Institution: University of Exeter

Unit of Assessment: 10 - Mathematics

Section 1. Unit context and structure, research and impact strategy

1.1 CONTEXT, VISION AND STRUCTURE

1.1.1 Overview of the unit

Mathematics at University of Exeter (UOE), situated on two campuses in the southwest of England, is at the heart of a university-wide vision in which mathematics plays a key role in creating a sustainable future for the economy and society. This has led to significant growth across all our research subjects in number of staff, students, and research activity. We have expanded from 35 academic staff members to 48, our research income has almost quadrupled, and the number of finishing PhD students has more than doubled (Table 1). Our staff have trained across four continents and maintain active collaborations world-wide, both with other mathematicians and across a range of applications. A distinctive strength of the unit is our thriving research collaborations with 4 of UOE's multidisciplinary Institutes: Environment and Sustainability Institute (ESI), Living Systems Institute (LSI), Institute of Data Science and Artificial Intelligence (IDSAI), and Global Systems Institute (GSI), described in Section 1.3 & 4.16, of the Institution Level Environment Statement (ILES). Our collaborations have significantly increased the scope of our impact, which ranges from local economic development in Cornwall to influencing international health policy in partnership with the World Health Organization (WHO) to improving weather forecasts by using novel numerical methods. Research is also embedded into our taught programmes, with all of our students exposed to research and many undertaking significant research projects.

Table 1: There has been a significant increase in staff, research income, and PGR completions during the assessment period as indicated in the table below.

	Staff FTE	Research Income, £	PGR Completions
REF 2014	34.6	5.7 M	30
REF 2021	48	20.5 M	65.7

1.1.2 Research Aims and Strategy

Our aims are to foster excellence in mathematics research in an open and inclusive environment, to generate impact capable of transforming the economy and society, and to increase the potential to do so in the future by pushing the boundaries of mathematics research using targeted collaboration, leading to marked increases in research activity and tangible impacts in the mathematics of the environment and healthcare.

To achieve this, we have: 1) hired creative and energetic people working at the forefront of their fields of research; 2) created an evolving, supportive, inclusive and stimulating environment for mathematics researchers at all stages to develop into innovative research leaders in the mathematical sciences; and 3) encouraged mathematics collaboration with a) UOE's multidisciplinary Institutes, b) our many international collaborators and c) our strategic partners. Our partners include:

1. The **Met Office (MO)**, one of the world-leading institutions for environmental science and impact**,** is an important strategic partner and in 2010 we became a founding Met Office Academic Partner (MOAP)**.** The MO invests in Departmental posts: 2 *Met Office Chairs* within the Department of Mathematics, one submitted to UOA10 (Thuburn) and the other delivered to UOA7 (Collins) and a jointly funded post (Economou). The partnership includes shared PhD CASE studentships and bespoke training at the MO (advanced statistics, numerical analysis, etc). Further, this collaboration has created new ideas and new methods that have significant impact and are visible internationally. Thuburn's

collaboration with MO on numerical methods forms one of our Impact Case Studies. Furthermore, in 2016-2017 Thuburn served as a consultant for the 'Dycore test Group', a part of the selection process for choosing the USA NOAA's Next Generation Prediction system, the basis of the USA's national weather forecasts.

2. The **Alan Turing Institute (ATI)**, critical for engaging in national and international initiatives in Data Science and Artificial Intelligence (AI). Our Department houses 5 out of the university's complement of 25 ATI Fellows, and Challenor and Williamson were instrumental in setting up the Uncertainty Quantification special interest group within the ATI.
3. The **World Health Organization (WHO),** the most important organisation in the world for directing and coordinating global health. As a direct consequence of Shaddick's collaboration with the WHO we became a strategic Collaborating Centre for Environmental Data Science for Air Quality and Climate, one of only three worldwide. This research underpins one of our Impact Case Studies.

This strategy, and our expansion, has also enabled a transformational change in the unit's overall research culture and intellectual environment in several important ways:

1. Our expansion in staff has been accompanied by significant growth in our student numbers at all levels. Both PhD (Figure 2, see 2.3.2) and undergraduate enrolment almost doubled (undergraduate FTE went from 444 in 2014 to 839 in 2019), further enhancing our research-led teaching environment.
2. Our increased research activity has allowed us to significantly expand our Departmental Seminar Series and Colloquia. Our seven themed seminar series are vital to research life in the Department, where local and international collaboration and dissemination take place. Combined with Institute interdisciplinary seminars, visitors from international collaborations, and funded research grants, we have access to expertise from all over the world within the Department. The 2019/20 Departmental Series alone brought in 76 visitors. In 2015, we created the David Rees Distinguished Fellowship, a programme to invite distinguished researchers for month-long visits to the Department and to deliver a lecture series on a research topic.
3. We have transformed our development of research impact pathways, in collaboration with the University's Innovation, Impact and Business (IIB) team (Section 3.2.4, ILES 4.5-4.8). This led to our 5 Knowledge Transfer Partnerships (KTP)s (Section 4.2.2), as well as creating and supporting the long-term pipeline of impact activities, including the 4 Impact Case Studies in this submission and an additional 3 under development.

1.1.3 Structure of the Department

The Department of Mathematics (Figure 1) consists of two geographically distinct groups, 42 staff members located on the Streatham Campus in Exeter, and 7 on the Penryn Campus, Cornwall. The **Environmental Mathematics** (EM) group in Penryn was created in 2011 to increase impactful mathematics resulting from research aligned with UOE's first institute, ESI. The remaining groups, located on the Streatham Campus, are **Number Theory, Algebra, and Geometry** (NTAG); **Dynamical Systems and Analysis** (DSA); **Geophysical and Astrophysical Fluid Dynamics** (GAFD); **Living Systems Mathematics** (LSM); and **Statistics and Data Science** (SDS). Communication and collaboration between the two campuses is maintained via shared research interests, and co-supervised PhD and Post-doctoral Research Fellows (PDRFs). Our PhDs and PDRFs are an important part of our research culture. At the REF census date, we had 49 PDRFs in the Department at different stages of career advancement (Associate Research Fellow, Research Fellow, Senior Research Fellow). Our Department also houses a Climate Dynamics (CD) group, submitted to UOA7, that collaborates with the GAFD, DSA, and SDS groups. In addition, we embed mathematicians in strategic scientific groups, across the University, for example McKinley in the Medical School, Beardmore in Biology (submitted to UOA5) and Dodwell in Engineering (submitted to UOA12).

Each group has an Academic Lead (AL) who provides mentoring and leadership. The Head of Department (HOD), Director of Education, Director of Research (DOR), Director of Impacts

(DOI), Director of Post Graduate Research, Director of Global Development, and the ALs form the **Mathematics Strategy Group**, which is responsible for research and education strategy within the Department. The Department sits within the College of Engineering, Mathematics and Physical Sciences (CEMPS). The HOD sits on the Senior Leadership Forum (SLF) of the University which is an important channel for the Department to influence University policy.

