models and hydrometeorological networks for 27 catchments within the Lake Victoria Basin for water resource assessments. Co-produced pilot projects involving 23 research, government and NGO organisations in Kenya and Uganda have applied climate model projections to urban water supply/sanitation (in partnership with School of Civil Engineering), rural livelihoods, tea production, and transport planning on Lake Victoria as part of a World Bank project.

GCRF African-SWIFT (2017-2021) [BIRCH, BLYTH, DOUGILL, MARSHAM, PARKER, SCHWENDIKE], with Leeds-based NCAS programme support, develops partnerships to improve African weather forecasting capability, linking 10 forecasting centres and universities in four African nations (Senegal, Ghana, Nigeria, Kenya), and 5 UK partners, with the World Meteorological Organisation as advisory partner. The programme delivered forecast testbeds and workshops in each nation, directly engaging with >200 users, and producing linked reports and policy briefings [ICS-1]. KE was enhanced via 5 African-SWIFT fellows, hosting a Cheney Fellow from the Ghana Meteorological Office (former Director General of the African Centre of Meteorological Applications for Development [LAMPTEY]), 6 secondments between African partner institutions, and a summer school (Ghana, 2019).



GCRF-AFRICAP (2017-2021) [CHALLINOR, DOUGILL, QUINN, SALLU, WHITFIELD] aims to translate agriculture and food systems research evidence into policy and practice, working in close collaboration with the Food, Agriculture and Natural Resources Policy Analysis Network (FANRPAN) in South Africa, Chatham House (UK), and national and regional governments in Malawi, South Africa, Tanzania, and Zambia. Interdisciplinary research has built a picture of national agriculture and food systems, evaluated, and modelled agricultural development pathways, and engaged with policy networks to share evidence and support decision making. Examples include providing evidence to the ongoing agricultural masterplan review in South Africa, and supporting the development of i) a soybean strategy (Zambia), ii) a district-level climate smart agriculture learning alliance (Tanzania), and iii) district-level implementation of the National Resilience Strategy (Malawi).

National Leadership

We host three national research centres, providing national leadership and capability, and enabling collaboration in Earth systems research by bringing together scientists from across the UK.

NCAS, headquartered at UoL, has >200 members of staff embedded across 12 UK Universities and research institutes. MOBBS, a member of NERC Council, has been the director of NCAS since 2005. NCAS-led collaborations at Leeds [BLYTH] include the UK component of EUREC⁴A, an international field campaign supporting the World Climate Research Programme's Grand Science Challenge on Clouds, Circulation and Climate Sensitivity, involving 40 institutions across Europe, USA, and the Caribbean. KE workshops link forecasters and researchers.

COMET, with the Directorate at UoL since 2014 [WRIGHT], brings together scientists across the British Geological Survey and 10 UK universities to deliver leadership and national capability science on Earth Observation, tectonics, and volcanism, and to foster a vibrant national community of postgraduate and early-career researchers. COMET works closely with governments, NGOs, and other international partners to shape policy decisions and improve the management of natural hazards. COMET scientists in SEE have provided responsive analysis following major earthquake events in the Philippines (2020), New Zealand (2016), Italy (2016), and Nepal (2015), and volcanic activity in Iceland (2014-2020), and Ecuador (2017) and provide an open data portal [ICS-9]. NEUBERG Chairs the Montserrat Scientific Advisory Committee. Our COMET scientists contribute to ODA-funded projects including the GCRF Hazard Urban Disaster Risk Transitions Hub and GCRF Seismic Cities to assess the vulnerability of cities to seismic and volcanic hazards.

CPOM, with Directorate at UoL since 2014 [SHEPHERD], provides UK national capability in Earth Observation and cryosphere modelling. The centre brings together researchers across 5 UK Universities and works in partnership with ESA and the British Antarctic Survey. CPOM provides scientific leadership for the ESA Cryosat-2 mission, and the ESA-NASA Ice-Sheet Mass Balance Intercomparison Exercise (involving 97 participants from 13 countries: UOA7-2525, 4746). The Ice-Sheet Model Inter-comparison Project for CMIP6 supports the land and sea ice components of the UK Earth System Model, hosting an open data portal.

