

Institution: University of Reading
Unit of Assessment: UOA7 – Earth Systems and Environmental Sciences
<p>Unit context and structure, research and impact strategy</p> <p>1.1 Introduction</p> <p>Our research community consists of more than 300 staff and doctoral students in the Department of Meteorology and the environmental science component of the Department of Geography and Environmental Science (GES) (collectively, ‘the Unit’).</p> <p>Our research focuses on the natural science of the environment, how it responds to and recovers from anthropogenic and natural perturbations, and the interplay between our environment, lives, and livelihoods. It covers atmospheric sciences, physical and biological oceanography, soil sciences, freshwater sciences including hydrology, land surface processes, cryosphere sciences, the role of solar activity on the Earth’s environment (‘space weather’), and the interactions between these fields.</p> <p>Activity includes: palaeoclimate sciences; research relevant to improving weather, hydrological and space-weather forecasts on timescales from hours to seasonal; and research relevant to recent and future global environmental change.</p> <p>We employ diverse techniques: laboratory and field-based measurements; surface and space-based remote sensing; advanced data assimilation; state-of-the-art numerical models; and theoretical frameworks for interpreting measurements and model output. We develop and exploit new techniques in all these areas.</p> <p>1.2 Context and structure</p> <p>Since REF2014, the University’s research activity has been structured around Research Divisions, in four broad Themes (Institutional Environment Statement (IES) Section 2). Our submitted staff belong to four of nine Environment Theme Divisions:</p> <ul style="list-style-type: none"> • Weather; Climate; Earth Observation & Space (in Meteorology) • Environmental Science (in GES). <p>Meteorology includes significant components of two NERC research centres: the National Centre for Atmospheric Science (NCAS), including its Computational Modelling Services (CMS), and the National Centre for Earth Observation (NCEO). Co-located with Meteorology is by far the largest group of Met Office research staff in any UK university (‘MetOffice@Reading’).</p> <p>Meteorology sits within the School of Mathematical, Physical & Computational Sciences (SMPCS). GES sits within the School of Archaeology, Geography & Environmental Science (SAGES).</p> <p>Our research is inherently multi- and interdisciplinary (covering the physics, chemistry, biology, and mathematics of the Earth system). A broader interdisciplinary perspective is achieved via various mechanisms including two University Interdisciplinary Research Centres (IES Section 2.1.1):</p> <ul style="list-style-type: none"> • The Walker Institute (henceforth Walker, directed by Cornforth) focuses on the development of climate-resilient and sustainable livelihoods, in some of the world’s most vulnerable regions. It uses evidence-synthesis generated through field work and stakeholder engagement, to translate research into evidence to inform decision-making. • The Centre for the Mathematics of Planet Earth aims to catalyse initiatives at the intersection between mathematics, theoretical physics, and earth sciences. It is led by the Department of Mathematics & Statistics with strong Meteorology involvement; Broecker and Shepherd are two of the Centre’s six board members.

S.Harrison is a Co-Director of the cross-disciplinary Leverhulme Centre for Wildfires, Environment and Society (led by Imperial College).

The University is lead partner in, and hosts, the Institute of Environmental Analytics (IEA). IEA is closely associated with the Unit, and a major development since REF2014. It was established via a 2014 HEFCE Catalyst Fund proposal led by O'Neill (now retired), providing £5.6m funding. It is now financially independent, having secured over £9m in further grant funding. IEA's current FTE staffing level is ≈30. IEA includes, among 21 University and commercial partners, the Universities of Oxford and Surrey, Microsoft, and the Met Office. It focuses on 'late-stage research, development of software applications and training' across areas including renewable energy, infrastructure and food and agriculture, and has worked with the Environment Agency, Highways England and governments and energy utilities in various tropical states. It plays an important role in enabling our research impact beyond academia.

We are involved in several doctoral training programmes which facilitate interdisciplinary interactions and help cement and expand our industry and policy partner engagement:

- We lead the **NERC Doctoral Training Partnership (DTP) SCENARIO** (Science of the Environment: Natural and Anthropogenic Processes, Impacts and Opportunities), which provides the core of our PGR cohort. Launched in 2014 and renewed in the second NERC DTP round (cohorts starting 2019-24), it has six host partners: University of Surrey, NERC's Centre for Ecology and Hydrology (CEH) and British Geological Survey (BGS), NCAS, NCEO and the Zoological Society of London. Four strategic partners contribute substantially to training: the Met Office, the European Centre for Medium-range Weather Forecasts (ECMWF), the National Physical Laboratory (NPL) and the Environment Agency. It has a further 22 UK public sector, industry and NGO partners.
- The University co-leads, with Imperial College, the **EPSRC Centre for Doctoral Training (CDT) in the Mathematics of Planet Earth** (cohorts starting 2014-18); Our staff are involved with leadership, training and supervision.
- The University is one of 3 HEI host institutes of **NERC's CDT in Quantitative and Modelling Skills in Ecology and Evolution** (cohorts starting 2017-20). We contribute PGR training and supervision.
- The **Leverhulme Trust Doctoral Programme in Climate Justice** (cohorts starting 2015-18) is led by the University's Department of Politics and International Relations and aims to improve 'understanding of ... scientific and justice aspects of climate change'; its Steering Committee includes 7 of our staff.
- The **BBSRC FoodBioSystems DTP** (cohorts starting 2020-24) is led by the University which is also an associate partner in the **BBSRC-Waitrose Collaborative Training Partnership** (cohorts 2017-20). We contribute expertise in environmental science underpinning food production. Walker provides interdisciplinary training courses for the Food BioSystems DTP.

Our STFC Consolidated Grants qualify us for STFC quota studentships (now labelled DTPs; typically one to two student starts per year) in solar system science.

The Unit supports extensive undergraduate and taught postgraduate programmes, founded on research-led teaching. These provide training opportunities for PGR students and are one important feed for PGR recruitment. Taught-course students undertake individual research projects, some in collaboration with outside organisations including the insurance and risk management, energy, water, retail, transport, and land-management sectors. Various initiatives support summer vacation placements. These activities benefit our research effort and ethos, including the testing of new ideas and enabling impact beyond academia.

1.3 Research strategy in REF2014

Our REF2014 mission was 'to carry out world-leading curiosity-driven environmental and Earth-systems research and use it to provide robust, focused and timely science evidence to support policy and business development' with a strategy to 'focus on areas where it has recognised world-leading strengths where there is a pressing need for applications outside academia'. We

recognised that 'blue-skies research is essential to the long-term quality of translational research'. Indicators of success in meeting our mission (noting our submitted staff FTE increased by 11%) include:

- Our submitted staff have been highly productive, on average publishing ≈ 320 papers per year (286 in 2014; 365 in 2020); $\approx 27\%$ are in the top 10 citation percentile and $\approx 4.4\%$ are in the top 1 citation percentile (of papers of a similar age) (SciVal, citation data excludes self-citations).
- Evidence of policy relevance includes high contribution to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report and heavy involvement in the Newton Fund and the Global Challenges Research Fund (GCRF).
- Average annual research income is 32% higher than in REF2014.
- Research income from UK industry (including the Met Office) increased seven-fold compared to REF2014; it now constitutes $\approx 10\%$ of the total (2% in REF2014).
- We have been proactive in shaping the research landscape, by proposing NERC Strategic Programme Areas and Highlight topics, and via involvement in senior committees of research funding agencies.
- The establishment of IEA aided translational activities to businesses through collaborative projects and training activities.
- We maintained our strong relationship with the Met Office and grew further links with ECMWF and NPL.
- The establishment of Loddon Observatory in collaboration with Environment Agency/ Defra's Catchment Partnership programme and other partners, allowed an interdisciplinary approach to address challenges of local flooding, water quality and sustainable agriculture.
- Walker's strategic collaborations in the development arena helped accelerate research translation.

1.4 Current research vision and objectives

Our strategy set out in REF2014 fed into the University's Environment Theme ('to explore, understand, and address the challenges of environmental changes, both natural and those shaped by humans') which is the principal mechanism for integrating environmental science research across the University. The strategy has been re-articulated with more specificity through the visions of our four Divisions. Delivery of these visions has been a principal focus during the REF2021 period and will continue to guide our strategy post-REF2021. The visions highlight our research breadth and focus:

- **Climate:** to innovate and provide scientific leadership across the breadth of climate research on the coupled atmosphere-ocean-cryosphere-land system, ranging from fundamental processes to global climate prediction, extending to impacts on human and natural systems, and including synergy with weather dynamics in the area of climate-related extremes.
- **Earth Observation and Space:** to deliver world-class research on the Earth system, from the solid Earth and deep oceans, via the atmosphere, to the magnetosphere and solar system environment. Our research will have both external impact and scientific rigour, achieved by approaches rooted in physics and exploiting a range of Earth Observation data, advanced data-assimilation techniques and numerical models of the Earth system and its components.
- **Environmental Science:** to deliver excellent cross-disciplinary environmental science with impact, with a focus on critical-zone functioning and related services and risks (such as in relation to floods, droughts, heatwaves, fires, glacier retreat, and exposure to pesticides and pollution) on a range of scales co-delivered with stakeholders.
- **Weather:** to conduct internationally leading weather-scale research with an increased emphasis on high-impact weather and its relation to climate-scale processes; and to use weather research to advance the science of wider environmental prediction through interdisciplinary collaboration.