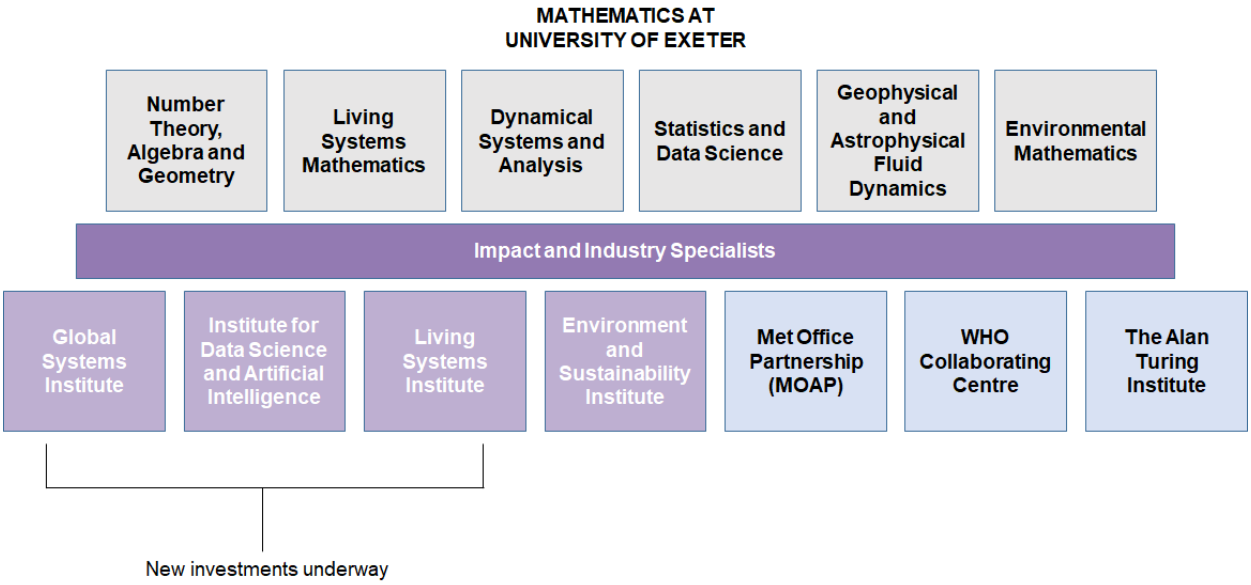


Figure 1: Grey boxes indicate research groups, lavender indicates UOE multidisciplinary Institutes, and light blue boxes indicate strategic partners. New investments are those begun in the REF2021 census period.

1.2 ACHIEVEMENTS IN RESEARCH AND IMPACT FROM REF2014 TO REF2021

Below, we present our research groups and a selection of their achievements. Specific examples of strategic grants and how we use them can be found in Section 3.1; examples of research activities are provided in Section 4.

1.2.1 Number Theory, Algebra and Geometry (NTAG)

Professor Langer, Saïdi; **Associate Professor** Andrade, Byott (lead), Johnston, **Senior Lecturer**; Chapman (deceased October 2020), di Proietto, Tseng.

NTAG is a long-established pure mathematics research group, with strong links to DSA (see 1.2.2). It is the focus of most of the pure mathematics research activity at Exeter, with some pure mathematicians also in DSA. The research interests of NTAG lie in number theory, algebraic/arithmetic geometry, and their connections with other areas of mathematics and physics. Research expertise in the group includes Langer (p-adic Hodge theory), Saïdi (anabelian geometry), Byott (Hopf-Galois theory), Chapman (combinatorial number theory) and Johnston (Iwasawa theory and Stark's conjectures). In 2016, we recruited four new pure mathematicians, with three appointments in NTAG (Andrade, di Proietto, Tseng), while the fourth, (Terhesiu) was hired into DSA. These posts allowed us to build new expertise and links between dynamical systems, number theory and analysis with the appointment of Andrade (analytic number theory) and Tseng (Diophantine approximation and homogeneous dynamics). The appointment of di Proietto enabled us to further consolidate our strength in p-adic geometry. The influx of new staff has resulted in an increase in the visibility of pure mathematics at Exeter, with a number a conferences and workshops including international workshops on Hopf-Galois Theory and Galois Module Structure (2015), on Iwasawa Theory and Stark's conjectures (2018), a CMI-LMS Research School on Analytic Number Theory (2018) and two LMS Celebrating New

Appointments workshops. We have also been able to develop new connections with physics through the work of Andrade on random matrix theory and Byott on algebraic structures related to the Yang-Baxter equation. The group currently hosts many international collaborations as well as two PDRFs, funded by the grants of Andrade and Langer, with two more PDRFs to arrive in 2021, from recently funded grants of Saïdi and Byott. Finally, Tseng is a former Heilbronn Research Fellow and has had a consulting agreement from 2017 to 2021.

1.2.2 Dynamical Systems and Analysis (DSA)
Professor Ashwin, Biktashev; **Associate Professor** Sieber(lead), Rodrigues, Holland; **Senior Lecturer** Bick, Terhesiu.

The research of DSA focuses on dynamical systems and analysis, ranging from fundamental mathematical theory to applications in science and technology. The appointment of Terhesiu (ergodic theory) allowed us to strengthen our work in pure and applied dynamical systems and analysis. The group's basic research includes networks, symmetry, low dimensional dynamics, ergodic theory, delay systems, stochastic dynamics, and spatially extended systems. Because this group has both pure and applied research, it serves as a hub of mathematical creativity, uniting interests in many of the Department's groups and multidisciplinary institutes. An example of its important role achieving the research strategy of our Department is that ideas seeded in DSA evolved into the Living Systems Mathematics (LSM) group (Section 1.2.4). Specific examples of DSA's research include: ergodic theory (Ashwin, Holland, Rodrigues, Terhesiu), continuation methods (Sieber, EPSRC fellow) non-autonomous dynamical systems and tipping (Ashwin, Sieber), network dynamics (Ashwin, Bick) and pattern formation (Biktashev). The group's results underpin applications in other groups in the unit and across the university, in particular Earth Systems and Medicine/Neuroscience. Collaborations have resulted in joint publications & PhD students with UOA7 staff: Cox, Luke, Stephenson from Mathematics, Lenton from Earth Sciences. Researchers in DSA (Ashwin, Holland, Sieber) have played a central role in EU PhD training networks, ITNs CRITICS and CriticalEarth, and the EU funded consortium TiPES, which develops new mathematical tools for understanding nonlinear dynamics of climate processes.

1.2.3 Statistics and Data Science (SDS)
Professor Challenor (lead), Shaddick, Stephenson; **Associate Professor** Kelson, Williamson; **Senior Lecture**r Economou, Kelson, Ferro; **Lecturer:** Maher, Siegert.

The research of SDS ranges from fundamental statistics to data science and its applications. The group was formed in 2015 based on a strategic decision to build on past success in uniting statistics with environmental science. SDS was initially comprised of five staff: Bailey (retired), Challenor, Ferro, Stephenson, and Williamson. Over the next few years, the group expanded significantly, with the addition of Shaddick, Economou, Kelson, Maher, and Siegert. Research activities in the group include: spatial statistics (Challenor, Stephenson, Ferro, Siegert, Economou, Shaddick), extreme values (Stephenson, Economou), climate risk (Stephenson, Siegert, Economou), uncertainty quantification both in theory and application in climate (Challenor, Williamson), healthcare, epidemiology and engineering, foundational mathematical development (Williamson), verification of probabilistic forecasts (Ferro, Siegert), epidemiological modelling (Economou), clinical trials (Kelson), the analysis of physical motion and modelling supply chains (Challenor, Economou, and Kelson). The SDS group forms a core part of the Department's involvement in the IDSAI and serves as a nucleus of collaboration with our UOA7-facing Climate Dynamics group, the Department of Computer Science, the GAFD (Section 1.2.5), LSM (Section 1.2.4) and DSA (Section 1.2.2). SDS is one of our most important groups aligned with the Industrial Strategy and in 2019 was awarded a (£5.2M) UKRI CDT in Environmental Intelligence (EI) (PI: Shaddick), bringing many more PhD students to the Department. DSA is contributing two of the unit's four Impact Case Studies (Economou and Shaddick) and has 2 of the Department's 5 KTPs (Williamson & Economou, Siegert). The SDS maintains key strategic relationship with the Met Office and ATI, and were instrumental in

setting up the 2019 WHO Centre (Section 1.1.2). This group has also recently made contributions to the fight against the pandemic virus, COVID-19 (Section 3.1).

1.2.4 Living Systems Mathematics (LSM)
Professor Tsaneva, Borisyuk; **Senior Lecturer** Akman, Goodfellow (lead), Rankin, Wan; **Lecturer** Walker, Wedgwood.

