Impact evaluation of the Space Weather Innovation, Measurement, Modelling and Risk (SWIMMR) programme.

Final Report

External Publication Date: July 2026

FNC 030299

60638R Issue: 1

Prepared for: Science and Technology Facilities Council (STFC)

SYSTEMS ● ENGINEERING ● TECHNOLOGY

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Date: July 2026

Classification: Public

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Issue No.:	1	Approved By:	Sam White
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Executive Summary

The Space Weather Innovation, Measurement, Modelling and Risk programme

The Space Weather Innovation, Measurement, Modelling and Risk (SWIMMR) programme was a £20 million UKRI Strategic Priorities Fund initiative delivered between 2020 and 2025 by the Science and Technology Facilities Council (STFC) and Natural Environment Research Council (NERC). Its overarching objective was to strengthen UK resilience to severe space-weather events by enhancing the UK's forecasting capability, accelerating research-to-operations transitions, and supporting the Met Office Space Weather Operations Centre.

Programme rationale

Space weather poses systemic risks to critical infrastructure, including satellites, aviation, and power grids. Severe events can disrupt GNSS navigation, elevate radiation exposure, and induce currents that damage energy networks. The UK's 2025 National Risk Register classifies severe space weather as a top-tier national risk, making investment in forecasting and mitigation essential for national security, economic continuity, and international leadership.

Programme objectives

The SWIMMR programme has the following high-level objectives, each of which includes a number of lower-level objectives:

1. Mitigate the potential radiation hazards of space weather to satellites and aviation operations
2. Mitigate potential space weather effects on communication and global positioning
3. Mitigate the potential risks of space weather to electric power distribution

In addition to this, the project has the following overarching objectives:

4. Establish a world leading UK system for space weather modelling and forecasting
5. Position the UK as a global leader in monitoring and mitigating effects of space weather
6. Develop a framework for supporting the transition of models and data sets from research in the academic community to operational use for space weather forecasting by MOSWOC.
7. Produce an updated space weather impact assessment study, building on the Royal Academy of Engineering report of 2013

Programme delivery and scope

SWIMMR was delivered as a coordinated portfolio of 11 projects across five technical strands (S1–S5 and N1–N5), combining instrumentation, modelling, and research-to-operations pathways. Activities included:

- Developing miniaturised radiation monitors for space and airborne platforms.

- Upgrading UK neutron testing facilities for radiation resilience.
- Creating a cloud-based platform for migrating academic models into Met Office operations.
- Advancing solar wind, ionospheric, and geomagnetically induced current (GIC) models for operational forecasting.

The programme involved over 20 organisations, including UK universities, national laboratories (RAL Space, BGS), industry partners (e.g., BJSS, CACI, D-Orbit), and the Met Office. Delivery was through a mix of open calls and direct procurement, ensuring competitive engagement and targeted capability building.

Purpose of this evaluation

The Science and Technology Facilities Council commissioned Frazer-Nash Consultancy to deliver an independent impact evaluation of the SWIMMR programme's implementation phase. The evaluation examines how SWIMMR has advanced UK space-weather capability, research-to-operations pathways, and stakeholder collaboration, to understand emerging economic and resilience benefits. As most long-term impacts will materialise after full operational integration in 2026, this evaluation provides early, exploratory evidence rather than a definitive assessment of SWIMMR's lifetime value for money. Furthermore, the breadth of the programme's outcomes will be fully realised through the future application and widespread use of these tools, enabling their potential to deliver significant benefits across multiple domains.

Methodology

The evaluation applies a mixed-methods, theory-based approach, aligned with HM Treasury's Green Book, the Magenta Book, and evaluation guidance from the Department for Science, Innovation and Technology (DSIT) and UK Research and Innovation (UKRI). Figure 1 presents a high-level overview of the three-stage methodological approach:

1. Scoping and theory development: define the SWIMMR programme's objectives and delivery context, map expected impact pathways through a Theory of Change (ToC) and derive evaluation questions aligned to strategic goals.
2. Collect evaluation evidence: gather quantitative and qualitative data from project teams, STFC and NERC stakeholders, operational partners, and secondary sources, including bibliometrics and programme records.
3. Analysis and validation: integrate evidence using mixed-methods comprising contribution analysis within a process-tracing framework to assess impact magnitude, attribution, and counterfactual plausibility.

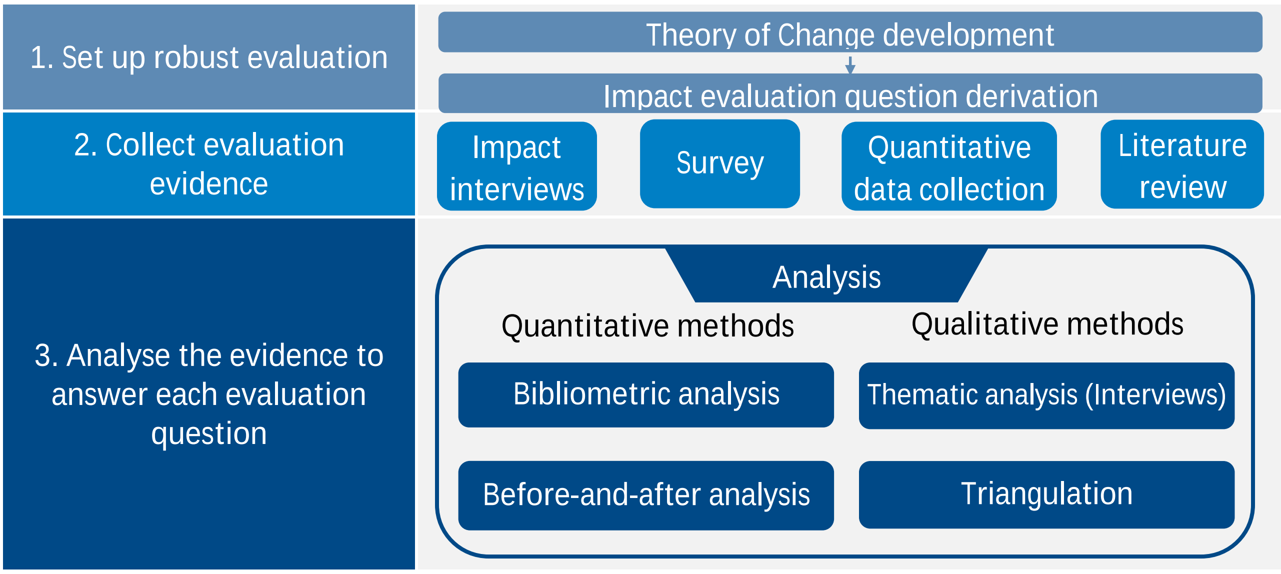

Figure 1. A high-level summary of the evaluation methodology

SWIMMR operated as a system-wide intervention, therefore it was not possible to establish a traditional counterfactual, meaning there were no direct comparators or suitable control groups against which to measure impact. Instead, we identified counterfactuals through contribution analysis and triangulated evidence.