Strategic Partnerships

SEE has several formal high-profile external partnerships increasing the effectiveness of research collaboration, KE, and PGR training:

The **Met Office Academic Partnership** (MOAP), led by MARSHAM, secures the UK's position as a world leader in weather forecasting and climate prediction, and contributes to training future leaders in atmospheric science. The partnership is supported by 3 jointly funded Professorships (MARSHAM, FIELD, LOWE), and LUMOS, which has 6 shared posts that enhance our capability to support end-to-end research into the development and use of Met Office atmospheric models for socio-economic impact [e.g., ICS-1|2]. We hold roles in multiple projects in the Newton Fund supported [Weather] Climate Science for Service Partnership ([W]CSSP China, India, Brazil, and SE Asia). Further collaboration is enabled via 4 Senior Met Office staff hold Visiting Professorships at SEE. Through



MOAP, we lead and participate in a large portfolio of research across 4 themes and co-supervise >22 NERC CASE PGR studentships. The MOAP has allowed 3 Met Office scientists to study parttime for a PhD at UoL, in one case leading to new method developments that enable probability estimates of UK tornado occurrence, increasing confidence in warning systems.

The **Karlsruhe Institute of Technology (KIT) partnership** builds on the longstanding collaboration between our atmospheric scientists and the KIT Institute of Meteorology and Climate Research. This provides an opportunity to share and exchange knowledge through internal/external seminars, for the co-supervision of PhD students [e.g., ADAMS, KING], for PhD and ECA research visitors, the convening of summer schools [SCHWENDIKE], the sharing of research facilities including atmospheric chambers (supporting MURRAY), and the production of research proposals and publications. The partnership has led to the submission of new patents to determine aerosol concentrations in a carrier gas.

UK-Sino Joint Research Centre for Earth and Planetary Sciences, established with the Institute of Geology and Geophysics, Chinese Academy of Sciences (CAS) [HAYWOOD], is underpinned by a £160k 5-year investment from both parties. This enables the collaborative use of research facilities, staff [MÜLLER, MURPHY, DE RIDDER] and PGR exchanges [HUANG, LOU, XU, ZOURA], and co-production of pilot research to develop joint proposals to UK/Sino funding councils.

SEE-led University platforms have facilitated expansion of our international partnerships. The **Priestley Centre** [FORSTER] has developed a strategic research partnership with the **Center for International Climate and Environmental Research** (CICERO), Oslo, Norway. CHALLINOR has consolidated an existing partnership with the international CGIAR Climate Change, Agriculture and Food Security research programme (CCAFS), outcomes of which have included the development of a learning platform on "Partnerships and Capacity for Scaling Climate-Smart Agriculture", hosted by the Priestley Centre. **GFEI** [BANWART] has established a new joint international research Centre in Critical Zone Science and a new dual PhD with **Nanjing University**, and a partnership with the **Chinese Academy of Sciences** to develop a Critical Zone Observatory with a focus on soil and water resources.

Researcher Mobility

SEE research visitors, from students to sabbaticals by senior academics, enrich the research environment by promoting collaborations. During REF2021, we hosted >100 international visitors in SEE, including 2 Leverhulme Visiting Professors, 5 Cheney fellows, and 10 Marie Curie International Fellows. We provide funds (e.g., Outstanding Academic Visitor Policy) to enable staff to host visitors and time to visit other institutions. Visits are linked to notable research successes (e.g., UOA7-931, 932, 2073, 2173, 2582 and ERC project DEEPVOLC, SMURPHS, CONSTRAIN), and the establishment of new partnerships (e.g., UK-Sino Joint Research Centre for Earth and Planetary Sciences).

4.2 Wider Contribution to Society and the Economy

We have contributed a wide range of social, economic, environmental, and educational benefits, beyond ICSs 1-9, through new and sustained collaborations and KE initiatives with business, government and third sector organisations.