Each Division has a professorial-level Leader (RDL) who works with the Research Dean for the Environment Theme; they meet regularly together to coordinate cross-working. Each Division has specific priorities which provide a structure for organising research. Yearly operating plans are agreed with the Dean, informed by annual Personal Research Plans submitted by Division members, as well as broader considerations. This structure has proven effective for highlighting wider and division-specific opportunities. Our approach emphasises cross-collaboration which extends to other Divisions including Mathematics & Statistics, Computer Science, Built Environment, Sustainable Agriculture & Food Systems, Ecology & Evolutionary Biology, Global Development, and Archaeology.

1.5 Research groups

Informal research groups meet on weekly to termly intervals and are open to all research-active staff, PGRs and MetOffice@Reading staff. These operate within and across the Division structure; individual staff and students may belong to several groups. Currently active groups include:

- Aerosol-Climate Interaction
- Atmospheric Composition, Radiation and Climate
- Aviation Meteorology
- Biogeochemistry
- Dynamical Processes
- Energy Meteorology
- Mesoscale Meteorology
- Ocean Processes
- Palaeo Environments and Climate Analysis
- Polar Processes
- Remote Sensing and Clouds
- Space and Atmospheric Electricity
- Tropical Applications of Meteorology (TAMSAT)
- Tropical Weather
- Turbulence
- Urban Meteorology.

Further groups enable interdisciplinary research between and beyond Divisions: the Soil Research Centre, the Data Assimilation Research Centre, Water@Reading, and the Land Surface Processes Cluster.

Research groups support a culture of research integrity. Research presented at meetings is subject to criticism and feedback; it is rare for research to be submitted for publication without constructive scrutiny in these or other meetings.

1.6 Open research

We are pro-active in implementing the University's Open Research strategy (IES Section 2.2) which nourishes the culture and practice of transparency and reproducibility. Examples that demonstrate that culture, combining open-source data, methods, code and documentation, include:

- The open availability of global river flow forecasts and associated documentation as part of the Global Flood Awareness System (GloFAS), a joint Copernicus Emergency Management Service with ECMWF.
- TAMSAT-ALERT's open-data, open-source models and free and open tools, providing information on potential adverse weather impacts for African agriculture.
- IEA's open-source software, ncWMS, enabling online exploration and visualisation of large-scale environmental datasets.
- Numerous palaeo environments and climate databases (e.g., Speleothem Isotopes Synthesis and Analysis, SISAL; EMBSecBIO modern pollen biomisation; Modern pollen data for climate reconstructions, SMPDS).

Open-source code is made available via environmental repositories (including the NCAS-CMS publicly accessible code repository) and more generic code repositories (including GitHub).

The University's open-access policy requires staff to deposit papers in its CentAUR repository (IES Section 2.2). We achieved high percentages of Gold Open Access publication, via internally

publicised institutional arrangements with publishers or individual research grants. In the REF2021 publication period 89% of publications from our submitted staff were open access, with 50% gold or hybrid-gold (data from SciVal; Russell Group averages were 63% and 27% respectively). The proportion of gold/hybrid-gold papers increased from 39% (2014) to 65% (2020) (Russell Group: 18% and 37%). In 2019 (the last full year unaffected by journal embargo periods), 95% of our publications were open access, up from 78% in 2014. Outputs comply with funder and publisher data depository requirements and use national services (notably NERC data centres), open-access repositories (e.g., Zenodo) or the institutional Research Data Archive (IES Section 2.2). Widespread use is made of journals with open peer-review processes (particularly European Geosciences Union journals); many staff have editorial roles in these journals (Section 4.9).

Gregory (with colleagues in NCAS-CMS and IEA) continued his lead role in the development and governance of the CF (Climate and Forecast) metadata standard. CF provides a standardised way to describe variables in geoscientific datasets stored in netCDF files. It is a widely used international standard for Earth system modelling and, increasingly, for Earth observation. It has, for example, helped enable efficient and open sharing of model output in the many model intercomparison projects that support IPCC assessments. **S.Harrison** chaired the International Science Council's World Data System, until 2019.

1.7 Impact strategy

Impact beyond academia is deeply embedded in our research ethos. It is a key motivator for much of our research and is considered throughout the design and execution of most projects. Project partners include weather forecasting agencies, insurance and re-insurance companies, national and local government, overseas development agencies, utilities (including the water, transport and energy supply industries), and businesses involved in agri-environmental quality and sustainable food production. Impact includes deep local engagement (e.g., the Loddon Observatory), direct collaboration with developing countries (e.g., via GCRF) and science translation (e.g., co-production of the Catchment Management Modelling Platform with Defra, NERC, Scottish Government, CEH, ADAS and Atkins).

Each Division has an Impact Lead (IES Section 2.3 and 3.3) to promote the research impact culture and identify opportunities for engagement and science translation. The Lead is supported by the University's Impact Development Manager for the Environment Theme.

We have engaged strongly with the University's impact development programme (BOISP) (IES Section 2.3), a major strategic investment since REF2014. BOISP provides a structured approach for identifying potentially impactful research, providing pump-priming funding for activities (including short-term staff, workshops, travel). BOISP includes a formal mechanism for regular progress reviews and suggests ways to broaden and evidence impact.

BOISP supported 20 projects in the Unit ranging from those with embryonic impact to those we selected as our submitted Impact Case Studies (ICS). The selected cases, which showcase the breadth and diversity of our impact, are:

- enabling humanitarian organisations to exploit seasonal flood forecasts
- enabling international climate agreements to compare the impact of emissions of different greenhouse gases
- delivering drought/rainfall early warning systems to sub-Saharan African farmers and insurance sector
- enabling the private sector to make health and safety decisions on risks to marine oil and gas infrastructure from mid-latitude and tropical storms
- enhancing airline flight planning through improved turbulence forecasts
- inventing now-iconic visualisation methods to make global audiences aware of historical climate change
- changing how the Met Office represents urban areas in weather and climate forecasts.

ICSs submitted to other UoAs involve our staff, emphasising the interdisciplinary nature of our research and its impact. **Dance** co-led a UoA10 ICS on 'Improved accuracy of weather forecasting internationally through advanced use of observational data'; this enabled a greater volume of data to be used in weather prediction by the Met Office, ECMWF and US Naval Research Laboratory. Lawrence, a joint appointee with Meteorology, led a UoA11 ICS on 'New computer systems for exploiting big environmental data for worldwide usability, model and policy development'. This has been used in developing the Earth System Grid Federation and by the European Copernicus Climate Change Service.

Other BOISP-supported work includes:

- the use of weather information to inform decision-making in the solar photovoltaic and wind sector including the National Grid
- the impact of climate change on freshwater resources in Kazakhstan
- enhanced methods to predict the impact of volcanic dust on aviation via interaction with regulators and engine manufacturers
- influencing policy on environmental exposure of humans and biota to hazardous substances
- use of lidar/radar data to improve weather forecasts.

One notable success was that our research (**G.Harrison, Nicoll**), assisted by the University's Knowledge Transfer Centre, led to commercial production of 'geigersondes' in collaboration with a UK electronics manufacturer; these measure atmospheric ion production rate via a Geiger counter integrated with conventional radiosondes. Via a long-term arrangement with Vaisala, a world-leading radiosonde supplier, over 200 such devices with a commercial value exceeding £100k have been supplied.

BOISP, aided by the Impact Development Manager, will continue to provide the basis of our future impact strategy, both in advancing existing impact and identifying and aiding emerging areas. The Impact Development Manager also provides input on funding-streams (e.g., Knowledge Exchange Fellowships, Innovation and Follow-on Schemes) aimed at ensuring knowledge is effectively shared.

2. People

2.1 Personnel

Following strong growth during the REF2014 period, when 18 new academic staff were appointed, we have grown further to fill strategic gaps. Category A FTE grew by 11% from 75.68 to 83.9; headcount grew from 84 to 89. We have 13 ECRs (by FTE and headcount).

In addition to Category A staff, on the Census Date there were 111 (FTE 105) non-independent Grade 6/7 researchers (GES 13, Meteorology 42, NCAS 48, NCEO 6, Walker 2) and 109 PGR students making a total headcount of 309 researchers.

Twenty-two Category A staff from REF2014 are not submitted: 8 retired or left academia (Blackburn, Bengtsson, R.Gurney, S.Gurney, Highwood, Hoskins (who remains an active emeritus), O'Neill, Skeffington); Belcher is now Met Office Chief Scientist, Hogan is now a Senior Scientist at ECMWF (retains an FTE<0.2 position in the Unit); 7 left for research-active posts elsewhere (Chiu, Johnes, Migliorini, O'Connor, Osborne, Pinto, Watt); 3 are no longer deemed research-independent (Bannister, Blower, Mason). Lawrence (joint Meteorology-Computer Science appointment, and NCAS Director of Models and Data) is submitted to UoA11; Mayle is submitted to UoA15.

Reflecting our extensive interactions with the Department of Mathematics & Statistics, 4 staff with joint appointments (**Broecker, Dance, Fowler, Lawless**) are submitted to UoA7; 3 further staff researching in UoA7 areas are submitted to UoA10. **Roy** (Associate Professor in Remote Sensing in Ecosystems Sciences) was submitted to UoA6 in REF2014.

Newly appointed academic staff are **Carrassi** (Professor and Director of Data Assimilation for NCEO), **Cornforth** (Director, Walker Institute), **Morrison** (Professor of Earth Observation with Radar, part-funded by NPL), **Sizmur** (now Associate Professor in Environmental Chemistry) and **Stein** (now Associate Professor in Clouds). These appointments reflect case-by-case strategic decisions. Professorial appointments were made where a leadership role, including contributing to national initiatives, was required; more junior appointments were appropriate to maintain breadth and critical mass in key areas.