Our first genuinely multidisciplinary group, LSM is one of the co-founding research groups based in the LSI building. The award-winning building (RIBA SW award 2017 and the Michelmores Building of the Year Award 2017) was designed to embed interdisciplinary research inspired by mathematical modelling of complex biomedical systems. One goal of this group is to bring mathematics to real-world applications. Examples include model-based optimisation of epilepsy surgery (Goodfellow), diagnosis of psychiatric disorders, novel therapies for menopause and infertility, and lung diseases (Tsaneva). Another key goal is to develop new branches of mathematics as outcomes of multidisciplinary research, for example expanding mathematical theories on system dynamics through research on epilepsy. The group has benefited from investment in 4 new Lecturers (Rankin, Walker, Wan, Wedgwood), who each integrate experiments into their mathematical research, and a Professor (Borisyuk), who is a leading expert on nonlinear oscillator models. The group maintains strong connections to the other departmental groups, in particular DSA and SDS, as well as the Colleges of Medicine and Health and Life and Environmental Sciences. The group's activities come under the umbrella Quantitative Health @ Exeter (QHE), which has grown out of a sequence of successful grants, for example (see Section 3.1 for more detail): 1) EPSRC Centre for Predictive Modelling in Healthcare and 2) EPSRC Hub for Quantitative Modelling in Healthcare, both of which bring together researchers, clinicians and stakeholders to address key healthcare challenges. We are one of only 3 centres in the country to have received both of these awards. International links include hosting a Fulbright US Scholar (Casey Diekman, to advance understanding of physiological rhythms) and joint studentships with NTU Singapore (e.g., Tsaneva-Chotirmall (NTU): modelling microbiome in lung disease, Nature Medicine paper accepted).

1.2.5 Geophysical and Astrophysical Fluid Dynamics (GAFD)
Professor Berger (lead), Gilbert, Thuburn, Vallis, Wingate, Zhang; **Associate Professor**, Hillier; **Senior Lecturer** Foullon, Kwasniok, Mason; **Lecturer** Shipton.

GAFD brings together expertise in mathematics and fluid dynamics of oceans, atmospheres and stars, increasing our research profile in UOE's strategic areas of environmental science and exoplanets. The group has a close relationship with Departmental staff submitted to UOA7 with shared PhD students (Thuburn/Beare, Vallis/Collins) and housing four members of UOA7 within the group (Beare, Lambert, Thomson, Seviour). There are also close ties to Astrophysics (UOA11) with biannual shared seminars bringing leading international researchers to Exeter. The group has important, strategic links with the Met Office including housing three Honorary Visiting Professors: Jackson, Shipway and Wood. In addition, the group hosts Honorary Visiting Professor Grimshaw. GAFD members work in a wide range of mathematical disciplines connecting these areas to theoretical fluid dynamics and its applications. This includes recent advances in geometry in fluid dynamics (Gilbert), oscillatory PDEs (Wingate), multi-scale analysis in magnetohydrodynamics (Hillier), discrete differential geometry in numerical weather prediction (Thuburn), in the analysis of in-situ satellite data (Foullon), understanding entangled and knotted structures using wavelets (Berger), and stability analysis with stochastic differential equations (Kwasniok). An emerging theme during the assessment period was the development of innovative, configurable numerical models: 1) ISCA, a planetary atmosphere model (Vallis); and 2) GUSTO, a compatible finite element model used for prototyping atmosphere/ocean dynamical cores (Shipton) housing a variation of the next generation Met Office dynamical core.

1.2.6 Environmental Mathematics (EM)
Professor Recker, Townley (lead)**; Senior Lecturer** McKinley, Mueller; **Lecturer** Ardakani, Das, Hughes.

The **EM** group is the main conduit for mathematics and data science into research activities on the Penryn campus, including the environmental sciences in the ESI, and makes significant contributions to developing potential economic impacts in the form of KTPs and ERDF activities (Section 3.1 and 4.2.2). During the assessment period four new staff members were appointed (Ardakani, Das, Hughes, McKinley), and a new degree programme in mathematics created in 2016, leading to a major increase in activity in mathematics research in Penryn. For example, there are currently 15 mathematics PhD students in the group and a further 6 jointly supervised with biosciences and renewable energy. The group's research includes the analysis and design of passive systems, with application to mechanical design and electric circuit synthesis (Hughes) and adaptive and set-point control for management of natural populations (Mueller and Townley), fractional order, intelligent control approach to handle complexity in smart grid models (Das); and geometric fluid dynamics and numerical analysis (Ardakani). One of the group's highlights is that Recker and collaborators made fundamental contributions to a WHO study on the safety and long-term impact of the first dengue vaccine. This research formed the evidence base for WHO's health policy recommendations for the use of this vaccine and forms one of our Impact Case Studies.

1.3 EXTERNAL INDICATORS OF PROGRESS SINCE REF2014

1. A factor of four increase in externally funded research (Section 3.1),
2. A doubling of the number of completed PhD students since REF2014 (Section 2.3.2),
3. The £5.6M UKRI Environmental Intelligence CDT (Section 1.2.3),
4. A significant enhancement of our research environment with a £23K per annum investment from the College that supports seven seminar series with invited speakers from all over the globe, and the creation of the David Rees Distinguished Fellowship for visiting academics,
5. A significant increase in leadership, commissions of trust, steering boards, and other activities in the international sector, expanding UK's international influence (Section 4),
6. Three partnerships vital to research creativity and developing new routes to impacts: the Met Office, the Alan Turing Institute, and the World Health Organization.

1.4 STRATEGY FOR RESEARCH AND IMPACT IN THE NEXT DECADE

Our aims and strategies, outlined in Section 1.1.2, will continue to drive our future development. A selection of our new initiatives include:

- Building on our two mathematics EPSRC Healthcare Centres (Sections 1.2.4, 3.1) to develop mathematics in healthcare decision applications; advance mathematics of diabetes, mood disorders, dementia, clinical microbiology, medical mycology, and fundamental biology applications.
- Developing untapped veins of research, with potential for global impact, through a new UOE-MO Joint Centre for Excellence in Environmental Intelligence, whose ambition is to develop solutions to real-world environmental challenges using data science and AI (https://www.metoffice.gov.uk/research/approach/collaboration/joint-centre-for-excellence-in-environmental-intelligence).
- Instigating a new ***Robin Chapman Lecture Series*** in which distinguished mathematicians visit the Department and give a Departmental Colloquia and a Lecture Series aimed at advances in pure mathematics. This new Lecture Series will be developed in honour of Chapman, who died in October 2020, and who was a greatly respected member of the NTAG group, a favourite teacher, and an icon of our Department.

1.5 Open Research and Research Integrity

The Department is committed to Open Access publishing (Section 3.2.2), and similarly committed to ensuring a high level of research integrity. For example, members of the department are encouraged to give open access to software and data outputs, to enable our results and code to be accessible to a wide range of users (e.g. via GitHub). We also have

access to a recently created group of Research Software Engineers (Section 3.2.3), which aids greatly in making our software repeatable and open-source. In addition, Kelson, who is also our Departmental Ethics and Integrity Officer, has led the way for UOE's participation in the UK Reproducibility Network and serves as our local representative. The Departmental Ethics and Integrity Officer advises staff and engages with CEMPS's Research Ethics Committee, which allows the Department to benefit from all the infrastructure and policies available from UOE's actions in response to membership in the Concordat to Support Research Integrity (ILES 2.9).

Section 2. People

2.1 STAFFING STRATEGY

Our approach to staffing, in line with our strategies (Section 1.1.2, 1.4), includes two essential types of investment: 1) departmental appointments decided by the Mathematics Strategy Group; and 2) targeted cross-university multidisciplinary research appointments associated with the University's strategic institutes (ESI, LSI, GSI, and IDSAI), which are decided by the institute's leadership team with representation from the Department. For both types of appointments, we carry out an international search. Over the assessment period we recruited 15 UOA10 Departmental posts:

- NTAG: Andrade, di Proietto, Tseng
- DSA: Terhesiu, Bick
- SDS: Shaddick (a new Chair in Statistics), Economou, Kelson, Maher, and Siegert.
- GAFD: Hillier
- EM: Ardakani, Das, Hughes, McKinley.