Policy Engagement

UK parliamentary engagement is evidenced by 4 mentions of our research in parliamentary debate and 6 POST Notes referencing our research, including 2 expert reviews. Our researchers have appeared as expert witnesses at Parliamentary Committee hearings on subjects including the UK carbon budget [BARRETT] and the Arctic [SHEPHERD], and reviewed briefings for the House of Commons Library [YOUNG]. BARRETT served as a member of the academic panel for Climate Assembly UK, the first UK-wide citizens' assembly on climate change established by 6 Select



Committees in 2020. Research presentations to UK government departments and agencies include BEIS, DEFRA, EA, Government Office for Science, Food Standards Agency, NHS, FCDO and the Scottish Government. We contribute to government advisory bodies, notably the CCC, through committee membership [FORSTER appointed 2018], acknowledged report contributors [BARRETT, AE-OWEN], or expert advisers [STEINBERGER, P-TAYLOR]. CHALLINOR and STRINGER were lead authors for the CCC's *UK Climate Change Risk Assessment* (2017) and MARTIN-ORTEGA's research influenced economic analysis supporting the CCC's Land Use report.

We play an active role in regional policy engagement as demonstrated by the work of our programmes and networks. AM-OWEN holds formal advisory roles for the Leeds City Region Local Enterprise Partnership Energy Strategy Steering Group and the Bradford Sustainable Development Partnership, which reports to a Local Authority Board.

See S4.3 for examples of international policy engagement via scientific assessments.

Business Engagement and Commercialisation

We have initiated 2 spinout companies (Satsense Ltd., PETRIVA Ltd.), 8 licences to unique technologies, and 3 patent families. Over 250 of our research publications through the period have included co-authors from corporate partners. Many of our large centres and programmes (S4.1) have developed partnerships with businesses. Our connections have expanded through Nexus (REF5a), which provides a gateway for businesses and researchers to interact. We have undertaken a Knowledge Transfer Partnership with Asda Stores Ltd., graded Outstanding [YOUNG, RUSSELL].

Our JIPs have enhanced PGR employability by engaging with over 35 national and multi-national companies. JIP research deliverables, including Turbidites Research Group ((TRG; Phases 8 and 9 [MCCAFFREY]), Fluvial and Eolian Research Group (FRG-ERG; Phases 2 and 3 [MOUNTNEY]), Shallow Marine Research Group (SMRG; Phase 2 [HODGSON]), Petrophysics of Tight Gas Sandstones (Phase 3 [FISHER]) and Lobe (Phases 2 and 3 [HODGSON]), are co-designed with industry partners. FRG-ERG, SMRG and TRG have developed the world's largest databases recording the arrangement of siliciclastic sedimentary rock bodies, which have been commercialised and marketed as the software "Ava Clastics", by Petrochemical Data Systems Ltd. As part of the net-zero initiative and new *Geosolutions Centre*, we are using our wide-ranging relationships with energy industry partners to accelerate industrial transition to low carbon energy production.

FORSTER was invited to deliver a keynote address at the Energy and Clean Growth in the Northern Powerhouse Conference in 2019, an agenda-setting event that brought together the 11 Northern Local Enterprise Partnerships with industry representatives to act on the economic opportunities presented by decarbonisation. AM-OWEN has acted as academic advisor to the Yorkshire and Humber Business Leaders for Sustainability, Arup's Retrofit UK project and the Construction Leadership Council. YOUNG has provided advice to the British Standards Institute on environmental performance evaluation and sustainability management.

Knowledge Exchange Initiatives

Two NERC KE [HOGG, Earth Observation; DALLIMER, Green Infrastructure] and three National Productivity Investment Fund Fellowships [PDRA HERNANDEZ MONTES DE OCA, PDRA K-SCOTT (now Manchester), PDRA RICHARDSON] enabled a range of partnerships. Researchers have acted as expert advisors to NGOs and charities, including the Joseph Rowntree Foundation [MIDDLEMISS] and Global Green and Healthy Hospitals [RUSSELL].