The evaluation questions

The evaluation questions stem from the SWIMMR Theory of Change, which links programme activities to outputs, outcomes, and long-term impacts on UK science, industry, and resilience. Each question tests a key step in this causal chain: whether activities occurred as planned, produced expected changes, and contributed to broader impacts such as scientific advancement, economic growth, collaboration, global reputation, and security and resilience. Together, they provide a structured basis for assessing SWIMMR's achievements, underlying drivers, and attribution. The questions are split into key impact areas (IMP) identified through the Theory of Change to ensure a structured and comprehensive assessment. The impact areas and evaluation questions are:

Scientific Advancement (IMP1)

1. How has SWIMMR contributed to the development of new transferable modelling and hardware deployment capabilities?
2. How has the SWIMMR programme contributed to advancing scientific research and improving understanding of space weather phenomena?
3. To what extent has SWIMMR strengthened the Research-to-Operations (R2O) ecosystem and supported the Research-to-Operations-to-Research (R2O2R) feedback loop?
4. To what extent have SWIMMR's innovations generated spillover effects in other fields and industries?

5. How has the SWIMMR programme facilitated the generation of intellectual property (IP) and patent applications?

Industry growth (IMP2)

6. To what extent has SWIMMR contributed to economic growth and commercial opportunities in the UK space sector?

Collaboration (IMP3)

7. To what extent has SWIMMR improved collaboration—both nationally and internationally and fostered closer alignment between academia, industry, and operational end users?

UK global reputation (IMP4)

8. How has SWIMMR enhanced the United Kingdom's position as a global leader in space weather research and forecasting?

Security and resilience (IMP5)

9. How has SWIMMR contributed to reducing health and safety risks associated with space weather events?

10. How has the SWIMMR programme increased the ability of government and industry to apply adaptation and mitigation measures for space weather hazards?

Key achievements and findings

Scientific advancement

Strong quantitative and qualitative evidence shows SWIMMR advanced transferable modelling, hardware deployment, and space weather research, while supporting the R2O and R2O2R ecosystem. Evidence of spillover effects is moderate and early-stage, and IP generation is limited and qualitative only.

- Operational modelling capability: Five domain-specific models (radiation belts, ionosphere–thermosphere dynamics, solar wind propagation, aviation radiation, and geomagnetically induced currents) advanced from research prototypes to pre-operational readiness at the Met Office. This strengthened the UK's sovereign forecasting capability and reduced reliance on international models. The models have advanced significantly toward operational readiness, as evidenced by substantial improvements in Application Usability Levels (AULs). Four of the five models (projects N2,N3/N5,N4,S4) achieved an AUL of at least 8, corresponding to 'prototype ready for validation' and 'validated by partner organisation', with the aviation radiation model (N2) showing the largest gain (from 1 to 8). They are currently being employed by the Met Office in a pre-operational capacity, marking a critical milestone in the evolution of modelling capability. Full operational integration is scheduled for 2026, at which point the models will have successfully completed all validation and quality assurance processes and will be fully embedded within the Met Office's standard operational systems.

- Measurement infrastructure: A multi-layer observation network, including miniaturised radiation sensors, airborne and balloon instruments, and upgraded neutron monitors, expanded UK empirical data collection and filled gaps in monitoring solar, magnetospheric, and atmospheric phenomena. These datasets are already supporting model verification and operational trials at the Met Office.
- Research-to-operations pathway: SWIMMR effectively reduced model transition times from several years to around six months per model, enabled by the AWS-cloud based platform developed under Project S3. This platform facilitated early integration on Met Office infrastructure, accelerating research-to-operations (R2O) and attracting international interest for collaboration. In addition, Interviewees consistently highlighted SWIMMR's success in closing the gap between academic research and operational forecasting. Early research-to-operations-to-research (R2O2R) feedback loops are also emerging.
- Knowledge creation: UK's space weather research output increased by 15% between 2020 and 2025, highlighting how SWIMMR's targeted investment accelerated scientific knowledge creation. New datasets across space, air, and ground platforms improved understanding of radiation environments, ionospheric variability, and solar-wind behaviour.
- Spillover potential: Upgrades to ChipIr (a proton irradiation accelerator) and NILE (the Neutron Irradiation Laboratory), combined with sensor innovations, created a foundation for applications in aerospace, defence, high-reliability electronics, and telecommunications. Early interest from industry suggests credible potential for commercial adoption.
- Intellectual property: SWIMMR prioritised shared capability over competitive intellectual property generation, facilitating collaboration and operational integration while limiting direct commercial revenue. Future programmes may consider balanced IP frameworks to support both resilience and commercial pathways.

Industry growth

Moderate qualitative evidence suggests SWIMMR has contributed to economic growth and commercial opportunities in the UK space sector, with attribution plausible but contingent on future uptake.

- Employment and skills development: Approximately 40 high-skilled roles were created or safeguarded across academia and the Met Office, spanning researchers, engineers, and operational specialists. These figures represent gross employment effects; while not formally adjusted for deadweight or displacement, survey evidence indicates high additionality, suggesting most roles would not have existed without SWIMMR funding.
- Commercial engagement: ChipIr and NILE now provide unique UK capabilities for assessing electronic and aerospace system resilience under simulated space-weather conditions. Early commercial activity demonstrates demand from companies such as Cisco, Boeing, Honeywell, and STMicroelectronics.

- Follow-on investment and economic momentum: For every £1 invested in SWIMMR, approximately £0.60 of further funding was leveraged through grants, contracts, and collaborations. Outputs also strengthened the Met Office's case for increased core funding, expanding space-weather teams and accelerating operational adoption of academic models.

Collaboration

Strong qualitative evidence, supported by bibliometric trends, indicates SWIMMR has significantly improved national and international collaboration and fostered closer alignment between academia, industry, and operational end users.

- Cross-sector integration: SWIMMR enhanced collaboration across the UK space-weather ecosystem, bringing together universities, research organisations, the Met Office, government bodies, and emerging industry partners. 29 of 42 collaborations across projects were newly formed, with growth in cross-sector links.
- National and international partnerships: 43 domestic and 33 international partnerships were established, including NASA, European Space Agency, Natural Resources Canada, and the University of Nagoya. They represent a mix of newly formed partnerships as well as enhancements to existing collaborations. These networks provide a foundation for joint missions, shared observations, and aligned operational forecasting capabilities.
- Academia–government alignment: Structured consortia pooled complementary expertise, ensuring models, datasets, and forecasting tools met operational standards. Embedding formal research-to-operations cycles will further strengthen performance and maintain alignment with national resilience needs.

UK's global reputation

Good bibliometric and qualitative evidence suggests SWIMMR has enhanced the UK's position as a global leader in space weather research and forecasting.

- International recognition: SWIMMR raised the UK's visibility within the global space-weather community through its research-to-operations advances and integrated programme structure. Stakeholders report recognition of the programme from NASA, National Oceanic and Atmospheric Administration, European Space Agency, and other agencies.
- Sovereign capability: The programme delivered UK-owned models, unique airborne and high-altitude datasets, and Europe's only neutron ground-level testing facility, reducing dependence on overseas resources and enhancing operational independence.
- Emerging leadership potential: Interview sentiment cemented that the UK is competitive with leading nations in specific technical areas, though sustained international leadership depends on operational performance validation.