We also had 5 targeted multidisciplinary appointments including:

- Rankin, Wan, Walker, and Wedgwood, hired using the proleptic scheme (see below).
- Borisyuk (20%FTE) strengthens our expertise in 1) nonlinear oscillator models for neuroscience applications and 2) neural network research in the Medical School.

We have a special Early Career Researcher (ECRs) route to a permanent post called Proleptic Lectureship, which allows PDRFs to function in a dual role. The staff member works initially as a PDRF with a promise of transition into an academic Lecturer post. These posts can be awarded to either exceptional PDRFs, PDRFs who receive Fellowships, or PDRFs with novel contributions to innovation or industrial collaboration. This is an important aspect of our staffing strategy because we have a record of attracting PDRFs on postdoctoral fellowships including Marie Curie Intra-European Fellowships, MRC Skills Development Fellowships, EPSRC Mathematical Sciences Fellowships, Royal Society–SERB Newton International Fellows. During the assessment period we have had 7 proleptic posts transfer from Fellowship Awardee to (Senior) Lecturer, with 2 additional conversions planned after the REF census date. Moreover, with the Proleptic route to a staff appointment, commercialisation can complement a research trajectory. MRC Skills Development Fellow Woldman (R-only leaver 2019), who began as a PhD student in the LSM group, was one of the co-founders of the start-up Neuronostics (Section 4.2.2), which provides decision support in epilepsy. Subsequently, Woldman worked part-time as scientific director for Neuronostics in addition to his academic research activities.

In any active and engaged mathematics department, staff will leave to take up promotions and opportunities elsewhere. During the REF period we had 2 staff take external promotion opportunities: Terhesiu moved to an Assistant Professor post at Leiden University, and Terry to a Directorship of a Multidisciplinary Institute at the University of Birmingham. One staff member retired (Bailey).

Our promotion process (see 2.2) led to 1 staff member advancing from Associate Professor to Full Professor, 9 staff advancing from Senior Lecturer to Associate Professor and 12 staff advancing from Lecturer to Senior Lecturer.

2.2 STAFF CAREER DEVELOPMENT AND SUPPORT

2.2.1 Training support for new staff

New staff undergo a formal induction process designed to support individuals to welcome, settle, and help gain knowledge of Exeter and the environment. This includes: University, College, and job-specific level inductions. The induction also includes a lunch with the Vice-Chancellor and New Starter meetings with the Dean and HOD. Staff are informed about the induction procedures in their appointment letters and are allocated a trained Induction Facilitator in advance of their start date. The College induction resources include a standard checklist with details of mandatory training, including Equality, Diversity and Inclusion training, IT access, building information, and a list of key people within the College.

2.2.2 Support through start-up, probation and promotion

Each new staff member is mentored by their group's Academic Lead (AL) through their 3-year probation period where the achievements required to pass probation are decided through discussions with the AL and HoD. Each new appointment is supported with a negotiable start-up package and often includes a PhD studentship, and a Professional Development Account (PDA). The PDA can be used for a wide range of research-related costs including local meetings, equipment, books, software, and travel. Module teaching is gradually increased to a full workload over the course of 2 years. We also use a workload model to achieve a balance of teaching, research, and administration. A minimum research allowance for all staff members (~20% of a workload) ensures all staff have time for research activities and grant development.

2.2.3 Concordat to Support the Career Development of Researchers

The University of Exeter participates in the International Researcher Development Framework and was awarded the European HR Excellence in Research award for putting in place strategies to support the principles of the Researcher Development Concordat (ILES 2.9). The effects of this can be felt throughout the University and the Department in a range of support measures embedded through Section 2 (see: 1.5, 2.2.1, 2.2.2, 2.2.6). For example, our PDRFs have three progressive career stages, allowing support and training to develop over time as their needs change, and which has the further advantage of preparing PDRFs for transition to Lecturer. ECRs, at all stages, are supported via an active ECR Network (ECRN), which organizes focused career events such as the pathway to promotion and how to write grant applications. This experience includes an 'ECR Hub' that serves as a focal point for training, new funding opportunities, collaboration, competitions, and strategic representation. The organisation of ECRN within the Doctoral College ensures that all ECRs have access to university-wide networking. Within the department, as we describe in Section 2.2.2, ECRs are mentored by their group's AL, and are supported throughout their early grant-writing experiences (Section 2.2.6).

2.2.4 Support for Career Development, including multidisciplinary collaboration, and Training

To ensure that each member of staff has feedback about their career goals, all staff participate in an annual Performance and Development Review (PDR) with their AL. This is an arena where formal mentoring and academic planning take place for future development. Training for PDR reviewers is mandatory, and includes the importance of encouraging networking, attending conferences and personal development, continuous professional development and EDI activities.

The University-wide '*Exeter Academic'* (ILES 3.3) web pages for academic staff provide clear guidelines about expectations for probation and promotion. The guidelines are split into three key areas which are linked directly with the promotion criteria and ePDR, a web-based interface

to managing the PDR, that take into account academic citizenship, impact, administration, research, teaching, pastoral and outreach work.

We also benefit from a 2019 University-wide People Development strategy. This programme intends to increase staff awareness of the importance of managing their career and put tools in place to assist them. New activities include 'Taking control of your career' workshops, CV writing skills sessions, shadowing opportunities, and one-to-one career coaching.

In addition to each staff member having a PDA for research expenses (Section 2.2.2), the College maintains a reservoir of Strategic Research Funds (SRF), available to all staff members by writing a 1-page request. The SRF funds can be used for visitor travel, conference travel, short term PDRF visits, or bridges gaps in funding to enable collaboration. As an example, these funds enabled a promising female PGR to have a 6-month research experience with Professor Kerrie Mengersen's Bayesian statistics group at Queensland University of Technology in Australia.

2.2.5 Support for Study Leave

Our Study Leave Programme, similar to a sabbatical, is an important part of our research culture, providing uninterrupted time for staff to focus on creativity in research, promote international collaboration, and gain experience in another research environment. The staff member works with their AL, the DOR and the HOD to purpose the Study Leave and develop potential outcomes, allowing each member of staff to have the best experience possible. During the REF Period seven staff members participated in the programme, namely Akman, Ashwin, Challenor, Ferro, Holland, Saïdi, and Zhang.

2.2.6 Support and planning of Research and Fellowship proposals

Vital to both achieving our research goals and sustaining our active research culture, our Department has a robust mentoring, grant-writing, and reviewing process that involves the DOR, ALs, and a Departmental Peer-Review College. This support is complemented by a comprehensive set of college-level services and training (e.g., research council grant prioritization panel training, writing workshops, etc) and the University, via Research Services. A key resource is our Research Development Manager (RDM), an expert in Mathematics-focused research, who assists staff in the creation and development of bids, providing tacit knowledge for different research councils, helping staff create budgets and support with grant submission portals. Any bids likely to lead to panel interviews are supported by communications training and mock panels with senior academics. Further, we benefit from a comprehensive Research Toolkit (ILES 4.7) and a bi-annual workshop series, 'IIB Essentials', which provides focussed training for impactful research (ILES 3.6). Particular focus areas for support are ECRs, returners from parental leave and those with more experience, who have had previous successes, but have not had a grant award for a few years. Finally, the RDM and DOR work together to create and maintain a pipeline of our staff's research ideas to ensure research development support is timely and strategic. As can be seen in Section 3, this approach has led to a significant increase in funding success during this REF period.

2.3 RESEARCH STUDENT SUPPORT AND TRAINING

PGR students make a crucial contribution to our research culture and activities, bringing ideas and energy from educational institutions from all over the world and forming a hub around which Mathematics staff from across the university convene. This includes shared PhD supervision between Penryn and Streatham staff members. In 2014/15 the UOA had 32 home/EU PGR students plus 14 international students. These numbers steadily increased over the REF assessment period to 48 home/EU and 20 international PGR students in 2018/2019. The UOA presently has 146 PGR students.