The Leeds Ecosystem, Atmosphere and Forest (LEAF) centre, initiated in 2014 (led by C-ScOTT), has developed partnerships with LCC, White Rose Forest, Woodland Trust, Forestry Commission and Forest Research. LEAF works in close partnership with the United Bank of Carbon (UBoC), a registered charity that seeks to protect and restore forests around the world. In partnership with UBoC, Forestry England, and the John Muir Trust, SPRACKLEN provides scientific expertise for the



Restoring Hardknott Forest project, which is restoring 630 hectares of conifer plantations in the Lake District to native woodland and other habitats, informed by research and monitoring.

PRINGLE and MCQUAID have contributed to increased awareness and action on air quality, a priority issue for Leeds and Bradford Councils. Through a UoL Engagement Excellence Scheme, and working in partnership with the Born in Bradford health study, PRINGLE developed a community air quality monitoring project, building, and testing low-cost air pollution sensors to enable local communities to monitor air quality, developing from a 2014 project "The Air in Saltaire". MCQUAID was invited to join the LCC Air Pollution and Health group in 2019. Both are involved in a major new interdisciplinary NIHR-funded programme to monitor the impact of the proposed Clean Air Zones on health in Bradford that began in July 2020, and involves clinicians, health economists, and transport researchers.

Public Engagement and Outreach

We are committed to enhancing public engagement and education to inform debate over critical environmental issues facing society. Our researchers have led 59 articles on the independent The Conversation platform. We have contributed exhibits and talks at large public engagement events including the UoL annual research showcase "Be Curious", NERC's Into the Blue, the Royal Society Summer Science Festival, Green Great Britain Week, Yorkshire Fossil Festival, Festivals of Science (Leeds, Bradford, York, Edinburgh, Cheltenham), Great Yorkshire Show and the Blue Dot Music Festival, reaching thousands of people. RUSSELL and SALLU held advisory roles for the Science Museums Group (London) and Eureka! (Halifax), respectively. PEAKALL contributed to an art installation for the 14th Istanbul Biennial Art Exhibition "Saltwater: A Theory of Thought Forms" (2015), which took place in 36 venues across the city. Our scientists have delivered >50 public lectures: internationally (e.g., Hawaii National Volcano Park), nationally (Science Museum, Natural History Museum), and locally (e.g., Yorkshire Geological Society, Royal Meteorological Society Yorkshire branch, Leeds library series, U3A). Researchers make regular appearances on the weekly Paul Hudson Weather Show broadcast on BBC Local Radio, on TV documentaries, and contributed to live TV via appearances on BBC Breakfast, The One Show and Sky News. Our scientists participated in the BBC's Terrific Scientific series and "I'm a Scientist get me out of here", which connects students to scientists in real-time conversations. HOGG, via CPOM, partnered with the Triathlon Trust in 2017 to promote interest in both fitness and Earth Observation, "The Space Earth Challenge", receiving support from astronaut Tim Peake.

To enhance the effectiveness of our educational activities, an outreach coordinator role was created (NEUBURG; 0.2 FTE). From 06/2019-03/2020, 9 events across the region gave ~600 school and college students interested in studying environmental subjects the chance to experience research-led teaching. We provide opportunities for continuing professional development of teachers via the *Environment Academy* and *Geophysics Teachers' Conference* that feature workshops and presentations by leading researchers. Through collaboration with the Leeds College of Art, we conducted pedagogic research to deploy immersive digital technologies to widen the accessibility of geological fieldwork (*Virtual Worlds Project*, winning the Times Higher Education Outstanding Digital Innovation in Teaching/Research Award).