Security and resilience

Indicative qualitative evidence shows SWIMMR is beginning to reduce health and safety risks from space weather events, with operational impacts emerging. Good qualitative evidence suggests it has improved government and industry capacity for adaptation and mitigation, though full benefits depend on complete operationalisation.

- Awareness of risks: SWIMMR raised awareness of space weather impacts among government and industry, informing strategic discussion and framing space weather as a material risk for critical sectors.
- Policy translation: Outputs inform internal planning and strategy, though widespread embedding into formal policy and practice is limited due to event rarity and unclear standards. Strengthened risk quantification and alignment with decision-making are needed to achieve systemic impact.
- Critical infrastructure resilience: Sensors and models support aviation, satellite systems, Global Navigation Satellite System, and the power grid, improving situational awareness and operational decision-making. Demonstrated utility includes informing responses to the May 2024 storm and engagement with National Electricity System Operator, airlines, and International Civil Aviation Organization.

Conclusions

The evaluation assessed SWIMMR's performance against its seven mission-led objectives to determine the extent to which the programme delivered on its intended outcomes. These objectives span technical capability, operational readiness, and strategic positioning from mitigating radiation hazards and communication risks to establishing a world-leading UK system and strengthening global leadership. The findings show that SWIMMR has met or partially met all objectives, laying the foundations for full operational integration by 2026. Below is a summary of achievement against each objective, supported by evidence.

1. Mitigate radiation hazards to satellites and aviation - *Objective largely met*

   Evidence: Delivered radiation-belt and aviation radiation models (AUL 7–8) and deployed space/airborne sensors (S1), alongside improved radiation test capability (S2). These assets now underpin Met Office pre-operational trials and validation to strengthen the UK's ability to monitor and manage radiation risks for satellites and aviation.

2. Mitigate space-weather effects on communication and GNSS - *Objective partially met*

   Evidence: Developed advanced ionosphere–thermosphere models and GNSS resilience tools under Projects N3 and N5, improving predictions for HF communications and navigation accuracy during geomagnetic disturbances. These models have entered pre-operational testing, with full integration into Met Office high performance computer scheduled for 2026 to formally validate outputs.

3. Mitigate the potential risks of space weather to electric power distribution - *Objective largely met*

Evidence: Produced a UK-specific GIC forecasting system and an updated ground conductivity model under Project N4, enabling improved risk assessment for power grids and pipelines. The capability was validated during the May 2024 geomagnetic storm, demonstrating operational utility and informing engagement with the National Electricity System Operator (NESO). Further steps are required to produce mitigation measures on the back of this evidence. While direct mitigation measures (e.g., reconfiguration protocols, hardware changes) have not yet materialised, SWIMMR is informing strategic planning and priority-setting for monitoring grid infrastructure.

4. Establish a world-leading UK system for space weather modelling and forecasting - *Objective partially met*

   Evidence: Transitioned five domain models covering radiation belts, ionosphere–thermosphere dynamics, solar wind/CME propagation, aviation radiation, and GICs from research prototypes to pre-operational readiness at the Met Office. These advances were supported by a cloud-based Research-to-Operations platform, creating the foundation for full operational integration of all models by late 2026.

5. Position the UK as a global leader in monitoring and mitigating effects of space weather - *Objective partially met*

   Evidence: Delivered sovereign models and datasets, including unique airborne and high-altitude observations, and established Europe's only neutron ground-level testing facility. SWIMMR strengthened international partnerships with ESA, NOAA, NASA, and ICAO, raising the UK's global profile and recognition, especially for its efficiency in research-to-operations advances and practices.

6. Develop a framework for supporting the transition of models and datasets from research to operational use - *Objective met*

   Evidence: Established a cloud-based R2O platform under Project S3, providing a repeatable, containerised pathway for model migration and API-driven data feeds for real-time testing. This innovation reduced transition times from several years to approximately six months per model and initiated early feedback loops (R2O2R) between researchers and Met Office forecasters.

7. Produce an updated space weather impact assessment study - *Objective partially met*

   Evidence: Delivered an updated national impact study under Project S6, synthesising evidence across critical sectors to inform policy and operator decision-making. The study improved the UK's evidence base for space-weather risk management, however, broader policy adoption remains limited due to the absence of formal endorsement by the Space Environment Impacts Expert Group (SEIEG).

Contribution analysis and triangulated evidence indicated that most outcomes, particularly technical and operational gains, would not have occurred without the programme. Longer-term effects relating to economic value, resilience, and global leadership remain prospective, and current estimates may overstate realised benefits. A follow-up evaluation after 2026 is therefore recommended to confirm operational performance and quantify the full impact.

Alignment with SPF objectives

SWIMMR also supports the key objectives set out by the UKRI Strategic Priorities Fund (SPF), an £830 million investment that has delivered 34 multidisciplinary and interdisciplinary research programmes across two waves. Specifically, SWIMMR contributes to:

- Increasing high-quality multidisciplinary and interdisciplinary research and innovation: by promoting collaboration and integrating expertise from space physics, engineering, data science, and operational forecasting, SWIMMR created a coordinated national capability that bridges academic research and real-world applications.
- Ensuring UKRI investment links up effectively with government research and innovation priorities: the programme directly addressed priorities identified in the UK National Risk Register and the National Severe Space Weather Preparedness Strategy, supporting national security, economic resilience, and critical infrastructure protection.
- Responding to strategic priorities and opportunities: SWIMMR targeted a top-tier national risk identified in the UK National Risk Register: severe space weather. It delivered new models, instrumentation and research-to-operations pathways, strengthening the UK’s position as a global leader in space-weather forecasting and mitigation.

Lessons learned

The evaluation highlights key insights for future research-to-operations programmes:

- Operational alignment: Early, detailed requirements capture is essential; ambiguity on operational readiness caused later rework for the project team. Future programmes should include Phase 0 feasibility and structured engagement.
- IT and integration: Parallel platform development led to late-stage fixes; early technical alignment, streamlined licensing, and clear interface standards are critical.
- Collaboration: Strong within projects but limited across programme; structured cross-strand reviews and shared artefacts would improve integration.
- Pandemic response: COVID-19 disrupted delivery but accelerated digital collaboration; virtual tools should be retained alongside in-person integration for complex testing.
- Funding continuity: Lack of assured follow-on funding risks capability loss; multi-year planning and bridge mechanisms are needed.
- End-user culture: Embedding operational thinking from the outset and maintaining continuous engagement ensures outputs are relevant and usable.