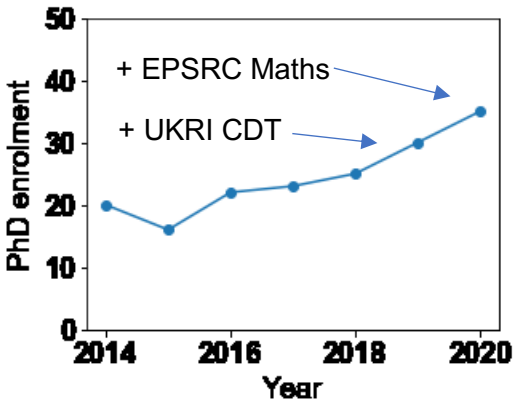
2.3.1 Recruitment

We recruit PhD students with a strong mathematics background by carrying out a national and international advertising process, underpinned by EDI considerations (Section 2.4), and facilitated by the Doctoral College (ILES 3.8-3.13). Students on the four-year MMath and MSci Mathematics undergraduate programmes regularly engage with research via summer research placements and final year projects. Many progress on to PhDs at Exeter or other institutions, and we have variants of the MSci programme that link directly to research activities in the research groups and the multidisciplinary institutes.

2.3.2 Funding

During the first part of the assessment period, funding sources for PGR students were primarily from: new members of staff provided with a College-funded PhD studentship, international studentships sponsored by their government, participation in the Met Office CASE studentship scheme, an EPSRC Doctoral Training Program (DTP), a GW4/NERC-funded DTP, and a BBSRC DTP. Since two of the DTPs are focused on multidisciplinary research, finding PhD studentships in foundational areas of mathematics was one of our biggest challenges. This changed with our 2019 UKRI EI CDT (Section 1.2.2), which allowed for a stronger mathematics recruitment and an increased volume of PGR studentships. We were also awarded new PhD studentships from an EPSRC Mathematical Sciences DTP leading to another strong increase in our enrolment. As evidence of progress on the vitality of our PhD programmes, Figure 2 shows the number of new enrolments of PhD students during the assessment period, showing a marked increase in the last 2 years.

Figure 2: PhD Enrolment



2.3.3 Training and Support

The University, College, and Department of Mathematics ensure that all students receive appropriate training independent of their source of funding. The Doctoral College offers, as part of the mandatory training for PGRs, the “Welcome to the University” induction event, and also offers career support (planning for a professional future) including 1-2-1 careers appointments with dedicated Researcher Development Careers Coach with whom PGRs can discuss issues such as next steps and options, CV and application preparation, and interview preparation. Besides training and career support, the Mathematics PGRs participate in a mentoring programme within their research group. First year PhD students must undertake a programme of training and assessment consisting of at least 100 hours of advanced PhD training modules, in compliance with EPSRC expectations for Mathematics PhDs. Opportunities for this training include MSc modules in Mathematics, lecture courses from the EPSRC-supported *MAGIC* Taught Course Centre (http://maths-magic.ac.uk) and participation at *Academy for PhD Training in Statistics* (APTS) courses. Exeter plays a leading role in the development of *MAGIC* (Ashwin is Director of the MAGIC TCC since 2016). We are a Member Institution for the APTS and make extra research funds available to ensure all our PhD students in statistics can attend the annual APTS training weeks, which are residential (in normal years) and attended by over 150 students from major statistics groups across the country. The courses play a key role in preparing our students for their research projects and future careers, and in helping them integrate with the UK statistics community. PhD students are also encouraged to attend relevant external courses and workshops such as the NCAS summer school in atmospheric modelling, the STFC course on solar physics and the European Research Course in Atmospheres (ERCA). Examples of skills training http://as.exeter.ac.uk/support/development/researchstudents/ provided by the University includes formalised Generic Skills training and employability skills.

Progress monitoring is captured by uploading reports, feedback, and other materials into MyPGR which maintains all of the student records as well as contact with supervisors. The first year monitoring includes a report, presentation to a small group of academic staff, a viva and a formal review of training undertaken, ensuring that students have clear objectives on entering

their second year. PhD students must give at least one research seminar during the first two years of their degree. They are actively encouraged to organize or co-organise events (such as group meetings or workshops) as well as being funded to participate in relevant international or national research conferences and workshops. Since October 2019 there is also a Department-wide PGR-organized seminar held every two weeks. In addition, our statistics PhD students hosted the 42nd Research Students' Conference in Probability and Statistics on the 18th-21st June 2019.

2.4 EQUALITY, DIVERSITY AND INCLUSION

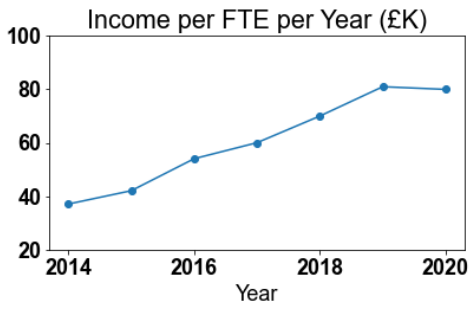
The Department of Mathematics strives to ensure that our staff and students experience a working environment built upon a foundation of inclusivity, diversity, equality and respect. In our most recent Departmental survey, 89% of staff indicated they had a good working relationship with colleagues. Our first Departmental EDI working group was focused mainly on gender issues, but after our 2014 Athena Swan Silver application, we expanded its mission to include all protected characteristics and renamed it to WIDER (Workplace Excellence, Inclusion, Diversity, Equality and Respect). To ensure our practices promote continuous evolution of EDI activities, members of WIDER develop and maintain the Department's EDI Action Plan and are allocated dedicated time within the UOE workload model ensuring they are able to commit to their EDI work. The Head of Department's membership on the group ensures there is an immediate conduit for actions that need to be taken. Examples of the types of activities intended to evolve and improve our EDI culture include the following: 1) Modifying Departmental communication to ensure there is no gender-bias; 2) EDI training for all interview panel members; 3) a female member of staff on every interview panel; 4) individual mentoring for females passing through key career transition points; 5) a comprehensive parental leave plan; and 6) new undergraduate recruitment plans to ensure all potential students feel welcome. We currently have two senior female professors from the UOA in key leadership roles: Wingate – DOR, Tsaneva – Associate Dean of the College. We have a number of new activities planned for 2021, for example, an EDI training module that covers all protected characteristics. We also recently (2019) became a member of Advance HE's Race Equality Charter and have implemented a number of initiatives such as BAME leadership development programs. WIDER also recently committed to decolonising the curriculum activities.

EDI considerations have fully informed the department's **REF2021 return**. All members of the Outputs Selection Panel have received externally provided unconscious bias training arranged by the University. Internal and external evaluations of the outputs and impact case studies have been discussed in terms of EDI and adjustments made when necessary. Furthermore, we have ensured the example activities in the Department represent a wide cross section our staff, especially those with protected characteristics.

Examples of how our policies have positively impacted our EDI environment for gender balance include: 1) of our new hires: 30% are female and 70% are male, improving the overall gender female/male balance of staff from 14% in 2014 to 17% in 2020**;** 2) The percentage of permanent female professors has gone from 9.2% in 2014 to 14.4% in 2020; 3) PhD student gender balance has gone from 22% in 2014 to 38% in 2020. Further evidence of our EDI activities includes the award of 3 Athena Swan Charters: Bronze 2014, Silver 2016 (4th mathematics department in the UK), and Bronze 2019.

Section 3. Income, infrastructure and facilities

3.1 RESEARCH FUNDING PORTFOLIO



We have attracted more than £31M in Research Grant Awards (an average of £92K/FTE/year) and £20.4M Research Grant Income (average £61K/FTE/year) over the assessment period, a significant increase since our REF2014 submission (average £33K/FTE/year). Evidence of our growing research strength includes success across all our research groups, as well as a steady annual increase in the research income per FTE per year, shown at left, from £38K/FTE/year in 2014 to £80K/FTE/year in 2020. The source of this increase is not only ~13 new staff, but a community spirit outlook on research creativity and grant writing that involves mentorship and review complemented by sustained research development and grant writing support (Section 2.2.6). The research grants come from a diverse range of funding sources: £14.05M from UKRI Research Councils, £1.5M other UK Government bodies, £1.8M UK Competitive Charities, £578K UK Industry, £2.11M from EU, £234K from Non-EU.