Five staff with individual fellowships (NERC, Royal Society, Leverhulme) in REF2014 moved to permanent positions, progressing to either Associate or Full Professorships (**Hawkins, Holloway, Stephens, Turner, Williams**). This emphasises our proactive role in career advancement for ECRs. **Nicoll** continued her NERC fellowship (split with University of Bath), moving to a 0.6FTE academic position in the Unit in October 2020.

There are three new NERC Independent Research Fellows: **Klingaman** (2015-20), **Ryder** (2015-22, including career breaks) and **Sun** (2017-22). Eighteen research staff (Grades 7-9) were appointed as, or progressed to, independent researcher status (**Bulgin, Carrea, Coceal, Dong, Fowler, Grant, Harvey, Kretschmer, Kuhlbrodt, Maidment, Martínez-Alvarado, Mittaz, Robson, Schiemann, Schroeder, Smith, Tarnavsky, Wilcox**).

2.2 Staff support structures

We are strongly supported by the Institutional staff strategy (IES Section 3); Human Resources support staff recruitment and management.

Newly appointed staff follow the University's induction and probation procedures (6 months for post-doctoral researchers and senior appointments, 3 years for new lecturers) to ensure appropriate training. A peer-mentor provides a route for more informal advice. Mentoring for new lecturers continues throughout their probation; for research staff it continues throughout their contract. We actively implement the Researcher Development Concordat (IES Section 3.3).

All research-active staff participate in the University's annual Performance and Development Review (PDR) process, with mandatory training for reviewers. For academic staff and GES research staff, PDRs are normally with their line manager. Meteorology's research staff usually have PDRs with someone other than their PI, following their expressed preference; this provides opportunities for additional, more detached advice. Staff are encouraged to reflect on their research output quality by self-assessment using the University's Research Outputs Support System (see Code of Practice for details). Independently of the PDR process, academic staff (and optionally research staff) provide annual Personal Research Plans to their RDL, to highlight proposed future activity and indicate where resource availability may inhibit ambitions.

To accompany the PDR, Meteorology research staff complete a Research Staff Development Prompter form. This was developed with research staff to consider additional activities to broaden experience, such as mentoring, teaching (including project co-supervision), conference organisation, learned society involvement, and media/outreach. The PI provides input to ensure activities are consistent with a researcher's other commitments. For GES research staff, broadening academic experience is discussed and documented within mentoring pairs.

Both Departments operate workload models to monitor academic staff load in funded research, teaching, administration, outreach, mentoring and academic citizenship. Staff see their colleagues' load profiles (in anonymised form) to compare their commitments. Newly appointed academics build up administrative and teaching loads gradually over a two- to three-year period. Both Departments operate sabbatical schemes; the norm is effectively one term's sabbatical for nine teaching terms (irrespective of periods of parental or other leave). Relief from teaching and administration is given based on time costed on research awards.

Peer mentoring is available to all staff (e.g., at career transition points such as promotion planning, preparing for a role change or career-break returnees). There are regular calls for mentors together with advice on appropriate training. Meteorology's mentoring pool includes visiting/emeritus staff who have often taken diverse career paths.

A School-wide Research Staff Committee (chaired and organised by research staff) reports to the SMPCS Executive Board each term. In 2019, Meteorology ran a career-development workshop for Grade 6 researchers, covering promotions, research funding and research independence, and intends to make these biennial events. Meteorology's termly staff meetings are open to all staff, with papers available on the intranet.

Academic staff hold individual Staff Development Accounts (SDAs) that enable discretionary spending on conference travel, books, and short-term staff funding. A set fraction of overhead income is allocated to SDAs annually; part is allocated equally to all academic staff (to reflect that overhead-earning opportunities vary with career stage and other commitments); part is allocated in proportion to overheads earned by individuals. Consultancy income can also be directed to SDAs. Further internal schemes to support research are available (IES Section 4.3).

2.3 Support for research proposals

Backed by strong institutional support from Research Development Managers, and specialist support for EU and GCRF funding streams (IES Section 4.2), our staff are alerted to funding opportunities and provided with pro-active support in developing proposals, including finance and collaborative agreements.

Collective action is often organised in response to funding calls. Inclusive meetings are convened to discuss calls, rather than dissipating energy in internal competition. This bottom-up activity is an example of the open, collaborative and interdisciplinary research environment in which we strive to operate.

During the REF2021 period, a formal mechanism was implemented to assess potential grant applications, partly driven by NERC's demand management process. Expressions of Interest (Eols) are submitted to a panel consisting of the Research Dean and RDLs; their advice on strengthening proposals, and ultimately a decision on when/whether to submit, is informed by internal peer review and panel discussions with PIs. We escaped the NERC demand management 'cap' early in the period and have remained free from it since. The University runs a similar process for BBSRC responsive mode, for staff working in the sustainable food production priority area. ERC proposals are supported in a similar way, with mock interviews where appropriate.

For individual fellowships, the University runs an Eol process. This is open to our current research staff and promising researchers from outside. Those successful at the Eol stage are assigned a mentor, actively supported by Research and Enterprise Services, and invited to a proposal development workshop.

2.4 Training and supervision of PGR students

2.4.1 Overview

PGR students are immersed in our research environment and are a vital strand in our research activity. On the census date we had 109 students registered (63 in Meteorology; 46 in GES). Of students registered in 2019/20, 46% were female, 54% male, 62% UK and 38% from outside the UK (33 different nationalities). Averaged over the REF2021 period, 55% were UKRI funded, the others from diverse sources. The average number of completions was 22.8/year, compared to 20.8/year in REF2014 (roughly constant per FTE); completions exceeded 23 from 2015/16 onwards, and reached 26.5 in 2019/20; 90% required no or minor thesis amendments. 94% of full-time students starting between 2010/11 and 2014/15 (and hence mostly completing in the REF2021 period) submitted within 48 months.

Extensive use is made of CASE (and National Productivity Investment Fund, NPIF) arrangements, enabling students to build links beyond academia; 29 students completing in the REF2021 period had CASE or NPIF studentships, as do 26 current students. We won 13 Industrial CASE studentships from NERC and 5 from BBSRC. The Met Office is a major CASE partner (20 completed, 12 current). Others come from a wide range of partners, including water companies (Affinity Water, Anglian Water, South East Water, Thames Water), energy/utility companies (BP, BT, EDF), the finance/insurance sector (AON Benfield, AXIS Capital, Risk management Solutions, XL Caitlin) and environmental, agricultural, forestry and fisheries sectors (EA, Defra, CEFAS, Forest Research, Syngenta).

Arrangements for training and supervision vary depending on which (if any) programme a student is attached to. Students identify both as members of these programmes and members of their host Department. Part-time students are welcome, with pro-rata arrangements for training and monitoring. PhD-by-distance students (e.g., Met Office employees, typically 2 per year) also follow these arrangements. SCENARIO has a strong multi-disciplinary element and in addition to in-depth subject-specific training, it provides broader training opportunities (e.g., computing skills, policy awareness) often via collaboration with DTPs elsewhere. Examples include an Annual DTP Conference (jointly with Imperial and London NERC DTPs) and Innovating for Sustainable Development (with Imperial), a group activity to explore and find solutions to environmental challenges. Our admissions procedure assesses relevant work experience, as well as academic background, to attract students from diverse backgrounds.

The PGR programme benefits from international capacity-building initiatives. Two students from Dhaka University, supported by the World Bank, and three students from the University of the Philippines, Diliman, supported by national initiatives, are currently enrolled, as part of their preparation to take up Faculty positions in their home countries. Other students have been supported by prestigious scholarships in DAC ODA list countries (e.g., Bolashak Scholarship, Kazakhstan) or bring external experience while on extended sabbaticals to complete a PhD (e.g., via Japan's Long-term Fellowship Program). Walker is experimenting with a new approach to address issues facing students from developing countries. It has recruited students from east Africa by supporting distance-learning and part-time approaches which mitigate visa and some funding difficulties.

Overall organisation of PGR programmes falls under the University's Graduate School (IES Section 3.6) which organises networking events and annual Doctoral Conferences, enabling our students to engage with the University's wider environment. Within each Department, student arrangements fall under a Director of Postgraduate Studies. All students have a lead supervisor and at least one co-supervisor, in addition to any external co-supervisors.

2.4.2 Induction and training

All students attend an induction programme, which includes guidance on the transition from taught-course environments. General information and guidelines are set out in each School's Research Student Handbook. Students are allocated a 'buddy', a student from an earlier cohort, to provide informal advice and guidance. Students participate in the generic Reading Researcher Development Programme (IES Section 3.6), taking 11 courses (or equivalent training elsewhere).

Mandatory subject-specific training is tailored to each student's background. Some have completed a directly relevant undergraduate or taught masters; others have more general degrees including physics, mathematics or geography. Each student completes a Learning Agreement with their supervisor which is monitored by Departmental PGR Boards of Studies. If larger budgets are needed (e.g., for fieldwork), students develop outline budgets with their supervisor. In their first year, students normally take up to 6 modules from our postgraduate Master's programmes, including 3 appropriate advanced modules. Performance in assessed modules is a major factor in considering student progression. Students are encouraged to attend focused short courses and summer schools, including extensive NCAS training opportunities and specific training programmes organised by DTPs. Some have training opportunities

associated with participation in larger research grant activities (e.g., NERC LANDWISE, FATHUM) and other University initiatives such as the Loddon Observatory.