Next steps

This end-of-programme assessment provides early evidence of impact, but most benefits, particularly operational integration, commercial uptake, and resilience outcomes, will materialise post-2026. A follow-up evaluation in 2027–2028 is recommended to measure realised impacts, validate forecasting performance, and quantify economic and resilience benefits. Future monitoring and evaluation activity should track:

- Full operational deployment of SWIMMR models at the Met Office.
- Industry adoption of testing facilities and sensor technologies.
- Spillover effects into aerospace, electronics, and critical infrastructure sectors.
- Long-term knowledge creation and international collaboration outcomes.

Future of SWIMMR capability

As SWIMMR concludes, sustaining its achievements requires deliberate action to prevent capability loss and maximise long-term impact. The programme has delivered a strong foundation for UK space-weather resilience, but full benefits depend on continued investment, operational integration, and strategic partnerships. The following priorities outline how the UK can secure and extend SWIMMR's gains, ensuring that technical advances translate into enduring national capability and international leadership.

- Maintain funding continuity for model integration, sensor networks, and specialist roles to prevent capability loss.
- Institutionalise Research-to-Operations-to-Research (R2O2R) cycles, embedding feedback loops for iterative improvement.
- Expand industry engagement through structured technology-transfer pathways and clear commercial use cases.
- Leverage international partnerships for joint missions and shared observation networks, positioning the UK as a leader in operational space-weather forecasting.
- Develop a sustainability plan for infrastructure such as ChipIr/NILE and airborne monitoring systems to ensure enduring national resilience

Contents

1 Introduction

The Science and Technology Facilities Council (STFC) commissioned Frazer-Nash Consultancy to undertake an independent impact evaluation of the Space Weather Innovation, Measurement, Modelling and Risk (SWIMMR) programme. The evaluation assesses evidence of scientific, operational, and economic impacts delivered during the programme's implementation phase, contributing to an early understanding of its long-term value. As most benefits will materialise after full operational integration, the study is exploratory in nature, examining what impacts have emerged, their scale, and the mechanisms through which they occurred.

This report presents the findings of the evaluation. It applies a theory-based, mixed-methods approach to analyse outputs and outcomes, focusing on the extent to which observed changes are attributable to SWIMMR and represent genuine additionality within the UK's space-weather ecosystem.

1.1 Scope

The SWIMMR programme ran from 2020 to 2025, funded through Wave 2 of the UKRI Strategic Priorities Fund. This end-of-programme impact evaluation builds on earlier assessment activities, including a mid-term process review and baseline monitoring. The evaluation was conducted between January and December 2025, with fieldwork completed July to September.

As SWIMMR formally concluded in Q3 2025, many benefits, particularly those linked to operational integration, commercial uptake, and policy influence, are expected to emerge over a longer timeframe, in some cases extending several years beyond programme closure. The scope of this evaluation is to:

- Assess whether SWIMMR met its objectives and evaluate its impact to date on government, industry, and research.
- Help to provide a foundation for future work examining the long-term value of STFC and UKRI investments in space.

1.2 Summary of the methodological approach

The methodology draws on Green and Magenta Book guidance and the evaluation strategies of the Department for Science, Innovation and Technology (DSIT) and UK Research and Innovation (UKRI) to provide a coherent approach to the evaluation of a diverse set of impacts.[1] Figure 2 presents the methodological approach at a high level.

[1] Green Book (2022); Magenta Book (2011); DSIT evaluation strategy (2025); UKRI evaluation strategy (2024)

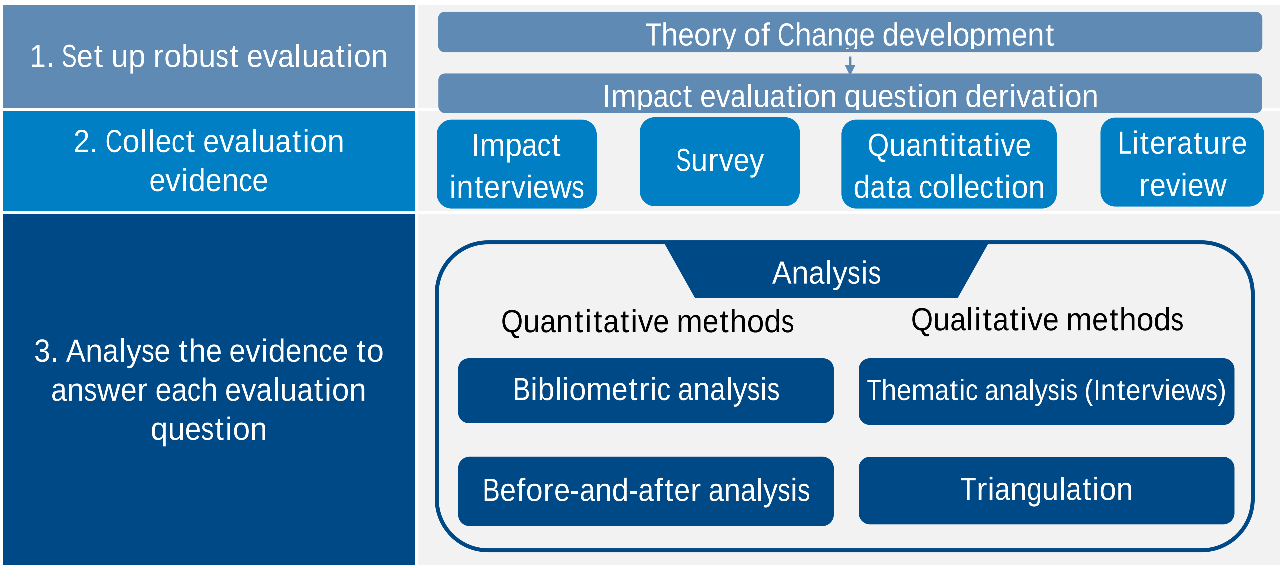

Figure 2. A high-level summary of the evaluation methodology

The evaluation methodology is detailed in full in the technical annexes. The approach was delivered in three stages:

1. Scoping and theory development: Establish an understanding of SWIMMR's objectives and delivery context, map expected impact pathways through a Theory of Change and define evaluation questions to guide analysis.
2. Evidence collection: Gather quantitative and qualitative data from project teams, STFC and NERC stakeholders, operational partners, and secondary sources, including bibliometrics and programme records.
3. Analysis and validation: Synthesise evidence using mixed-methods and contribution analysis within a process-tracing framework to assess impact magnitude, attribution, and counterfactual plausibility.

This evaluation draws on established UKRI guidance and best practice from science and research impact evaluations. The approach combines quantitative and qualitative methods to capture outputs, outcomes, and emerging impacts across SWIMMR's objectives. A Theory of Change underpins the design, mapping causal pathways from programme activities to intended impacts in resilience, scientific advancement, and economic growth. Evidence was triangulated from multiple sources, programme records, bibliometrics, ResearchFish data, surveys, interviews, and case studies, to strengthen attribution and assess additionality. Table 1 collates the possible approaches and highlights their inclusion in this evaluation.

Table 1. The evaluation methods available to calculate the construction phase's economic impacts.