Our external funding has not only been important for mathematics research but has also been critical to 1) creating impact from our research and 2) contributing to the career development of our staff, PDRFs, and PhDs. We also use our funded projects as opportunities to create research ecosystems of academic staff, PDRFs, PhD students, M-level students and 3rd year project students that allow mathematics students to experience working on cutting-edge research projects. Another example of the important role of research grants is the opportunity for ECRs to focus attention on research early in their career and in this period, we had 9 ECR-focused awards (e.g., EPSRC New Investigator, MRC Fellowship, ERC Starting grant, STFC Ernest Rutherford Fellowship).

Highlights of our funded research grants by group:

- **NTAG**: Awards include a Leverhulme Research Project Grant (Andrade, £280K), an EPSRC Standard Grant (Langer, £382K), and two EPSRC New Investigator Award/First Grant (Tseng, £125K and Johnston, £99K) and two new EPSRC Standard Grants (Byott, £362K and Saïdi, £364K) set to begin in 2021. An important outcome of these grants is the presence of two PDRFs in the group, and another two more to be hired in early 2021.

- **DSA**: Awards include an EPSRC Fellowship (Sieber, £639K), two EPSRC New Investigator Awards (Bick, £237K and Terhesiu, £140K), an EPSRC New Horizons award (Sieber, £200K, beginning in 2021), two EPSRC Networks (listed in Section 4.1.3), EPSRC grants in nonautonomous dynamical systems (Ashwin, £492k) and statistics of extremes (Holland, £344k), and two major recent EU awards: The EU H2020 project "Tipping points in the Earth system (TiPES)" 2019-2023, €8.8M (€600K to Exeter) and Marie Sklodowska-Curie ITN "CriticalEarth" 2021-2025, €4.1M (€500K to Exeter) and ITN "CRITICS" 2015-2019 (€500K to Exeter), hosting two PhDs and a regular stream of PhD visitors from around Europe. DSA also has significant roles in the EPSRC Centre for Quantitative Modelling in Healthcare (Ashwin and Biktashev Co-I) and the EPSRC Hub for Quantitative Modelling in Healthcare.

- **SDS**: Examples of UKRI funding include the EPSRC Mathematical Sciences Models to Decisions (Challenor £379K), NERC BigFoot (Challenor £1.8M), and CAMPUS (Challenor £387K) as well as funding from non-research council sources such as the Alan Turing Institute (Challenor, Williamson), the World Bank (Stephenson), WHO (Shaddick), and Willis Towers Watson (Stephenson). More recently, members of the

group were awarded funding to aid in the fight against COVID-19: Uncertainty Quantification for Expensive COVID-19 Simulation Models (Williamson £357K). The group has a significant role in both the EPSRC Centre for Quantitative Modelling in Healthcare (Challenor Co-I) and the EPSRC Hub for Quantitative Modelling in Healthcare.

- **LSM**: Strategic research grants includes 2 key multidisciplinary EPSRC Healthcare Centres: 1) £2M for the EPSRC Centre for Predictive Modelling in Healthcare in 2016 (PI: Terry) and 2) £1.2M EPSRC Hub for Quantitative Modelling in Healthcare in 2020 (PI: Tsaneva), as well as 3) a ~£3M combined Welcome Trust institutional Strategic Support Fund (ISSF) 2&3. These grants brought in a number of ECR fellows who went on to win key ECR research grants, including Wan (ERC Starting grant £1.95M), Walker (MRC fellowship £800k), Wedgwood (£360k MRC fellowship) and Rankin (EPSRC New Investigator).

- **GAFD**: Two important EPSRC Mathematical Sciences grants: 1) on oscillations in PDEs (Wingate £868K), and 2) on geometry and fluid dynamics (Gilbert, Mason £700K). Funding was also attracted for mathematical modelling of physical systems from STFC (Berger, Hillier, Wingate, Zhang £1.2M), and NERC (Thuburn Phase I: £738K, Phase II £495K).

- **EM**: Examples of the group's economic-facing mathematical activities include the completion of 3 KTPs and 3 European Regional Development funds (ERDF) detailed in Section 4.2. These, along with an EU H2020 project OPERA, devoted to developing clean energy, total well over £1.6M in mathematics' contributions toward £12.7M invested in Exeter University for regional, national and EU economic development.

3.2 SPECIAL INFRASTRUCTURE AND FACILITIES

3.2.1 Library facilities

Members of the Department have access to research literature through the University of Exeter Library (ILES 4.15), which maintains subscriptions to more than 14,000 journals, including those used by the unit and provides extended access to monographs through the inter-library loan scheme at no cost to researchers. The UOA coordinates with the Library through a dedicated library liaison officer.

3.2.2 Open Access

Open Access in publishing ensures our research is freely available, and in 2014 UOE set up a central fund, regularly accessed by the unit's staff, to help facilitate open access publishing. The Exeter University Library also facilitates and maintains funds for Open Access publishing (ILES 2.8), as well as helping people navigate the existing agreements between journals and Open Access. We require all researchers to submit their outputs to ORE within 3 months of acceptance and these are made publicly available as soon as possible after publisher's embargo periods. ORE is not only a repository for research outputs but also provides facilities to make research data openly available. During the REF period, over 230,000 of our unit's outputs and other research related files have been downloaded from ORE by users across the globe.

3.2.3 Computing facilities and IT and Research Software Engineering

Computing capability is critical infrastructure in an era where computer architectures are changing; UOE resources include both standard HPC clusters and novel architectures. The University's investment in computing and research facilities (ILES 4.20) includes the University's £3M HPC (ISCA), which combines a traditional computing cluster of nodes with a virtualized cluster environment and is available to all members of staff. Access to novel architectures comes through our membership in the GW4 consortia that successfully bid for a novel architecture, the £3M EPSRC Tier-2 Computer: GW4 Advanced Architectures project (CO-I: Wingate). A further £4.1M of funding has recently been granted

(https://gtr.ukri.org/projects?ref=EP%2FT022078%2F1, February 2020) for Isambard 2 that will make use of cutting-edge A64fx processors that offer memory bandwidth and floating-point performance closer to GPUs than CPUs. Also, critical, both to research repeatability and developing research capability in mathematical algorithms, is the recent creation and recruitment of a Research Software Engineering (RSE) group to provide support to researchers in the development of effective and efficient codes on the increasing complement of diverse architectures.

3.2.4 Impacts and Industry Infrastructure

One of the major themes of development in the unit was increasing the potential for mathematics impacts, partnerships and industrial engagement. In response we have engaged with the University's 100 FTE+ Innovation, Impact and Business Directorate (IIB) (ILES 4.5-4.8) resulting in thematic teams that provide one-to-one support for the development of partnerships and impact. Academics who desire to take their work toward economic impacts are assigned an IIB specialist and they work together to ensure success, in many situations identifying new potential impacts and outcomes that academics had not known were possible. In short, if research involves engagement with business or policy makers, IIB are there every step of the way to provide skills and support that allow the mathematician to focus on problem solving and on furthering their own research within new contexts, safe in the knowledge that impact will be secured and recorded and that any additional complexities that arise as a consequence of working with non-academic partners will be managed. Since 2018, IIB and the DOR and DOI meet on a regular basis to monitor and identify opportunities to grow our impacts through tailored initiatives aimed to build the discipline's strengths and impact culture, such as the establishment of an 'IIB Essential Series' in 2018 with academic training sessions focused on partnership development and pathways to impact. In addition to supporting the 4 impact case studies submitted to this REF, IIB maintains a pipeline of development that includes 3 additional impact case studies, which will mature over the next REF period.

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

In this section we provide examples of our 1) collaborations, networks and partnerships, 2) our relationships with key research users, 3) contributions to the research base, the economy and society.