As much as possible, training opportunities are open to all students, including international students, irrespective of their funding. The Climate Action Studio, where students interview COP (Conference of the Parties) delegates in person and virtually (led by Walker and SCENARIO) is a good example that has been recognised as a partnership activity with the United Nations Framework Convention on Climate Change. All students are strongly encouraged to attend our regular seminar series.

2.4.3 Monitoring, progression and representation

Arrangements are broadly aligned in Meteorology and GES. Students usually meet supervisors weekly or fortnightly. Each student has a Monitoring Committee (MC) which meets biannually. Meteorology's MCs have 2 staff members; ordinarily one has knowledge of the student's research area. In GES, MCs consist of supervisors and an independent Panel Chair who is responsible for reporting progress to the Graduate School. Students prepare a progress and planning report and defend these at MC meetings; supervisors prepare short assessments of student progress. In Meteorology, supervisors attend part of each MC meeting but leave when supervisory arrangements are discussed and when the MC completes its report. The report assesses research knowledge, technical progress, and plans for future work, and considers overall progress to submission; it makes recommendations to the Director of Postgraduate Studies on progression and can place actions on the student and supervisors which are reviewed at subsequent meetings.

Students are members of our research groups, which provide frequent opportunities to present their work; they also give poster and oral presentations at Departmental annual postgraduate research conferences and new-intake induction events. Meteorology students run their own weekly Research Student Club; GES students lead a Journal Club.

In both Departments, students feed back on their experience via a Postgraduate Research committee which meets 3 times per year. It includes elected representatives from each cohort. Meteorology's committee is convened by a student chairperson and includes an international representative; the Director of Postgraduate Research Studies and a Head of Department attend. In GES it is chaired by the School Director of Postgraduate Research Studies. PGR representatives sit on the equality and diversity committees in both Schools.

2.4.4 Other training aspects

Students are encouraged to attend national (normally one per year) and at least one major international conference. In Meteorology they receive a meeting budget of £2000, plus funds for summer school attendance, if this is not available from their funding source; in GES, funds are also available for these purposes. There are opportunities for paid demonstrating on taught courses (up to 60 hours/year including problems classes and instrumental and computing labs); the Graduate School's Preparing to Teach programme is mandatory for such students. An Annual Distinguished Visitor Programme is organised by Meteorology PhD students, with extensive scientific interaction (normally over one week) and discussion of career paths. During the REF2021 period, visitors included Jürg Beer (Eawag Institute, Switzerland), Craig Bishop (NRL, USA), Cecilia Bitz (University of Washington, USA), Olivia Romppainen-Martius (University of Bern, Switzerland), Richard Rotunno (NCAR, USA) and Tapio Schneider (JPL/Caltech, USA).

2.4.5 Career outcomes

Our students are highly successful in obtaining employment for which their postgraduate training is relevant. Available first-destination statistics covering cohorts graduating in 2013/14 to 2017/18 show all respondents in employment: 48% were postdocs at UK HEIs (including Reading), 8% were postdocs elsewhere, 17% worked in non-HEI research establishments and

15% worked for commercial companies including environmental consultancies, government, the insurance/finance sector, and the energy sector.

2.5 Equality and diversity (E&D)

Institutional strengthening in this area since REF2014 is described in the IES (Section 3.1). Both our Schools have Athena SWAN Silver Awards. SMPCS renewed its award in 2017; SAGES attained Silver in 2015, renewed in 2019. To advance E&D commitments, both Schools initiated standing committees. In SAGES, an Equality, Diversity and Inclusion Committee includes staff and student representatives from all areas of the School and is chaired by a School Diversity and Inclusion Champion. Responsibility for Wellbeing has moved to the School Health and Safety Committee, which is better placed to act on workplace stress. In SMPCS a Director of Wellbeing, Inclusion, Diversity and Equality (WIDE) is supported by a committee drawn from across the School.

Examples of good practice, applying to all academic and research staff, include:

- promotion of flexible working, including location and working pattern; since 2019, 9 female and 3 male Meteorology staff have taken advantage of this scheme for reasons of health, childcare, work-life balance or semi-retirement, and three female staff in the relevant part of SAGES have flexible working arrangements for childcare
- recognition of the value of part-time arrangements; between 2016 and 2019, 13 male and 6 female part-time researchers were promoted, with 18 male and 6 female part-time academics being promoted between 2017 and 2019
- mentoring schemes
- mandatory unconscious bias training for staff involved in recruitment
- support for promotions. SAGES ran a mandatory disability awareness training session (the first time this has run in the University) and self-confidence/combating imposter syndrome/diversity workshops as part of the Water@Reading cluster.

SMPCS organised a survey to identify principal sources of stress (e.g., workload, communications, short-term contracts) and to identify remedial actions (including training for staff and managers, enhanced communication and a review of contract processes). SAGES has a similar approach to stress management, including a survey and a Stress Action Plan; it ran a Stress Management Workshop for all staff in 2019/20.

We take a pro-active approach to staff and PGR well-being. Our initiatives include Department-wide celebrations of significant events such as PhD passes and prize awards, and social events such as a summer barbeque and Christmas pantomime; these continued, in virtual form, during 2020.

Overall, the submitted staff male/female headcount split is 72%/28% compared to 75%/25% in REF2014. This compares with the HESA 2018/19 national average in earth, marine and environmental sciences of 64%/36%. Meteorology's staff are largely drawn from mathematical and physical sciences; our gender balance compares more favourably with HESA figures for Physics (80%/20%) and Mathematics (78%/22%). We are not complacent about these figures and, as part of Athena SWAN planning we are committed to advancing gender equality, including the balance in senior roles. An increase in female applicants for senior posts is encouraged through unconscious bias training and gender-balanced search committees. Two of our four current RDLs are female.

Feedback from the 2019 Athena SWAN awards commended SMPCS's recruitment process, communications, and career development and SAGES' positive impact in terms of promotion, culture and flexible working, with gender balance achieved in the professoriate and on the School Management Board. SAGES' strong promotion support mechanisms, including workshops, mentoring and one-to-one meetings, were noted. For SMPCS, identified areas for improvement include gender imbalance within the workload model and a requirement for more beacon activities (i.e., activities promoting good practice more widely). Workload models within the School were reviewed and beacon activities are continually being developed such as our

mentoring scheme and stress survey. SMPCS is currently preparing a Gold submission. For SAGES, areas for improvement include enhancing the Action Plan to include success measures to enable more detailed future evaluation, and further thought to career progression for professional and support staff.

Both Schools aspire to a supportive and inclusive working environment for all staff and students. We recognise equality and inclusivity issues for people with protected as well as unprotected characteristics (e.g., socio-economic status, health). We recognise that diverse institutions are more successful and innovative, and that people are more productive when they feel free to be themselves.

We strive to extend working practices to cover PGR students. For example, feedback from an informal survey among PhD students was included in our stress management action plan. One resulting action was a mental-health workshop at the last Annual Joint DTP Conference.

Both Schools proactively support parental leave. Expectant mothers are sent information on University guidance and policies. Keep-in-Touch Days are scheduled during maternity and shared parental leave. SMPCS has a quiet room where staff can rest during pregnancy and express milk on their return. SMPCS has a parents' network which meets monthly and cascades information about the recently established University Parents' Network. A flexible approach to work following birth is available for both parents, in agreement with line managers. As University policy, a sum of money is kept aside to facilitate a flexible return to work after parental leave (25% of salary during the period of leave).

To enable transparency and inclusivity, internal vacancies for senior leadership and academic administrative positions are openly advertised. Coaching is available for those with significant line management responsibilities from the University's Henley Business School, as is accreditation from the Institute of Leadership and Management through the University's Inclusive Leadership programme. Both Departments adhere to the University's LGBT+ ally programme and Working Together principles.

E&D played a significant role in constructing this submission, following the University's Code of Practice. Staff were kept informed of deadlines and the process of assessing independent researcher status. All submitted staff were asked to provide assessments of their most suitable outputs, and periodically to update them. Assessments were subject to an internal peer review process, with each output graded by two staff. These grades, along with self-assessment and appropriate use of bibliographic metrics, informed final selection. The internal peer review was more inclusive than previous assessment exercises; all submitted staff took part (not just senior staff). We achieved a peak of 2 in the distribution of outputs attributed to submitted staff and examined cases for significant deviations, to ensure there were strong academic reasons.

During the COVID-19 lockdowns, both Schools quickly moved activities online (e.g., PhD supervision, seminars, staff meetings and line management) to enable home-working. Subsequent communications from Heads of School and support staff ensured important information was shared quickly, including advice on well-being and creating an effective and safe home-working environment. This included allowing essential equipment and furniture to be taken home.

3. Income, infrastructure and facilities

3.1 Income

Our average research income increased by 32% to £14.6m/year (REF2014 £11.1m/year), compared to our 11% increase in FTE; it reached £17.2m in FY2019/20. We achieved a marked diversification of funding sources; direct UKRI funding remained at an average of about £8.4m/year but dependence on it decreased to 60% (REF2014 74%). While UKRI income is dominated by NERC, more than £0.4m/year came from BBSRC, EPSRC and STFC.