4.3 Contribution to the Sustainability of the Discipline, Interdisciplinarity, Agility, Esteem

Our international research esteem and agility is reflected in SEE collaborations with scientists globally (Fig. 8), and our diverse and expanding group of visiting researchers (4.1). Our collaboration/partnership base has expanded during REF2021. Of the papers published during REF2021, 86% have an external co-author and 67.7% have an international co-author¹⁴ (compared to 85% and 60% respectively for REF2014). Academics from 127 different countries (118 in REF2014) are co-authors on SEE papers. We collaborate with all international research powerhouses (e.g., North America, Europe, China), but are committed to developing research expertise and capacity to deliver social and economic benefits globally. This commitment is

¹⁴Based on SciVal/Scopus data



demonstrated by our REF2021 papers published with international co-authors from 73 different countries in receipt of Official Development Assistance (ODA; DAC list 2021).



Figure 8: Global distribution and number of published papers including an international as well as UOA REF-eligible academic (2014-2020; source SCOPUS 18.01.20).

Leadership in International Scientific Assessments: We engage with international scientific assessments and advisory groups to influence policy decisions. We have provided 8 coordinating-lead/lead/contributing authors covering the three IPCC AR6 working groups. STRINGER was a coordinating lead author for the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) *Regional Assessment for Africa*, and lead author for the IPBES *Land Degradation and Restoration Assessment*. The UN Environment Programme (UNEP) has published two *Scientific Assessments of Ozone Depletion* (2014 and 2018) with CHIPPERFIELD as co-author in 2014 and Steering Committee member in 2018, and MAYCOCK as co-author in 2014 and lead author in 2018. Given renewed CFC-11 emissions, parties to the Montreal Protocol requested a special assessment in 2018, CHIPPERFIELD was a Co-ordinating Lead Author of the modelling analyses.

Leadership in Emerging Interdisciplinary Endeavours Tackling Global Priorities: In 2019, the UoL announced bold plans for action on achieving net-zero (REF5a). Internationally, we have supported this effort through leadership of/engagement in assessments such as the IPCC Special Reports on *Global Warming of 1.5*°C [FORD (UOA14), FORSTER] and *Climate Change and Land* [CHALLINOR, STRINGER]. Nationally, our research and expertise has underpinned the ground-breaking commitment by the UK government to reduce greenhouse gas emissions to net-zero by 2050 [e.g., ICS-3]. The recommendations from the UK CCC, on which this commitment is based, includes a broad range of input from our scientists [FORSTER, SMITH, STEINBERGER, P-TAYLOR], and key evidence on remaining emissions, the UK's carbon footprint, and energy demand reduction [ICS-7].

An Agile Research Environment: Our agile research environment is evidenced by rapid responses to emerging research priorities during REF2021, such as major GCRF projects (S4.1), successful NERC urgency grant applications (Italian earthquakes [BOOTH/GREGORY], mining wastewater [BURKE]; Chilean volcano [MANVILLE]), leadership or major involvement in five NERC Highlight topics (ACRUISE, CARSLAW; LOCKED UP, PEACOCK; SMURPHS, FORSTER; SWIGS, LIVERMORE; ULTRA, LITTLE) and the NERC strategic programme Uncertainty in Climate Sensitivity due to Clouds [BLYTH, CARSLAW, MURRAY]. Utilising the capabilities of the *SEFDL* [S3], HODGSON was awarded a GCRF/Royal Academy of Engineering grant to develop low-cost methods for assessing the fit of respirators used by health care staff when dealing with COVID-19 patients. COVID-19 related papers include UOA7-1800.



Indicators of Wider Influence and Esteem: During REF2021, SEE researchers have been involved in >700 separately funded national and international research collaborations across academia, industry, and the public sector, interacting with a wide range of stakeholders and leading to high-quality discovery and applied research outputs (Table 4). These projects include 52 consortia/large grants¹⁵ (led 17). As highlighted in S2.4, we contribute to 7 national training programmes for PGRs, which works to enhance the sustainability of the discipline.

Table 4: Indicators of wider influence (research income, received awards/prizes, impact of scientific outputs, community roles, UOA linked news stories during REF2021).