Method	Summary of approach	Magenta Book compliant?	Used in this evaluation?
Pre/post trend analysis	Compare programme outcomes against baseline indicators before and after SWIMMR delivery	Yes, when supported by robust baselines	✓
Bibliometric benchmarking	Use global space-weather research community as an indicative comparator for publications and collaboration trends	Yes, with clear caveats on attribution	✓
Qualitative contribution analysis	Triangulate interviews, surveys, and case studies to assess causal pathways and additionality	Yes	✓
Economic leverage analysis	Examine follow-on funding and commercial engagement linked to SWIMMR outputs	Yes, with transparent assumptions	✓
Quasi-experimental evaluation	Compare funded and unfunded groups using a formal control group	Yes	✗

- Pre/post trend analysis: This method establishes an evidence base for changes in capability, collaboration, and research outputs by comparing conditions before and after SWIMMR. It uses baseline indicators to track progress and provides a structured foundation for attribution, helping to distinguish programme-driven outcomes from broader sectoral trends.
- Bibliometric benchmarking: Bibliometric analysis situates SWIMMR's research outputs within the global space-weather research landscape. While not a formal control group, this comparator offers valuable context for assessing additionality by examining publication volumes, citation patterns, and collaboration networks relative to international norms.
- Qualitative contribution analysis: Interviews, surveys, and case studies are integrated to explain causal mechanisms and validate quantitative findings. This approach is critical for capturing operational impacts, cultural shifts, and spillover effects that cannot be observed through secondary datasets alone.
- Economic leverage analysis: This examines follow-on funding, commercial engagement, and early industry uptake linked to SWIMMR outputs. Transparent assumptions and triangulation

ensure credible attribution, highlighting the programme's role in stimulating economic momentum and strategic investment

- Quasi-experimental methods, which compare outcomes to a matched counterfactual, were not feasible due to SWIMMR's system-wide design and absence of unaffected organisations. Because such a high percentage of eligible organisations received SWIMMR funding and self-organised into consortia aligned with programme objectives, there were no natural counterfactual groups. Traditional comparative methods, such as funded versus non-funded applicants, were therefore not applicable. Instead, contribution analysis and triangulation were used to strengthen causal inference.

Triangulation was used to integrate the evidence from these methods and strengthen attribution. Evidence was drawn from programme records, bibliometrics, ResearchFish data, surveys, interviews, and case studies. Quantitative indicators, such as pre/post trend analysis and bibliometric benchmarking, were combined with qualitative insights from stakeholder interviews and thematic case studies to explain causal mechanisms. This mixed-methods design compensates for the absence of a formal control group by cross-verifying results across independent sources. This also supports contribution analysis, enabling evaluators to assess whether observed changes are plausibly linked to SWIMMR rather than external factors. By applying this approach, the evaluation provides credible, transparent evidence of SWIMMR's role in advancing UK space-weather capability and fostering collaboration, while acknowledging limitations in experimental inference.

1.2.1 Data sources

The evaluation findings are based on the outcome of the following data collection and analysis activities:

- Data analysis:
  - Analysis of the programme datasets (grants and participants, project completion forms, baseline data).
  - ResearchFish data supported impact analysis by identifying trends in IP, research publications, collaboration and further funding. Where possible, ResearchFish data were used to triangulate findings from stakeholder interviews and surveys, and to validate claims of additionality and spillover.
  - A bibliometric analysis was conducted using SciVal to explore patterns in scientific publishing and citation activity, map collaborative networks through co-authorship links, and trace connections between research outputs and innovation by identifying publications cited in patent filings.
- 17 interviews: Semi-structured interviews were conducted with a purposive sample of stakeholders, including principal investigators (PIs) or project leads, Met Office operational staff, industry partners, and government users. These interviews explored themes such as programme delivery effectiveness, collaboration, and perceived impacts on operational capability and resilience. Qualitative evidence was used to provide depth and context, helping

to explain how and why the observed outcomes occurred. Refer to Annex A.1.1 Interviews for the list of interviewed stakeholders.

- Stakeholder survey: Structured online surveys targeted academic participants, industry partners, and operational end users to quantify adoption rates, satisfaction, and perceived benefits. The survey achieved 21 responses: 13 project participants, 2 Met Office staff, and 6 members of the management or strategic advisory board. This represents 44% of the total eligible population engaged in SWIMMR delivery (35 project staff, 13 programme management or advisory group members; n=48). At this achieved sample size, the survey results carry a margin of error of approximately ±17% at the 95% confidence level (finite population correction applied), which is acceptable for indicative evidence in an impact evaluation but should not be interpreted as statistically definitive.[2]

  Importantly, responses included the Principal Investigator (PI) for 9 of the 11 SWIMMR projects, providing strong coverage of project-level delivery. This concentration of PI responses increases confidence that survey findings reflect the scope of technical, operational, and scientific outcomes achieved. To mitigate limitations associated with the sample size and response distribution, survey data were triangulated with interviews, programme documentation, and bibliometric analysis, improving attribution and reducing potential response bias. See Annex A.12 for the list of surveyed project groups or members.

- 4 case studies: Four case studies were developed to provide insight into SWIMMR's impacts beyond headline metrics. Each case study examined a distinct dimension of the programme:

  1. Radiation Belt Modelling: Delivered the UK's first multi-orbit radiation risk forecasting capability, reducing reliance on international models and informing satellite resilience.
  2. Research-to-Operations Transition: Assessed the cloud-based integration platform that accelerated model migration to Met Office systems and catalysed cultural change toward operational thinking.
  3. Aviation Radiation Risk: Evaluated the MAIRE+ model and airborne sensors, highlighting improvements in flight safety and engagement with International Civil Aviation Organization (ICAO) standards.
  4. Power Grid Resilience: Explored geomagnetically induced current forecasting tools and their role in informing NESO's strategic planning.

  These case studies combined technical evidence, stakeholder interviews, and operational context to illustrate how SWIMMR outputs translate into real-world capability and resilience benefits.

[2] Using the standard margin of error formula for proportions with finite population correction. This reflects a conservative assumption (p=0.5) and provides an appropriate indication of the precision of survey estimates for an impact evaluation of this scale.

1.2.2 Limitations

While the evaluation employed a robust mixed-methods approach, some limitations should be acknowledged:

- Attribution complexity: Given the multi-stakeholder nature of SWIMMR and concurrent initiatives in the space weather domain, isolating the programme's unique contribution to observed outcomes was challenging. Attribution relied on stakeholder testimony rather than experimental controls.[3]
- Baseline gas: Baseline data on collaborations and partnerships were incomplete or unavailable, requiring retrospective reconstruction through interviews and surveys. This may introduce recall bias and limit precision in before-and-after comparisons.
- Survey limitations: Response rates varied across stakeholder groups, potentially introducing non-response bias. While efforts were made to triangulate findings, some perspectives may be underrepresented, such as the viewpoints of government bodies and industry.

These limitations were mitigated where possible through triangulation, transparent documentation of assumptions, and the use of theory-based evaluation techniques.