External funding confirmed during FY2019/20 with end-dates in FY2020/21 and beyond, amounts to £14.6m (excluding any funding-in-kind) which indicates our continued competitiveness. Additionally, one new Royal Society University Research Fellow and one new NERC Independent Research Fellow were confirmed during FY2019/20, with start dates in FY2020/21.

We achieved a notable seven-fold growth in income in the UK Industry, Commerce and Public Corporations category to £1.5m/year (REF2014 £0.2m/year). About 65% of this was from the Met Office, much due to their role as delivery partner for the Newton Fund Weather and Climate Science for Service Partnership Programme. Other sponsors in this category include BP Exploration, Mars Chocolate, NPL, National Grid, Risk Shield (a Zambian agriculture insurance company) and BT.

Funding in the EU Government and EU Other categories increased from 6% to 20% (and by factor of four to £3m/year), partly due to our strong involvement in the EU Copernicus EO Programme. [Note that European Space Agency was incorrectly reported in HESA Finance Return in 2013/14 - 2017/18 as UK other. As per REF team guidance, the reported income on REF4b aligns with HESA reporting.] Four staff won five ERC Advanced Grants (**Gregory** x2, **S.Harrison**, **Shepherd**, **van Leeuwen**) and one ERC Synergy Grant (PI **Grimmond**, with a total of ≈£2.25m to Reading). A total of £3.7m came from the European Space Agency including lead roles in ESA's Climate Change Initiatives in Sea Surface Temperature (PI **Merchant**) and Water Vapour (Science Lead **Heggin**).

This large income is a key factor in enabling our production of high-quality research outputs; it provides funding to maintain our large post-doctoral researcher community, to maintain and enhance the University's research infrastructure, to allow access to national facilities, and to enable collaboration with other leading research groups in the UK and worldwide.

UKRI income comes from national capability funding to support NCAS and NCEO long-term science programmes (ACSIS and UKESM), research programmes and standard grants. Examples of our leadership in UKRI research programmes, with funding to Reading noted, include:

- **IMPETUS** (Improving Predictions of Drought for User Decision-Making; £975k over 4 years, led by **Shaffrey**, and including collaboration between our Climate and Environmental Science Divisions) as part of NERC's UK Droughts and Water Scarcity Programme; this has seven collaborating institutes and project partners including weather forecasting organisations (Met Office, ECMWF) and water authorities.
- **FATHUM** (Forecasts for Anticipatory Humanitarian Action; £1.9m over 4.5 years) led by **Stephens** as part of the NERC/DFID/ESRC Science for Humanitarian Emergencies and Resilience (**SHEAR**) research programme. It includes collaboration with the Red Cross Red Crescent movement, the World Food Programme and universities in three African countries.
- **BRAVE** (Building understanding of climate variability into planning of groundwater supplies from low storage aquifers in Africa; £1.2m over 4 years, led by **Cornforth**) as part of the NERC/ESRC Unlocking the Potential of Groundwater for the Poor Programme; it focuses on the Upper Volta catchment and includes collaboration with institutes in Burkina Faso and Ghana.
- Three projects from NERC's five-year Flooding from Intense Rainfall Programme including **FRANC** (Forecasting Rainfall exploiting new data Assimilation techniques and Novel observations of Convection) (led by **Dance**), **SINATRA** (Susceptibility of catchments to INTense RAInfall and flooding) (led by **Cloke**) and **TENDERLY** (Towards END-to End flood forecasting and a tool for Real-time catchment susceptibility) (led by **Cloke** and **Dance**).
- Three projects in the NERC/Met Office Understanding and Representing Atmospheric Convection across Scales programme. Revolutionizing Convective Parameterization (led by **Plant**); Circle-A: Parametrizing Convection in the Hard Grey Zone: Modelling the Interaction of Turbulent Cloud processes with Explicit Cloud Dynamics (led by **P.Clark**);

Understanding and Representing Atmospheric Convection across Scales (led by **Plant**); this totals ≈£2.5m over 4 years including collaborations across all Meteorology Divisions.

- **LANDWISE** (£1.46m over 4 years) funded by NERC's Natural Flood Management Programme, led by **J.Clark**. It includes four external research institutes and over 40 project partners from environmental policy, regulation, consultancy, conservation, farming and farm advisory sectors, water industry, local authority and community groups.
- **Reading Solar System Science** (£1.6m over 7 years) via STFC Consolidated Grants (**Owens, G.Harrison, Lockwood, Scott**) to further our space plasma physics and planetary research, including space weather in near-Earth space, with UK and international partners. This group is also part of a NERC-funded consortium Space Weather Impacts on Ground-based Systems led by the British Geological Survey.

Examples of leadership roles in EC H2020 projects include:

- **FIDUCEO** (Fidelity and Uncertainty in Climate data records from Earth Observations) a 4-year €5.5m project coordinated by **Merchant** which applies metrological principles to the creation of satellite-based fundamental climate data records. The project included 11 other partners across Europe, including NPL and EUMETSAT.
- **PRIMAVERA** (PProcess-based climate sIMulation: AdVances in high resolution modelling and European climate Risk Assessment) a 4-year €5.5m with **Vidale** as Scientific Coordinator, and co-led with the Met Office, involves 18 other partners across Europe including ECMWF.

An example of success in diversification of funding is Electrical Aspects of Rain Generation funded by the United Arab Emirates' Rain Enhancement Program (US\$1.5M over 4 years, led by **G.Harrison**) which advances understanding of electrical properties of clouds and aerosols through theoretical and experimental work.

A major development in the assessment period has been heavy involvement in Newton Fund (including Weather and Climate Science and Service Partnerships in Brazil, China, India, South East Asia) and GCRF projects. This involves about one-third of our submitted staff as PI or co-Is across all Divisions. The diverse funding includes collaboration on cocoa cultivation (including soil remediation, environmentally friendly exploitation of husks, and climate impacts); understanding and sustaining Brazilian biome resources; urban air quality in China; convective and urban-scale modelling in China; monsoon variability and teleconnections in south-east Asia; impact of aerosols and dust on weather and climate in south-east Asia; and supporting exploitation of weather forecast data, and assessing sub-seasonal forecasts of the hydrological cycle in Brazil. We have supported capacity building in countries on the DAC ODA list; one example is initiating and growing a water quality and isotope monitoring network with local researchers in the Tien Shan mountains of Central Asia for work on climate change and glacier-fed catchments, including training activities in the region and in GES.

An example of a major GCRF project is African-SWIFT (led by NCAS-Leeds, £1.33m to Reading over 4 years). This focuses on improving weather forecasts from short lead times to seasonal, and involves partners in Ghana, Nigeria, Kenya, and Senegal and two Regional Climate Centres. We lead the Evaluation (**Stein**) and the Sub-seasonal (**Woolnough**) work packages and ran two forecasting test beds in Kenya and a summer school in Ghana.

Our staff are heavily involved in novel satellite missions. **Illingworth** is the Science Lead of the joint ESA/Japanese Earth's Clouds, Aerosols and Radiation Explorer (EarthCARE), due for launch in 2022. **Morrison** and **Wadge** are Science Team Members for Hydroterra, a geostationary synthetic aperture radar, a candidate mission for ESA's Earth Explorer 10 (launch 2027-28); **Black** and **Quaife** are involved in associated feasibility studies.

3.2 Infrastructure and facilities (see also IES Section 4.4)

Staff and PGRs are mostly located in five buildings on the University's Whiteknights Campus. During the assessment period, extensive refurbishment helped co-locate NCAS and Earth Observation staff.

The University's Chemical Analysis Facility provides access to instruments for mass spectrometry, optical spectroscopy, thermal analysis, NMR spectroscopy, SEM and TEM. Our staff also use the crops research facilities to conduct field experiments and large-scale plant growth experiments in controlled and semi-controlled environments.

SAGES houses purpose-built laboratories supported by six technicians for experimentation and analysis in environmental physics, chemistry and biology with equipment maintenance and replacement supported by SAGES and University equipment budgets. Laboratories include: automated wet chemistry analysis; elemental analysis; gas chromatography for greenhouse gases and lipid/non-polar organic pollutant analysis; high performance liquid and ion chromatography; inductively coupled plasma optical spectroscopy; water isotope analysis; laser granulometry; polymerase chain reaction and gel documentation; soil moisture release analysis; total organic carbon analysis; and UV/VIS Spectrophotometry. SAGES also use a four-frequency Ground Penetrating Radar and maintain two unmanned aerial vehicles. One is used for low altitude photogrammetry. The other provides multispectral and thermal imaging, in addition to photogrammetry. These also support work in Meteorology to develop a drone-based Synthetic Aperture Radar platform for forestry research.

Together with the University's School of Agriculture, Policy & Development, we lead the Loddon Observatory. This brings together several projects working in the Loddon catchment, close to the University, that address globally relevant challenges in food and water, e.g., LANDWISE (see above) and PASQUAL (Monitoring and prediction of pasture quality and productivity from satellites). The Loddon Observatory consolidates environmental experimentation, monitoring and modelling, in relation to flooding and biogeochemical cycling in an exemplar lowland river catchment ecosystem, and also addresses social aspects of catchment management. Networking events bring together researchers (including PGR students) across the University with local partners. Long-term monitoring platforms have also been set up to monitor natural flood management in the Upper Whitewater (Loddon Catchment) and the Bourne (Pang Catchment). Long-term water quality monitoring has been carried out in the Loddon and the Exe catchment in association with the water industry.