4.1 RESEARCH COLLABORATIONS, NETWORKS AND PARTNERSHIPS

4.1.1 Academic multidisciplinary collaborations

Examples of multidisciplinary research and outcomes include:

- *Multidisciplinary research funding and outputs.* In terms of research funding 39% of grants (by number) are held with researchers in other UOAs. The EI CDT, for example, is led by Mathematics, but involves investigators from Computer Science, Geography, Sociology, and the Business School to tackle contemporary environmental challenges using AI and data science. Our multidisciplinary contributions are also reflected in our research output: 18.6% of research papers from UOA10 are jointly co-authored with colleagues outside the UOA (this does not include outputs that are authored by someone in UOA10 and colleagues from another discipline at a different institution).

- *Research students across institutes.* Many of the UOA's PGR students have supervisors in different research groups or involve colleagues outside of the UOA. This type of interaction is facilitated by structured programs such as the EI CDT, but also evolves naturally due to multidisciplinary research projects. For example, PhD projects across groups include exploring delay effects in climate tipping points (Cox-CD/Sieber-DSA), perceptual rivalry in haptic sensors (Rankin-LSM/Ashwin-DSA) and understanding brain dynamics in Alzheimer's disease (Goodfellow-LSM/Jon Brown-Medical School), as part of the Alzheimer's Society Exeter Dementia Doctoral Training Centre.

- *Research initiatives across the University.* Mathematical novelty is a key component of UOE's research strategy. As such, we have many cross-university research initiatives such as data science (organised through the IDSAI) and high-performance computing (cross-university interactions occur through the joint High-Performance Computing seminar series). Further examples of multidisciplinary contributions include a recently established group in network science, involving researchers in Mathematics, Computer Science, Neuroscience, the Business School, and other parts of the University. This has led to sustained activities, for example a "Networks Day" in 2019 led to collaboration with Computer Science in providing speakers for CompleNet 2020 (a leading network science conference due to be held in Exeter in April 2020, but postponed due to the pandemic), and a cross-departmental "Networks Colloquium" in September 2020.

4.1.2 Non-academic collaborations

In addition to our two key non-academic collaborations, the Met Office and the World Health Organization (Section 1.1.2), we also collaborate with numerous industrial partners mentioned throughout; examples including Hirst Magnetic Instruments (Section 4.2.2) and Willis Towers Watson (see Section 1.2.3). Further examples follow:

4.1.3 Regional and national collaboration

As a major research cluster in the South-West of England, we are synergizing by forming networks in the region and the nation.

- *The GW4 Alliance* (https://gw4.ac.uk/) between the Universities of Bristol, Bath, Cardiff, and Exeter, the UOA collaborates on numerous projects (ILES 1.8). Relevant to the unit are collaborations on the EPSRC Tier 2 high-performance computing (HPC) architecture and a shared NERC-funded GW4+ CDT (PhD studentships and research projects) cutting across the earth, environmental and life sciences.
- *Regional collaborations.* Exeter led the EPSRC funded project Research on Changes of Variability and Environmental Risk (ReCoVER) from 2015–2018 (PI: Ashwin). ReCoVER involved a number of experts from the South-West of England (including Bristol and Bath). This built on collaborations initiated in the CliMathNet network (co-founded by Ashwin in 2010) to promote the development of novel mathematical tools and applications for understanding, predicting and managing the effects of environmental change. ReCoVER funded 21 research projects across four funding schemes, while also running a number of complementary meetings and workshops: These projects produced lasting impact beyond their research goals: For example, Shipton, who worked on a pilot study Time-Parallel Methods For Climate Models as a PDRF from Imperial College, recently joined the UOA as a Lecturer and works with Met Office to explore the potential of these ideas for next-generation weather models.

4.1.4 Global collaborations and outreach

Our staff members have international collaborators from around the globe. A sample of our activities include:

- *Conference and workshop organization.* To bring communities together, we regularly hold leading international conferences and other meetings that attract experts from around the world. Examples include (a) Dynamics Days Europe 2015 at the UOE (Ashwin, Bick, Sieber, Rodrigues), (b) London Mathematical Society and Clay Mathematics Institute Research School Conference (Andrade; 2018), (c) Theo Murphy Royal Society international meeting at Chicheley Hall (Wan; 2019), (d) Erwin Schrodinger Institute Thematic Programme `Mixing flows and averaging methods' (Terhesiu; 2016), (e) International Astronomical Union Symposium 335 'Space Weather of the Heliosphere: Processes and Forecasts (Foullon; 2018), (f) Newton Institute programme on Mathematical and Statistical challenges in landscape decision making (Challenor; 2019), (g) International Conference for Technology and Analysis of Seizures (Goodfellow, 2019).

- *Visiting Scholars Program.* The David Rees Distinguished Visiting Fellowship scheme enables mathematicians of international renown to spend an extended period of time at the UOE. Recent Rees fellows include Michael Benedicks (Royal Institute of Technology–KTH, Sweden), Zeev Rudnick (Tel-Aviv University, Israel), and Arek Goetz (San Francisco State, USA).
- *Staff International Collaboration.* A selection of examples includes 1) **Vallis**: NSF-NERC grant with Harvard University (2019), and a separate grant with researchers from the Chinese Academy of Science; 2) **Saïdi**: joint publications on anabelian geometry with Tamagawa in the Research Institute for Mathematical Sciences at Kyoto university (RIMS); 3) **Hillier**: coauthor with academics from Kyoto University, Osaka University, KU Leuven, Instituto de Astrofísica de Canarias, Stanford-Lockheed Institute for Space Research and more; 4) **Wan**: co-author with colleagues from University of Southern California, Georgia Tech, and Tsinghua University; 5) **Economou**: co-author with researchers from Norwegian Meteorological Institute, and Fiocruz public health institute in Rio de Janeiro, Brazil, whose collaboration is imperative for Economou's Impact Case Study.

4.2 RELATIONSHIP WITH KEY RESEARCH USERS

Due to our multidisciplinary collaborations, the research users lie within the Department, in other disciplines and beyond. In the following we give explicit examples how we foster and exploit mathematics impact in academic and industrial contexts, sometimes feeding directly into the local and national economy.

4.2.1 Impactful research informs new mathematics

Mathematics research in collaboration with UOE's Institutes (Section 1.1.1) is not only a rich environment for advancing problems of scientific and societal importance, but also creates brand new veins of research in mathematics itself that would not have been identified without the multidisciplinary motivation. Two examples during the assessment period are:

- *Critical Transitions in non-autonomous systems:* As an outgrowth of multidisciplinary research, we are developing new methods for understanding instabilities in multiscale dynamical systems. An example is our work in critical transitions and applied non-autonomous dynamical systems, which led to a successful EPSRC grant (see Section 3.1 DSA). This work applies mathematical analysis to problems of very wide potential relevance and impact, particularly in both environmental science and healthcare applications.

- *Applications inspire new fundamental results in statistics.* Williamson's applied work with the National Oceanography Centre, which looked into quantifying uncertainty in climate change projections using complex computer models, led to new results in foundational Bayesian statistics. The paper won the 2016 Lindley prize awarded by the International Society of Bayesian Analysis (see also Awards below).

4.2.2 Impact with industry and beyond

We also work directly with users of our mathematical research. This includes researchers that work at the interface of research and commercial spin-off. Commercialisation is facilitated and supported by IIB (Section 1.1.2 and 3.2.4), which directly fed into each of the examples below.

- *Exploitation and Commercialization.* IIB has successfully supported the UOA to commercialize research results and secure intellectual property; we secured 2 patents in the assessment period. For example, IIB worked with members of LSM to put funds in place to develop clinical decision support tools and at-home monitoring devices for people with suspected neurological conditions. This led to the formation of the spin-out company Neuronostics supported by Innovate UK funding (£159,710; Woldman, Terry) and Innovate UK Health & Life Sciences scheme for BioEP Proof of Concept (£344,138;

Neuronostics, Woldman as PI & Scientific Director). Patents relating to the work above include GB1209975.0; PCT/GB2013/051485—Assessing Susceptibility to Epilepsy 06.06.2012 (Terry, Richardson), GB1514740.8; PCT/GB2016/052556—Epilepsy Surgery 19.08.2015 (Terry, Goodfellow).