1.3 Structure of this report

This report presents the impact evaluation of SWIMMR. The report is structured as follows:

- Section 1 - Introduction: The remainder of the introduction presents an overview of the Theory of Change, evaluation framework, and addresses programme additionality.
- Section 2 – The SWIMMR programme: Programme context, objectives and scope. SWIMMR projects, activities, and participants. Additionality of the programme.
- Section 3 – Main findings: Key findings on programme outcomes and impacts, including benefits to government, industry, and research communities.
- Section 4 – Conclusion and lessons learned: Conclusions and lessons learned for future programme design and evaluation.
- Appendix: List of stakeholders consulted.

1.4 The Theory of Change

The Theory of Change provides a structured framework for understanding how the SWIMMR programme is expected to generate outcomes and impacts across the UK space weather ecosystem. It is used in impact evaluation to articulate the programme's underlying hypotheses before evidence is collected. The Theory of Change maps how SWIMMR's inputs, activities and immediate outputs are expected to lead to short- and medium-term outcomes, and ultimately to long-term impacts that align with national and UKRI strategic objectives. It also shows how the

[3] Experimental attribution was not feasible due to the complexity of the intervention. SWIMMR operates within a multi-stakeholder environment alongside concurrent space-weather initiatives, making it impractical to isolate its unique contribution through controlled experiments. Attribution therefore relied on triangulated evidence and stakeholder testimony rather than experimental controls.

various components of SWIMMR, ranging from scientific skill development to the creation of new space weather assets, interact to generate wider benefits for society, industry and government. Figure 3 presents the Theory of Change and logical framework.

The Theory of Change was developed based on the existing logic model outlined in the *Baseline Economic Analysis of Space Weather Research* report. This reflects the complex, multi-component nature of SWIMMR, which spans research, instrumentation, modelling, operational transition, skills and collaboration. It is intentionally broad to capture all plausible pathways to impact, including those that may be uncertain or only partially evidenced at this stage. This means that the evaluation explores a comprehensive evidence base and avoids overlooking any materialised effect.

1.4.1 Inputs, activities and outputs

SWIMMR's inputs, activities and outputs represent the elements under the direct control of STFC and NERC delivery partners. The key inputs include £20m in programme funding, specialist scientific and technical expertise, existing UK space weather assets such as the ChipIr facility, and governance structures for coordinated programme delivery.

Activities centre on project definition, instrumentation development, creation and validation of new space weather models, scientific collaboration across academia, government and industry, and dissemination efforts such as workshops and symposia.

These activities lead to a suite of direct outputs, including:

- Skills and knowledge: Improved understanding of research-to-operations processes, experience of model development, deployment and maintenance, and enhanced hardware and software capabilities.
- New transferable capabilities: Including upgraded experimental facilities and more robust IT infrastructure.
- New space weather assets: Such as advanced instruments, improved operational models, and new data products delivered to MOSWOC.
- Datasets and new tools: Enabling improved model validation, impact assessment and scientific analysis.
- Interdisciplinary collaboration outputs: Such as new partnerships, strengthened relationships, and more integrated working practices between academia, government and industry.

These outputs form the foundation for subsequent outcomes.

1.4.2 Outcomes

Outcomes are follow-on effects influenced by SWIMMR but dependent on external stakeholder actions and wider system conditions. SWIMMR is expected to contribute to:

- Transferable knowledge and process improvements (OTC 1), including improved modelling, enhanced hardware deployment, strengthened understanding of solar–terrestrial processes, and the generation of spillovers across sectors reliant on space weather information.
- Space weather knowledge utilisation (OTC 2), with new IP, increased ability for industry and government to apply SWIMMR-generated tools, and improved evidence supporting policy, risk mitigation and regulatory action.
- Upskilling (OTC 3), through the development of specialist scientific, technical and operational skills across the research base, suppliers and MOSWOC staff.
- Strengthened UK space weather capability (OTC 4), including higher-fidelity monitoring, improved modelling accuracy, more robust operational readiness, and enhanced experimental and observational data.
- Collaboration outcomes (OTC 5), such as strengthened coordination between academia, industry and government, improved knowledge exchange, and increased engagement with international partners.

These outcomes are expected to accumulate across the lifetime of the programme, setting the foundation for long-term impacts.

1.4.3 Impacts

Impacts are long-term changes to which SWIMMR contributes alongside other programmes and actors. SWIMMR is expected to support:

- Scientific advancement (IMP 1) through increased capability in space weather research, strengthened research-to-operations pathways, and enhanced ability to generate and deploy advanced models and tools.
- Industry growth (IMP 2) including increased employment, greater GVA contributions, and expanded commercial opportunities derived from SWIMMR-enabled modelling, instrumentation and data services.
- Collaboration (IMP 3) with deeper and more sustained partnerships between academia, industry and government, greater coordination between operational agencies, and improved alignment with international networks.
- UK global reputation (IMP 4) through the UK's strengthened presence in international space weather research, enhanced leadership in standards-setting and service provision, and recognition of the UK as a capable and reliable contributor to the global space weather community.
- Resilience and security (IMP 5) with reduced risks to health, safety and critical infrastructure, improved forecasting accuracy, better preparedness for severe space weather events, and strengthened national risk frameworks.

These impacts align directly with the UK National Space Strategy and UKRI's strategic objectives, particularly those relating to scientific excellence, world-class places, commercial growth and national resilience.

1.4.4 Theory of Change

Inputs

Funding (INP 1)
- £20 million SPF funding (INP 1.1)

Existing human resource (INP 2)
- Researchers and professionals (INP 2.1)
- NERC & STFC strategic programme delivery teams (INP 2.2)

Existing knowledge and skills (INP 3)
- Existing knowledge in space weather technologies (INP 3.1)
- RAEng space weather impact report 2013 (INP 3.2)

Governance (INP 4)
- Programme board (INP 4.1)
- Strategic advisory group (INP 4.2)
- Expert peer review panel (INP 4.3)

Organisations (INP 5)
- Universities (INP 5.1)
- UK research institutes (INP 5.2)
- Industry partners (INP 5.3)
- Met Office (INP 5.4)

Facilities (INP 6)
- ISIS ChipIR (INP 6.1)

Activities

Plan and design (ACT 1)
- Define all project requirements (ACT 1.1)
- Plan implementation and research activities (ACT 1.2)

Instrument development (ACT 2)
- Develop technical solutions and scientific instruments (ACT 2.1)
- Deploy instruments to measure space weather activity (ACT 2.2)

Collaboration (ACT 3)
- Collaboration between research institutes, academia and industry (ACT 3.1)

Modelling and simulation (ACT 4)
- Creation of new space weather models (ACT 4.1)
- Refinement of research models to enable operational application (ACT 4.2)

Information dissemination (ACT 5)
- Presentations and symposiums (ACT 5.1)

Outputs

Skills and knowledge (OTP 1)
- New understanding of research to operations process (OPT 1.1)
- Experience building, testing, hosting and maintaining models (OPT 1.2)
- Experience designing, manufacturing, iterating and deploying hardware (OPT 1.3)