Meteorology's five technicians support laboratory and field measurements, including PGR projects. The Department invested in a Reading Radar Facility during 2016-17 following **Morrison's** appointment to characterise geo- and biophysical environmental targets, notably soil moisture; this enabled the development of a portable outdoor rig for soil moisture measurement for LANDWISE. Lab-based projects include NERC-funded research on the aerodynamics of complex ice crystals, enhanced radiosonde measurements, and miniaturised instruments for measuring atmospheric electrostatics.

The Urban Meteorology group has deployed extensive instrumentation in London; our London Urban Meteorological Observatory has sites in Islington, Kensington and Chelsea, Southwark, Westminster and instrumentation on the BT Tower. This includes two types of lidar, infra-red thermal cameras, and radiation and eddy covariance systems.

The University's Atmospheric Observatory, located on campus, has been further enhanced to include more extensive automation and the addition of instruments including a cloud lidar, visibility probes and equipment to monitor atmospheric electricity. An almost complete daily record from 1908 is readily available on the Observatory website; we ensured that these observations continued uninterrupted during COVID-19 lockdowns. We continue to host a Defra facility for daily ozone and spectrally resolved ultra-violet measurements, which Defra make available in near real-time.

In the REF2021 period, the University's support of academic computing was centralised. A new Academic Computing Cluster was purchased and expanded and is available to all research staff and PGRs. Dedicated nodes can be purchased for individual projects. The compute nodes currently provide about 1000 CPU cores for serial and parallel batch jobs. Several login nodes,

equipped with multi-core processors, large memory and fast network connection to the research data storage volumes are available for interactive use, including data analysis, visualisation and code development. Multiple methods to enable remote access are available (including VPN, web browser and Secure Shell); capacity was enhanced during the COVID-19 closure. Research Data Storage has been expanded to provide three tiers of resilient storage, including a new Research Data Archive.

3.3 Exploitation of external facilities

We make considerable use of national research facilities, which contribute extensively to our submitted outputs, including:

- NERC's Facility for Airborne Atmospheric Measurements (FAAM) (a BAE-146-301 large research aircraft) to support field campaigns for research projects on weather systems, clouds and aerosols
- the NCAS Chilbolton Facility for Atmospheric and Radar Research for its cloud and radar research (often in tandem with FAAM)
- the NCAS Atmospheric Measurement Facility Environmental Flow Wind Tunnel, based at the University of Surrey, for urban meteorology research
- NERC's Field Spectroscopy Facility and Airborne Research and Survey Facility for in-situ environmental research field studies and airborne surveys, to support NERC and Innovate-UK funded projects and PGR work
- NERC's Biomolecular Analysis Facility to support research in GES
- various national computing facilities including ARCHER, the UK National Supercomputing Service; the Met Office and NERC joint supercomputer system (MONSooN); and the JASMIN 'super-data-cluster' funded by NERC and the UK Space Agency, to support modelling and data analysis.

As an example of the diversity of our research, we have used FAAM (at PI or co-I level) in a range of applications, sometimes funded via collaborators (including the Met Office) or at the programmatic level. SAVEX (Sunphotometer Airborne Validation Experiment) and AER-D (Aerosol-Dust) campaigns (**Ryder**) investigated properties of Saharan dust. NAWDEX (North Atlantic Waveguide and Downstream Impact Experiment) (**Methven**) explored the impact of diabatic processes on disturbances of the jet stream and their influence on downstream high-impact weather events. PICASSO (Parameterizing Ice Clouds using Airborne observations and triple-frequency doppler radar) (**Westbrook**) investigated how the scattering behaviour of snowflakes changes with radar wavelength. INCOMPASS (Interaction of Convective Organisation with Monsoon Precipitation: Atmosphere, Surface and Sea) (**Turner**), believed to be the first deployment of a foreign atmospheric research aircraft in India, aimed to improve monsoon rainfall prediction. CLARIFY-2016 (Cloud-Aerosol-Radiation Interactions and Forcing) (**Bellouin**), targeted the interaction of aerosols from wildfires with the stratocumulus off the coast of southern Africa.

We also exploit the UK Environmental Change Network, most notably Forest Research's Alice Holt site. This has supported research projects looking at forest carbon dynamics (e.g., NERC iCASE). Further collaboration with Forest Research across their research forests and BioSoils monitoring programme has supported PGR projects.

Extensive use has been made of ECMWF models, its high-performance computer, and its forecast archives.

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

Earlier sections highlighted our many collaborations with private sector and research-led organisations in the UK and beyond. The following sections focus on specific major collaborations.

4.1 Contribution to major NERC activities

Sutton, as NCAS Director of Science (Climate), is a member of the NCAS Management Board. Nationally, NCAS has three Science Themes; two are led by Unit staff (Climate and High-Impact Weather Theme, **Shaffrey**, and Long-term Global Change, **Kuhlbrodt**). We host most of the NCAS CMS group (8 staff) (including its Director, Lister).

We contribute strongly to NCEO, providing the Director of Data Assimilation (**Carrassi**) who is one of their five-member Executive Team. It provides 'Capability Leads' of three of NCEO's twelve sub-themes: Ocean-Atmosphere Data Assimilation (**Haines**), Integrated Climate Data-Model Systems (**Merchant**) and Data Assimilation Framework and Theory (**Carrassi**). Some University NCEO staff are based in Mathematics & Statistics and submitted to UoA10; they collaborate strongly with our staff.

We are heavily involved in two of NERC's five long-term science, multi-centre projects: Reading provides four members of the Core Development Team (including **Kuhlbrodt** and **Smith**) of the joint NERC/Met Office UK Earth System Modelling Project (UKESM). **Sutton** is Project Director and **Robson** is Scientific Programme Lead of the North Atlantic Climate System: Integrated Study (ACSIS).

We have strong involvement in the Centre for Polar Observation and Modelling (CPOM), a NERC Centre of Excellence. **Feltham** is a CPOM PI, and the sea-ice lead. The NERC-led £8m Soil Security Programme was coordinated by **C.Collins** (2015-20).

4.2 Met Office collaboration

We are one of six universities in the Met Office Academic Partnership (MOAP) which, in the Met Office's words, is 'a cluster of research excellence that brings together the Met Office and institutions who are among the leading UK Universities'. The Unit has a Met Office Joint Chair (**Grimmond**) and an Honorary Fellow (**P.Clark**). MOAP includes priority access to Met Office CASE studentships; we typically receive 4 new starts per year. Of ≈2900 papers published by Met Office authors in the REF2021 period, the University was the top collaborating institute, co-authoring 19% (SciVal).

MetOffice@Reading consists of about 20 staff. Four Met Office staff were Category C staff in REF2014; six current staff are at or above Science Manager/Expert Scientist level and would have been listed as Category C in REF2021 had that option been available. MetOffice@Reading includes two Met Office research groups almost entirely based in Reading (Data Assimilation and Convective-Scale Modelling, including urban-scale modelling), as well as activity in observational networks, ensembles and predictability, climate change and the next generation dynamical core for Met Office models. In all areas there is substantial synergy with our core activity. As of July 2020, the Met Office, including MetOffice@Reading, were project partners/collaborators in over 50 funded projects (including 20 funded by UKRI, 17 from European sources, 17 Newton Fund).

Our MOAP interaction is organised via a committee with joint University and Met Office chairs and includes Met Office staff (based both at Reading and Met Office HQ in Exeter), our 4 RDLs (or their representatives) and the Research Dean for Environment. It meets twice yearly to discuss collaboration foci. Cross-MOAP governance is via a Science Programme Board which includes the Joint Chair and Research Dean.

Current collaboration foci include:

- improved models and data assimilation for space-weather forecasting
- cloud electrification parameterisations for Met Office models
- high-resolution modelling of urban areas, including use of observations for model evaluation and parameterisation development
- data assimilation including assimilation of the coupled atmosphere-ocean-land surface system and use of novel surface observations for convective-scale assimilation
- exploitation of radar observations for model evaluation and nowcasting

- regional scale climate risks
- Earth's energy imbalance
- computational science for next-generation models and informatics
- high-resolution model evaluation through novel observations.

Two themes (in data assimilation and computational science) also involve staff from Mathematics & Statistics and Computer Science, reflecting our cross-disciplinary links.

In addition to MOAP and MetOffice@Reading, we are heavily involved in the Met Office and NERC's Joint Weather and Climate Research Programme (JWCRP). This includes (i) UKESM development; (ii) the Joint Sea Ice Modelling Programme (**Feltham** is co-chair); and (iii) the High-Resolution Climate Modelling Group (**Vidale** is co-lead). **Quaife** is on the management board of JWCRP's Joint Land Modelling Programme.

The Met Office is a strategic partner in SCENARIO and an industrial partner in the Mathematics of Planet Earth CDT. A notable activity is an annual one-week summer course co-organised with MPE CDT.

4.3 ECMWF collaboration

We continue to work closely with ECMWF which is located in Reading. ECMWF, a 34-nation partnership, develops and uses an integrated global Earth system model to produce global forecasts on time ranges up to one year ahead. Of ≈ 1250 papers published by ECMWF authors in the REF2021 period, the University was the third-highest collaborating institute, co-authoring 15%; and the highest-placed UK university (SciVal).

Since 2014 about 50 projects included collaboration with ECMWF. These include:

- the Copernicus Emergency Management Service-Floods operational services EFAS (European Flood Awareness System) and GloFAS (Global Flood Awareness System)
- IMPETUS (Section 3.1)
- SHEAR (Section 3.1)
- IMPREX (IMproving PRedictions and management of hydrological Extremes)
- TOPROF (COST action: Towards operational ground-based profiling with ceilometers, Doppler lidars and microwave radiometers for improving weather forecasts)
- ANYWHERE (EnhANCing emergencY management and response to extreme WeatHER and climate Events).