		Awards			REF Papers			C)	
Research Theme	Staff FTE	Research Income ^a	Fellowships ^b	Prizes	# Papers	% in top 1%	Editorships ^d	Peer Review College	News Stories ^f
Atmospheric Science	15.3	59.6	1	11	49	12.2%	8	6	166
Phys. Climate Change	11.0	12.3	5	12	49	16.3%	3	4	899
Climate Change Mit.& Adapt.	13.6	14.8	2	2	35	25.7%	14	3	108
Energy Pathways	23.45	20.1	6	5	51	7.8%	15	3	174
Env. Proc. Man. & Pol.	25.1	8.1	6	13	41	9.8%	13	5	113
Ancient Environments	12.7	12.3	5	7	41	7.3%	6	4	163
Earth Dynamics	26.0	10.8	11	13	52	7.7%	21	7	185
Total	127.15	138.0	36	63	318	11.9%	80	32	1808

^aResearch income from HESA data (01.08.2014-31.07.2020).

^bIncluding UKRI (1), NERC (8), EPSRC (5), ESRC (1), ERC (4), Royal Society (2), Leverhulme (6), ESA (2), Marie Curie (2), Royal Commission for the Exhibition of 1851 (1), Visiting/Sabbatical Fellowships (4).

^cPercentage of publications in top 1% of most cited (SciVal 12.01.21).

^dAdditionally, 65 editorial board roles and >23 guest editors on thematic journal issues.

^eNERC (29), EPSRC (2), ESRC (1).

^fNexis media search 04.01.2021.

We support the wider Earth and Environmental Science community by playing an active role in organising and participating in scientific meetings, and as editors of peer-reviewed journals (Table 4). Staff helped organise 204 scientific symposia (e.g., the Royal Society, the Royal Astronomical Society, the Royal Meteorological Society, the Royal Society of Chemistry, and the Geological Society, the European Society for Ecological Economics, the Fairtrade International Symposium) and chaired over 200 sessions at national and international conferences (e.g., AGU, EGU, Goldschmidt). Additionally, they gave over 600 invited lectures, including 86 keynote addresses at national and international conferences/workshops.

SEE staff acted as chief editors for 11 journals and editors for 69 others, and have provided 32 members of Research Council Peer Review Colleges (Table 4). Our staff review on average 8 journal articles per year. Staff are regular reviewers for grant/fellowship schemes including UKRI, ERC, Royal Society, Leverhulme Trust, NASA, and national research councils from 5 continents. As part of our ongoing commitment to the broader academic community, our staff undertake 102 national and 111 international committee roles, leading working groups, acting as members of advisory boards and leading scientific societies.

¹⁵NERC (19), EPSRC (2), ESRC (2), EU (22), ESA (3), DIFD (2), other (2).



The research of our staff has been externally recognised through the award of 36 personal or ERC fellowships, through >1800 news stories reporting our research, and 63 prestigious awards or prizes, including 5 from AGU¹⁶, 3 from EGU¹⁷, 2 from the Geol. Soc.¹⁸, and 2 from Royal Societies¹⁹. Researchers including CARSLAW (2014-19), FORSTER (2019), and SPRACKLEN (2016, 2018-19) are recognised as highly cited researchers (Web of Science), and we have 44 papers with an Altmetric score above 500. Due to their ongoing positive impact, 2 of our staff were recognised in the Queen's Honours (MOBBS MBE 2019; LOWE OBE 2020).

¹⁶Fellowships [CARSLAW, CHIPPERFIELD, FORSTER], Ascent Award [CARSLAW], Macelwane Medal [HOOPER] ¹⁷Jean-Baptiste Lamarck Medal [WIGNALL], Arne Richter ECR Award [MAYCOCK], Cryospheric Sciences ECR Award [HOGG]

¹⁸Geological Society of London Bigsby Medal [BENNING, POULTON]

¹⁹Royal Society of Chemistry John Jeyes Award [CHIPPERFIELD], Royal Astronomical Society Price Medal [LIVERMORE]