New transferable capabilities (OTP 2)
- Improved experimental facilities (OTP 2.1)
- More robust IT infrastructure (OPT 2.2)

New space weather assets (OTP 3)
- Advanced instruments to monitor space weather phenomena (OTP 3.1)
- Operational models delivered to MOSWOC (OPT 3.2)

Datasets and reports (OTP 4)
- Newly formed empirical space weather datasets (OTP 4.1)
- New model-based outputs (OPT 4.2)
- Updated space weather impact report (OPT 4.3)

Interdisciplinary and intersectoral collaboration (OTP 5)
- Improved alignment of objectives across government and academia (OTP 5.1)
- New relationships between academic partners, research institutes and industry (OTP 5.2)
- Strengthened existing relationships (OPT 5.3)

Outcomes

Transferable knowledge and process improvements (OTC 1)
- New transferable modelling capabilities (OTC 1.1)
- New transferable hardware deployment capabilities (OTC 1.2)
- Refined understanding of model and hardware limitations, including technological, legal, and procurement barriers (OTC 1.3)
- Development of specialist space weather processes and tools (OTC 1.4)
- Spillovers (OTC 1.5)

Space weather knowledge utilisation (OTC 2)
- IP generation and patent application (OTC 2.1)
- Increased ability for industry to apply adaptation and mitigation measures (OTC 2.2)
- Increased ability for government to prioritise and apply policies promoting adaptation, mitigation and security measures (OTC 2.3)

Upskilling (OTC 3)
- Specialist skills development (OTC 3.1)
- Increased productivity (OTC 3.2)

Strengthened UK space weather capability (OTC 4)
- Improved space weather empirical data (OTC 4.1)
- Improvements to the UK's monitoring and forecast capabilities (OTC 4.2)
- Greater utilisation of experimental facilities (OTC 4.3)

Collaboration (OTC 5)
- Progress towards an effective research to operations (R2O) and research to operations to research (R2O2R) ecosystem (OTC 5.1)
- Closer alignment between academia, industry and end users (OTC 5.2)
- Strengthened international relationships (OTC 5.3)

Impacts

Scientific advancement (IMP 1)
- Advancement of scientific research in space weather (IMP 1.1)
- Advancement of research to operations process (IMP 1.2)
- Spillovers of research-operation process into other research sectors (IMP 1.3)
- Commercialisation of new technologies and advanced tools (IMP 1.4)

Industry growth (IMP 2)
- Increased employment (IMP 2.1)
- Increased GVA (IMP 2.2)
- Increased wages (IMP 2.3)

Collaboration (IMP 3)
- Strenghthened academia, industry and end users relationships (IMP 3.1)
- Strengthened international relationships (IMP 3.2)

UK global reputation (IMP 4)
- UK's position as a leader in space weather research (IMP 4.1)
- Strong international interest and persistent collaboration (IMP 4.2)

Resilience and security (IMP 5)
- Reduced health and safety risks (IMP 5.1)
- Improved forecasting and monitoring leading to enhanced resilience to space weather events (IMP 5.2)
- Improved space weather mitigation policy (IMP 5.3)

Strategic Objectives

Contribution to the National Space Strategy (SO 1)
- Unlocking growth in the UK space sector (SO 1.1)
- Collaborating internationally (SO 1.2)
- Growing the UK as a science and technology superpower (SO 1.3)
- Developing resilient space capabilities and services (SO 1.4)

Contribution to UKRI Strategic Objectives (SO 2)
- World-class people and careers (SO 2.1)
- World-class places (SO 2.2)
- World-class impacts (SO 2.3)
- A world-class organisation (SO 2.4)

Figure 3. Theory of Change

1.5 Impact evaluation questions

The evaluation questions are structured directly around the causal logic articulated in the SWIMMR Theory of Change. The ToC outlines how programme activities, ranging from targeted scientific research to the development of operational capabilities, are expected to generate outputs, intermediate outcomes, and ultimately long-term impacts across the UK's scientific, industrial, and national resilience landscape.

Each question in Table 2 therefore tests a specific link in this logic chain: Whether the activities took place as planned, whether they led to the expected changes, and whether these changes contributed to broader impacts such as scientific advancement, economic growth, improved collaboration, enhanced global positioning, and strengthened national security and resilience. Together, these questions provide a structured framework for assessing what SWIMMR delivered, how and why those results were achieved, and the extent to which they can be attributed to the programme rather than external factors.

Table 2. Evaluation questions aligned to impact areas

Impact area	Evaluation question
Scientific advancement (IMP1)	Q1. How has SWIMMR contributed to the development of new transferable modelling and hardware deployment capabilities? Q2. How has the SWIMMR programme contributed to advancing scientific research and improving understanding of space weather phenomena? Q3. To what extent has SWIMMR strengthened the Research-to-Operations (R2O) ecosystem and supported the Research-to-Operations-to-Research (R2O2R) feedback loop? Q4. To what extent have SWIMMR's innovations generated spillover effects in other fields and industries?

Impact area	Evaluation question
	Q5. How has the SWIMMR programme facilitated the generation of intellectual property (IP) and patent applications?
Industry growth (IMP2)	Q6. To what extent has SWIMMR contributed to economic growth and commercial opportunities in the UK space sector?
Collaboration (IMP3)	Q7. To what extent has SWIMMR improved collaboration—both nationally and internationally and fostered closer alignment between academia, industry, and operational end users?

Impact area	Evaluation question
UK global reputation (IMP4)	Q8. How has SWIMMR enhanced the United Kingdom's position as a global leader in space weather research and forecasting?
Security and resilience (IMP5)	Q9. How has SWIMMR contributed to reducing health and safety risks associated with space weather events? Q10. How has the SWIMMR programme increased the ability of government and industry to apply adaptation and mitigation measures for space weather hazards?

1.6 Evaluation framework

Table 3 summarises the high-level framework used to assess SWIMMR's impacts across the five domain areas. For each impact area, we set out the corresponding evaluation questions, where feasible, the comparison group used to assess additionality, and the primary methods applied. Together, these components provide a structured basis for examining how SWIMMR contributed to advancements in scientific capability, industry growth, collaboration, the UK's global research standing, and national security and resilience. The framework combines quantitative trend analysis with qualitative contribution evidence to build a robust, triangulated assessment of programme outcomes.