A further focus has been the World Weather Research Programme Sub-seasonal to seasonal prediction project, co-led from ECMWF; our staff (**Woolnough, Klingaman, Charlton-Perez**) are members of the steering committee or lead activities. **Shepherd** led a task force to improve the representation of the stratosphere in ECMWF models.

We are involved in nine projects as part of the EU's Copernicus Climate Change Service (with IEA involved in six), and lead a Copernicus Atmospheric Monitoring Services project, both of which are implemented by ECMWF. ECMWF is a strategic partner in SCENARIO and an industrial partner in MPE CDT.

A relocation of ECMWF's Headquarters and core staff to the University's campus is in planning between the UK Government and ECMWF Council, with a final decision due in 2021 (IES Section 2.1.1). The project demonstrates the University's ambition to enhance further its reputation as a world-leading centre for weather and climate science. The resulting co-located cluster of weather and climate researchers and operational forecasting would be the world's largest (by most measures). It would be a strong attractor for research talent and offer potential to attract companies in private weather and climate services that contribute to medium and long-term planning in sectors including water, transport, agriculture and food, national infrastructure, and energy.

4.4 NPL collaboration

In 2017 the University signed a Memorandum of Understanding with NPL leading, among other activities, to a jointly funded Chair (**Morrison**) and a five-year Grade 7 research fellowship (**Mittaz**) plus a visiting chair position (Fox, NPL). **Morrison**'s work focuses on quantifying uncertainties in retrieval of forest carbon stocks from radar remote sensing. The TRUTHS satellite mission (led by Fox) was accepted into ESA's Earthwatch programme in 2019, to make SI-traceable measurements of the Earth's radiation budget. It brings together two strategic strands in our relationship: quantifying climate and developing the fundamentals of EO metrology. This interaction represents net growth of joint activity and builds on extensive research grants and PGR interaction on the interface between metrology and environmental sciences. NPL is a strategic partner in SCENARIO and an industrial partner in MPE CDT.

4.5 International assessments

Our heavy involvement in IPCC Assessment Reports continued. In its ongoing Sixth Assessment Report (AR6), due for publication in 2021/22, six staff (**Allan, Arnell, Bellouin, W.Collins, Hawkins, Turner**) are Working Group I lead authors (The Physical Science Basis); the University is believed to have the largest number of lead authors of any single-site institution. Other staff provide input to AR6 as contributing authors and reviewers. **Arnell** was Lead Author of IPCC 5th Assessment Report Working Group II (Impacts, Adaptation and Vulnerability) published in 2014.

The UN's Montreal Protocol on Substances that Deplete the Ozone Layer requires Scientific Assessments of Ozone Depletion 'to periodically update governments on the latest scientific findings related to the ozone layer'. Two assessments were published in the REF2021 period. In 2014, **Shepherd** was on the Scientific Steering Committee, **Hegglin** a convening lead author and **Charlton-Perez** a co-author. In 2018, **Hegglin** was a convening lead author and **Ferreira** a contributing author. Other staff were reviewers for both assessments. **Hegglin** was co-author of the IGAC Tropospheric Ozone Assessment Report and a co-lead author of the 2020 WMO/UNEP Interim Assessment Report on Increased Emissions of CFC-11.

4.6 Outreach, public engagement, citizen science

Meteorology has a senior Academic Lead for Public Engagement and a dedicated Executive Support Officer for Outreach and External Affairs. We aim to (i) promote and enhance our reputation for scientific excellence; (ii) promote, more generally, meteorology, atmospheric science and environmental physics to policymakers, industry and the general public; (iii) in our role as 'good citizens', act to reduce our carbon footprint and communicate actions taken and if they have been successful.

During a typical 6-month period in 2019 there were:

- 17 interactions with primary school and other Key Stage 1 and 2 groups (estimated audience 640), two visits to secondary schools (estimated audience 100) and 9 public outreach events (estimated audience 650)
- 422 media engagements were recorded, including 25 on national radio, 7 on national TV, 62 in national papers and mentions in 125 on-line news sites.

Several staff are active on Twitter; **Hawkins**' continued climate science engagement is particularly noteworthy, with over 50,000 followers; his work on visualising climate change for non-specialist audiences is reported in an ICS. The [ShowYourStripes](#) website was developed in collaboration with IEA.

We have been highly active in several citizen science projects.

- **Scott** led **Solar Stormwatch** which uses data from the NASA STEREO mission to track eruptions of material from the solar atmosphere as they expand through the inner solar system. Now in its tenth year, this has attracted around 30,000 active volunteers (over 6,600 to date for the most recent activity) contributing to 8 scientific publications and a PhD thesis. An associated project 'Protect our Planet from Solar Storms', in conjunction

with the Science Museum's exhibition 'The Sun', attracted 3,688 volunteers; results will contribute to another PhD thesis.

- **Hawkins** led the **Weather Rescue** and **Rainfall Rescue** projects, attracting over 20,000 volunteers to digitise millions of weather records from across the UK and western Europe, including hourly measurements collected at the Ben Nevis Observatory (1883-1904), sub-daily and daily European weather observations (1862-74 and 1900-1910), and 5 million monthly UK rainfall records (1800-1960). These have been used to assess and improve meteorological reanalysis products and enhance Met Office reconstructions of past climate. These efforts have inspired collaborations with groups in other countries.
- **National Eclipse Weather Experiment (NEWEx) (G.Harrison, Gray)** collected ≈15000 observations from about 500 locations during the 2015 UK partial solar eclipse leading to a clear demonstration of robust reductions in observed temperature and wind speed during the eclipse, as well as research outputs.

Our staff also play active roles in learned society outreach activities. We make regular contributions to Royal Society's climate science briefings, including recent briefings on IPCC's AR6 Special Reports. Staff also contribute to Royal Meteorological Society's (RMetS) climate science briefing papers and membership of its Education and Outreach Committee.

Our staff contributed to Royal Society Summer Exhibitions in 2017 (A Model Earth), 2018 (Soil: Our Buried Treasure) and were to have presented 'Beware: Floods Ahead!' in 2020 (moved to 2021).

4.7 Visitor programme

We run active visitor programmes. Meteorology's is led by a member of academic staff with dedicated administrative support. At any one time, there are typically 12 visitors, with duration ranging from a few days to over a year. As a snapshot, in early 2020 there were 5 Chinese scientists visiting for durations of about a year or more, in areas such as space physics, data assimilation, urban meteorology and climate variability. Each visitor has a named host to enable a two-way interaction with the wider Department. The Visitor Programme has an annual budget of £12,000 for visits by both researchers and PGR students registered elsewhere; this includes the Distinguished Visitor Programme organised by PGR students. In GES, Environmental Science staff host an average of 5 international visitors each year (including from Australia, central Asia, China, France, Ghana, India, Spain and South America) typically for 3-12 months. Walker is an associate member of the Himalayan University Consortium, hosting visiting scientists from South Asia as part of this.

4.8 Committee membership

We continued our high level of service to national and international science initiatives and programmes during the REF2021 period. Selected examples illustrate the range and depth of activities.

UK Learned Societies

- RMetS: Atmospheric Electricity Specialist Group (**G.Harrison, Nicoll**); Climate Communications Group (**Hawkins**); Data Assimilation Specialist Group (**Lawless**); Meteorological Observing Group (**Nicoll**); Education Committee (**Charlton-Perez**); Book Series Editor (**Williams**); Publications Committee (**Methven**)
- Other: Royal Society of Chemistry Environmental Chemistry Group (**Sizmur**); Wind Engineering Society Steering Committee (**Barlow**); Institute of Physics Environmental Physics Group (**Ryder**); Remote Sensing and Photogrammetry Society Publications Committee (**White**); Royal Society Science Policy Expert Advisory Committee (**Shepherd**); Royal Society Publishing Board (**Lockwood**); Royal Society Sectional Summer Exhibition Committee (**Lockwood**).

UK Government and industry

- Defra Hazardous Substances Advisory Committee (**C.Collins**, chair); Natural Capital Committee (**C.Collins**); Defra Air Quality Strategic Evidence Leadership Group (**Coceal**)

- Met Office Scientific Advisory Committee (**Barlow**); Met Office Hadley Centre Science Review Group (**Shepherd**, Chair)
- UK Space Agency Earth Observation Advisory Committee (**Merchant**)
- Airports Commission Expert Advisory Panel (**Shine**)
- Environment Agency Long Term Investment Scenarios Advisory Group (**Cloke**); Defra/Environment Agency Flood Incident Management Theme Advisory Group (**Cloke**); Environment Agency Future Flood Hydrology Roadmap Advisory Group (**Cloke**)
- UK Climate Change Risk Assessment Advisory and Peer Review Panels (**Arnell**, **Hawkins**); UK Climate Projections Peer Review Panel (**Hawkins**, **Haines**)
- London Climate Change Partnership (**Grimmond**)
- REF2014 Earth Systems and Environmental Sciences Sub-Panel (**Shine**).