- *Knowledge Transfer Partnerships (KTP) and impact to the economy.* The UOA is developing innovative mathematics together with its users directly to benefit the economy; this has resulted in 5 KTPs. For example, the EM group on the Penryn Campus in Cornwall contributes to the economy of the Southwest of England: Mueller and Townley have completed two KTPs, KTP9848 with NJW Ltd. in built environment and KTP10698 with Hirst Magnetic Instruments Ltd. on magnet characterisation. McKinley and Das are collaborating in KTP11666 with Chelonia Ltd. on data analytics for marine-life monitoring.
- *Impact of EM on the Wider Economy.* EM also hosts two industry-funded PhD project students. Through the ERDF funded projects Marine-i, Smartline and Tevi, the EM has established substantive engagement with Cornish SMEs. For example, in Tevi, Mueller leads the "electric vehicle charging network challenge", which draws on multi-objective optimisation methods to enable the decarbonisation of transport in Cornwall. In Smartline, Mueller works with Buzz Interactive Ltd. on the development of a self-assessment and assistance application for Meniere's Disease. Townley leads an industrial collaboration with Hirst Magnetics on world-leading technology development in the characterisation of magnetic materials.

4.2.3 Recognition

The innovative efforts of the unit and their impacts have also attracted interest beyond the mathematics community. Recognition of non-academic interest in our research is that our work is featured in the popular press: 93 outputs (9%) of UOA outputs created over the REF period received popular news coverage according to Altmetric by a combined total of 1069 (national and international) news outlets. This includes for example an article on the burden of disease attributable to ambient air pollution published in The Lancet (Shaddick, 2017). These outputs not only cover publications in journals like Nature and The Lancet but also in mathematics journals like the SIAM Journal on Applied Mathematics. Finally, participation in international computer architecture activities, such as GW4's Isambard and Isambard 2 (Section 4.1.3) contributed to promotion of the UK-based ARM processors (e.g. see https://www.nextplatform.com/2017/11/13/arm-benchmarks-show-hpc-ripe-processor-shakeup/).

4.3 CONTRIBUTIONS TO THE RESEARCH BASE, ECONOMY AND SOCIETY

Here we give concrete examples as evidence of our achievements and their recognition.

4.3.1 Contribution to the discipline

Through our national and international communities as outlined above, we directly contribute to mathematics as a discipline. This effort includes hosting researchers and conferences at Exeter as mentioned in Section 1 and in other parts of Section 4. Apart from this we contribute in other ways:

- *Leadership in Academic Societies.* Many staff members participate in academic societies, for example, the London Mathematical Society (LMS), the European Mathematical Society (EMS), the Society for Industrial and Applied Mathematics (SIAM), Institute of Applied Mathematica (IMA), the Royal Astronomical Society, the Royal Meteorological Society. Beyond membership, our faculty includes fellows of academic societies: These include Fellows of the IMA (Gilbert, 2002; Wingate, 2015; Tsaneva, 2020), Royal Astronomical Society (Gilbert, 2001). Further our academics take up leadership roles within the community: For example, Ashwin is a founding member of the SIAM Activity Group of the Mathematics of Planet Earth and Wingate recently served as its secretary. Since 2021 Ashwin serves on the Council of the LMS.

- Vallis published the second edition of his book, Atmospheric and Oceanic Fluid Dynamics, a significant contribution to classical applied mathematics and now regarded as the standard text in the field.
- *Editorial roles.* Our academics have served on editorial boards of a broad range of academic journals, including the SIAM Journal on Applied Dynamical Systems (Sieber), Philosophical Transaction of the Royal Society B (Recker, Wan), Proceedings of the Royal Society B (Recker), Bayesian Analysis (Williamson), Bulletin/Journal/Proceedings of London Mathematical Society (Byott), Annual Reviews of Fluid Mechanics (Vallis).

4.3.2 Contribution to wider society

The academics in our UOA are active beyond the discipline and work to contribute to local and global challenges.

- *Contributing to societal challenges.* As a UOA we contribute to solving some of the crucial challenges facing society. Examples of wide interest in the UOA's contributions is evidenced by coverage in the popular press (see 4.2.3) and include (a) the burden of disease attributable to ambient air pollution, (b) permafrost loss as a function of global warming, and (c) neurodegenerative diseases and epilepsy that affect a large part of the population. Moreover, Data Science is essential to make progress towards some pressing challenges of our times, for example, tracing contacts during a pandemic. Further, 4 of our ATI Fellows contribute, for example, to uncertainty quantification (Challenor, Kelson, Shaddick, Williamson).
- *Promoting mathematics locally.* Members of our UOA promote mathematics locally and specifically to underprivileged groups. In addition, the Department has a close relationship with the Exeter Mathematics School (EMS), a state funded sixth form school jointly sponsored by the UOE and Exeter College, established in 2014. It is one of only 2 specialist mathematics schools in the UK and is open to gifted students from across Cornwall, Devon, Dorset and Somerset. Academics from our UOA are directly involved with many of the student-facing activities at the EMS. For example, we supervise student projects, help with mock admission interviews, and ensure students engage with academics with protected characteristics, which promotes EDI for EMS students during their sixth form experience.
- *Promoting mathematics globally.* We also promote mathematics teaching and research globally in developing countries. Recent activities include a PGR student teaching as part of the new "International Masters in Mathematics" programme in Lahore (Pakistan). Bick is an External Visiting Scholar for the UNESCO-funded Abdus Salam International Centre for Theoretical Physics to develop mathematics teaching and research capacity in Yangon (Myanmar/Burma). As part of this work, our academics provided expertise to help develop the mathematics curriculum at the University of Yangon.

4.3.3 Recognition of Exeter's leadership

Our leadership and contributions to the community, society, and beyond are recognized by the community. Examples of this recognition include:

- *Keynotes and Named Lectures*. Members of the UOA have given more than 65 keynote and named lectures worldwide during this REF period. Examples include specialized meetings in pure and applied mathematics, e.g., a workshop on *p-adic Analytic Geometry and Differential Equations* at the Centre International de Rencontres Mathématiques—CIRM (di Proietto), medium-sized international conferences, e.g., Dynamics Days Europe 2016 (Sieber; 300+ delegates), as well as plenary lectures at large international conferences such as the *SIAM Conference on Computational Science and Engineering* (Wingate; 1000+ delegates). In 2017–2019, Wingate alone gave four plenary lectures at leading international meetings with more than 500 delegates.
- *Prizes, awards, and fellowships.* Examples of recognition within the current REF period includes the Wolfson Merit Award–Royal Society (Stephenson, 2015; Vallis, 2015),

L. F. Richardson Prize–Royal Meteorological Society (Ferro, 2016), Adrian Gill Prize–Royal Meteorological Society (Vallis, 2014), Lindley Prize–The International Society for Bayesian Analysis (Williamson, 2016), Hans Fischer Fellowship (Bick and Tsaneva, 2019).

- *Commissions of trust.* Members of our UOA serve on international committees and in advisory roles for the government and other international institutions. This includes (a) advisory boards for international conference series, e.g., Dynamics Days Europe (Ashwin, Bick), (b) advisory committees of the national research councils and learned societies, e.g., BBSRC Research Committee C Core (Tsaneva), EPSRC Mathematical Science Strategic Advisory Team (SAT) (Challenor), EPSRC e-Infrastructure SAT (Wingate), EPSRC Strategic Advisory Network (Tsaneva from April 2021); Scientific steering committee of ExCALIBUR–SPF (Wingate), LMS Council (Ashwin, beginning in 2021) (c) the UK government, e.g., the UK Space Agency's Science Programme Advisory Committee (Foullon) (d) advisory roles for international agencies, e.g., the advisory team for NOAA's Next Generation Global Prediction System, USA (Thuburn), and (e) prize committees, e.g., the Blavatnik Awards, SIAM, London Mathematical Society (Wingate). Members of the UOA also regularly take part in funding Prioritization Panels of the UKRI-associated funding bodies.