UKRI

- NERC: Science Committee (**Sutton**); High-Performance Computing Committee (**Woolnough**); Centre for Ecology and Hydrology Science Direction Group (**Wade**); Constructing a Digital Environment Panel (**Van Leeuwen**); Governance Group of NERC-Met Office Joint Marine and Modelling Programme (**Feltham**); Natural Flood Management Coordination Team (**J.Clark**); Peer Review College (18 staff; many others have served on panels for individual calls, fellowship and doctoral training programme selection); FAAM Strategy Committee (**Methven**); NCAS Atmospheric Measurement and Observation Steering Committee (**Westbrook**)
- Other: EPSRC UK Fluids Network Low Energy Ventilation Network Steering Committee (**Barlow**); EPSRC UK Fluids Network Urban Fluids Steering Committee (**Grimmond**); BBSRC Pool of Experts (Committee B) (**Shaw**); NERC/DFID/ESRC panel on Disaster Risk Forecasting (**Gray**); EPSRC Environmental Change Challenge Fellowships Call (**Dance**).

European institutions

- EUMETSAT Climate Monitoring Satellite Applications Facility Review Board (**Allan**)
- ERC Earth System Science Advanced Grants and Consolidator Grants Evaluation Panels (**S.Harrison**, **Shine**)
- H2020 Gap Analysis and Integrated Assessment for Climate (GAIA-CLIM) Steering Committee (**Merchant**)
- External evaluator of tenders to the Copernicus Climate Change Service (**Cloke**).

Other national

- US Department of Energy Regional and Global Climate Modelling Programme Panel (**Klingaman**)
- NOAA Climate Grant Panel (**Lawless**)
- US National Academy of Sciences Committee on Extreme Weather Events and Climate Change Attribution (**Shepherd**)
- NASA Clouds and the Earth's Radiant Energy System science team (**Allan**); NASA Physical oceanography review panel (**Ferreira**); NASA Mission Selection Review Panel (**Owens**)
- American Meteorological Society Board of Urban Environment (**Barlow**); American Meteorological Society Nominations Committee and Fellows Committee (**Grimmond**)
- Consultation panel on DFG German Research Centres/Excellence Clusters (**Hegglin**)
- Irish Flood Forecasting Centre Scientific Advisory Group (**Cloke**)
- Dutch National Research Agenda programme and Dutch Spinoza Prize Selection Committee (**Verhoef**)
- Canada Research First Excellence Fund review group for Environment and Agriculture (**Wade**)
- Advisory board of the Japanese Institute of Statistical Mathematics (**Van Leeuwen**).

International organisations and subject associations

- WCRP/SPARC Stratospheric Network for the Assessment of Predictability (**Charlton-Perez**); WCRP/SPARC Dynamics and Variability Committee (**Kretschmer**); WWRP Data Assimilation and Observing Systems Working Group (**Dance**); WWRP Predictability, Dynamics and Ensemble Forecasting Working Group (**Methven**); WCRP CLIVAR Scientific Steering Group (**Hawkins**); The Decadal Climate Prediction Project of the WCRP/WWRP Sub-seasonal to Interdecadal Prediction Working Group (**Robson**); WCRP Polar Climate Predictability Initiative (**Shepherd**)
- WMO Expert Team on Megacity Implementation Plan/ Integrated Urban Services (**Grimmond**); WMO Madden-Julian Oscillation Task Force (**Klingaman, Woolnough**)
- IAMAS-IUGG International Commission on Atmospheric Electricity (**G.Harrison**)
- INQUA Palaeoclimate Commission (**S.Harrison**, President)
- IGAC/SPARC Chemistry Climate Model Initiative and SPARC Data Initiative (**Hegglin**)
- Committee on Earth Observation Satellites (CEOS) Working Group for Climate (**Merchant**)
- GEO-BON Ecosystem Function Working Group (**Roy**)
- CLIVAR/GEWEX Monsoon Panel (**Turner**)
- GEWEX System Studies Panels (**Verhoef, Woolnough**)
- International Association for the Properties of Water and Steam (**Tailleux**)
- ICSU World Data System (**S.Harrison**)
- Committee on Earth Observation Satellites Working Group on Calibration and Validation (**Morrison**)
- NATO Science and Technology Organisation SET-250 on Multi-Dimensional Radar Imaging (**Morrison**)
- GHRSSST Climate Data Records Technical Advisory Group (**Mittaz**, chair)
- International Precipitation Validation Working Group (**Tarnavsky**).

Staff played a pro-active role as steering committee members or convening session conveners at major national and international meetings, including the EGU General Assemblies, European Meteorological Society Annual Meetings, AGU Fall Meetings, AMS Annual Meetings, IUGG General Assemblies, IGARSS and EUSAR.

4.9 Editorial

Editorial roles for major journals (both established and newly emerging open access) included:

Senior Editorships

- Geophys.Res.Lett. (**Williams**)
- Hydrology and Earth System Sciences (**Cloke**)
- Proc.Roy.Soc. A (**Lockwood**)
- QJR.Meteorol.Soc. (**Methven**).

Associate Editorships and memberships of Advisory/Editorial Boards

- Advances in Atmospheric Sciences (**Dong**)
- Agriculture and Forest Meteorology (**Verhoef**)
- Agronomy (**Robinson**)
- Ann.Geophys. (**Scott**)
- Atmospheric and Oceanic Science Letters (**Dong**)
- Atmos.Sci.Lett. (**Black, Dacre, Gray, Holloway, Kretschmer, Martínez-Alvarado, Westbrook**)
- Current Climate Change Reports (**Gregory**)
- Environmental Research Letters (**G.Harrison, Shine**)
- Environmental Toxicology and Chemistry (**Sizmur**)
- Frontiers in Climate (**Wilcox**)
- Frontiers in Marine Science (**Roy**)
- J.Appl.Meteor.Climatol. (**Grimmond**)
- J.Atmos.Oceanic Technol. (**Grimmond**)

Unit-level environment template (REF5b)

- J.Climate (**Allan, Charlton-Perez**)
- J.Geochemical Exploration (**Sizmur**)
- J.Geophys.Res.Space (**Owens**)
- J.Atmos.Sci. (**Holloway**)
- Meteorol.Appl. (**Brayshaw**)
- Mon.Wea.Rev. (**Carrassi, Gray, Fowler, Lawless, van Leeuwen, Weller**)
- Nature Scientific Reports (**J.Clark, Hegglin, Singarayer**)
- npj Climate and Atmosphere Science (**Gray, Grimmond**)
- Nonlinear Processes in Geophysics (**Carrassi**)
- Phil.Trans.Roy.Soc (**Williams**)
- Plant and Soil (**Shaw**)
- PLoS ONE (**Charlton-Perez**)
- QJR.Meteorol.Soc. (**Ambaum, Frame, Illingworth, Turner**)
- Quaternary (**S.Harrison**)
- Quaternary Review (**S.Harrison**)
- Remote Sensing for Ecology and Conservation (**Roy**)
- Remote Sensing in Earth Systems Science (**Roy**)
- Soil Biology and Biochemistry (**Shaw**)
- Solar Physics (**Owens**)
- Surv.Geophys. (**G.Harrison**)
- The Anthropocene Review (**S.Harrison**)
- The Cryosphere (**Feltham, Schroeder**)
- Urban Climate (**Grimmond**)
- Vadose Zone (**Verhoef**)
- Weather and Climate Dynamics (**Dacre**).

4.10 Senior fellowships

Dance is an EPSRC Senior Fellow in Digital Technology for Living with Environmental Change (2016-21). **Arnell** held a Cabinet Office High Level KE Fellowship (2018-20).

4.11 Awards and prizes

Prizes and elections to learned societies are an indicator of reputation and standing and contribution to the wider community. During the REF2021 period:

- **Cloke** received an OBE 'for services to flood forecasting and the development of hazard early warning systems' and **Hawkins** an MBE 'for services to climate science and science communication'.
- **Shepherd** (2016) and **Gregory** (2017) were elected Fellows of the Royal Society, bringing our total number of submitted FRSs to four (along with **Lockwood** and **Shine**).
- **G.Harrison** was elected to Academia Europea.

UK learned society awards

- British Hydrological Society's President's Prize (**Cloke**)
- Royal Society Kavli Medal and Lecture (**Hawkins**)
- RMetS: Mason Gold Medal (**Shine**); Buchan Prize (**Allan, Gray, Methven**); Climate Science Communication Award (**Hawkins**); RMetS FitzRoy Prize (**Dacre, Gregory**)
- Royal Astronomical Society Gold Medal (Geophysics) (**Lockwood**)
- Royal Geological Society Murchison Medal (**Wadge**)
- Institute of Physics Appleton Medal and Prize (**G.Harrison**).

Awards recognising impact and communication

- NERC Early Career Impact Award (**Cloke**)
- NERC Societal Impact Award (**Williams**).

Awards recognising high-quality reviewing of papers

- Publons Sentinels of Science reviewers award (**Allan**)

Unit-level environment template (REF5b)

- RMetS Quarterly Journal Editor's Award (**Ambaum**)
- AMS Editor's Award (**Holloway**).

International awards

- International Association for Urban Climate Luke Howard Award (**Barlow**)
- EGU Plinius Medal (**Cloke**)
- IAMAS Union Lecture (**Hawkins**)
- **Gregory** was co-recipient of the 2019 €400k BBVA Foundation Frontiers of Knowledge Award (Climate Change Category).

Seven staff have been Web of Science Highly Cited Researchers between 2014 and 2020: **Arnell, Bellouin, W.Collins** (4 times), **Gregory, S.Harrison** (3 times); **Hawkins, Shepherd** (twice).