Table 3. Counterfactual comparison groups and evaluation methods by impact area

Impact Area	Evaluation question	Comparison group	Primary method(s)
Scientific Advancement	Development of modelling, hardware, specialist tools, scientific research, R2O/R2O2R, spillovers	Space Weather research from the wider community. Baseline scientific, technical, and operational capabilities prior to SWIMMR	Contribution analysis; pre/post trends; case studies; bibliometrics
Industry Growth	Employment, GVA, wage change	Baseline employment and investment trends in UK space sector	Contribution analysis; trend comparison; stakeholder evidence
Collaboration	National and international collaboration patterns	Collaboration structures and levels pre-SWIMMR	Social network analysis; contribution analysis

Impact Area	Evaluation question	Comparison group	Primary method(s)
UK Global Reputation	International standing and research leadership	UK's pre-SWIMMR international citation, publication, and collaboration profile	Bibliometric trend analysis; contribution analysis
Security & Resilience	Risk reduction, mitigation capability	Operational protocols, resilience measures, and hazard response capacity prior to SWIMMR	Contribution analysis; pre/post comparisons; case studies

Chapter 3 presents an analysis of each evaluation question. The next chapter examines impacts on scientific and operational capability, including modelling, measurement infrastructure, and research-to-operations pathways. Subsequent chapters assess wider outcomes across the remaining impact areas: industry growth, collaboration, UK global reputation, and security and resilience. Each section aligns with the evaluation framework, linking questions to evidence drawn from pre/post analysis, bibliometric benchmarking, surveys, interviews, and case studies. Where relevant, findings are connected to Section 1.7 on programme additionality, so that observed outcomes are interpreted in the context of SWIMMR's enabling role and the contribution of its funding.

2 The SWIMMR programme

2.1 The rationale for SWIMMR

Space weather, the interaction of solar activity with Earth's near-space environment, poses pervasive, systemic risks to critical infrastructure. Disturbances such as coronal mass ejections and high-speed solar wind streams can disrupt satellites and Global Navigation Satellite System (GNSS) performance, elevate radiation exposure for aviation, and drive geomagnetically induced currents (GICs) that stress power grids, rail, and pipelines. Reflecting these realities, the UK's 2025 National Risk Register classifies severe space weather as a top-tier national risk, making sustained investment in forecasting, warning, and mitigation a matter of national security and economic continuity.[4]

Across UK policy, including the National Space Strategy (2021)[5] and the National Severe Space Weather Preparedness Strategy (2021)[6], there is a consistent call for more capable forecasting, robust impact modelling, and seamless operational integration.

Before SWIMMR, the UK had already established a credible operational and research foundation:

- Operational hub (MOSWOC): The Met Office Space Weather Operations Centre provides the standing national forecast and advisory service and represents the UK within international networks.
- Research infrastructures for resilience: The British Geological Survey (BGS) magnetometer arrays and conductivity models underpin national GIC assessment. These provide ionosphere and thermosphere data, historically vital for research and, increasingly, for operations.[7] [8] [9]
- Policy-defined operational needs: The Royal Academy of Engineering's 2013 report on extreme space weather and the National Severe Space Weather Preparedness Strategy (2021) identified concrete operational requirements in aviation radiation, GNSS, and GIC forecasting, framing SWIMMR's problem statement and success criteria.[10]

These priorities align with global warning systems:

- ESA Space Safety Programme (including Space Weather): E-services and the Space Weather Service Network, and developing new assets, such as Vigil, for side-on Coronal Mass Ejections (CME) monitoring.[11]
- The National Oceanic and Atmospheric Administration's Space Weather Prediction Center (NOAA SWPC): Based in the United States, is the world's largest operational space-weather

[4] https://www.gov.uk/government/publications/national-risk-register-2025
[5] https://www.gov.uk/government/publications/national-space-strategy
[6] https://www.gov.uk/government/publications/space-weather-preparedness-strategy
[7] Models include SAMNET (Lancaster University), and UK participation in SuperDARN and EISCAT.
[8] https://www.bgs.ac.uk/geology-projects/geomagnetism/
[9] https://www.lancaster.ac.uk/physics/research/space-planetary-physics/research/samnet/
[10] https://raeng.org.uk/publications/reports/space-weather
[11] https://www.esa.int/Space_Safety https://www.esa.int/Space_Safety/Vigil

centre and serves as an International Civil Aviation Organization (ICAO) global advisory provider. It operates coronagraph and in-situ measurement assets, such as the Compact Coronagraph (CCOR) imager aboard the Geostationary Operational Environmental Satellite-U (GOES-U) launched in June 2024, and is preparing the Space Weather Follow-On Lagrange Point 1 (SWFO-L1) mission, a joint NOAA/NASA initiative, to continue solar wind and interplanetary magnetic field observations.[12] [13] [14]

- The NASA Heliophysics Division: Runs the Living With a Star (LWS) programme, focusing on understanding the Sun–Earth system and its impacts on space weather. Alongside this, NASA operates the Community Coordinated Modelling Center (CCMC), which provides a global testbed for model development, validation, and research-to-operations (R2O) transition. These resources are widely used by the international community to advance forecasting models and operational readiness.[15]
- The International Civil Aviation Organization (ICAO): Since 2019, has operated a global advisory framework through three designated centres, NOAA, the PECASUS consortium in Europe, and the ACFJ consortium (Australia, Canada, France, and Japan). These centres issue standardised space-weather advisories for aviation, creating a consistent international demand for operational forecasting models and radiation risk products.[16]

However, despite these assets and the strength of international partnerships, several critical capability gaps persisted. The UK did not have integrated radiation monitoring for aviation, sufficiently advanced modelling of Global Navigation Satellite System resilience, or operational forecasting for geomagnetically induced currents. Pathways for transitioning research into operations were fragmented, and opportunities for systematic model validation using real-time data were limited. Collectively, these gaps constrained the UK’s ability to meet policy-driven requirements and align with emerging international standards, highlighting the need for targeted investment.

2.2 Programme objectives

Launched in 2020, the SWIMMR programme was a £20 million, five-year initiative delivered under Wave 2 of the UK Research and Innovation (UKRI) Strategic Priorities Fund (SPF). The programme concluded in the summer of 2025.

The SWIMMR programme was conceived as a national, end-to-end enabler to strengthen the UK’s resilience to space-weather hazards. At its core, SWIMMR set out to close three structural gaps that limit operational capability:

- Predictive Skill: Advancing coupled Sun-to-Earth models and sector-specific impact modelling to improve forecasting accuracy.

[12] https://www.swpc.noaa.gov/
[13] https://www.nesdis.noaa.gov/news/goes-u
[14] https://www.noaa.gov/space-weather-follow-on.
[15] https://lws.gsfc.nasa.gov/ https://ccmc.gsfc.nasa.gov/
[16] https://www.icao.int/Newsroom/Pages/ICAO-announces-designation-of-global-space-weather-centres.aspx.

- Trusted Data: Expanding and validating spaceborne, airborne, and ground-based sensing networks for reliable, continuous data streams.
- Research-to-Operations (R2O) Pathways: Establishing repeatable, low-friction processes for migrating academic models into Met Office operations.

This initiative was closely aligned with strategic priorities set by the Department for Science, Innovation and Technology (DSIT), the Ministry of Defence (MoD), and the Department for Transport (DfT). It supported the Met Office Space Weather Operations Centre and directly contributed to the delivery of key UK policy objectives.

- National security: Strengthening the resilience of space-enabled defence and Intelligence, Surveillance, and Reconnaissance (ISR) assets, and mitigating vulnerabilities in national grid and communications infrastructure caused by space weather.
- Economic continuity: Reducing the risk of disruption to critical sectors, including aviation, telecommunications, navigation, and energy, that underpin UK productivity and trade.[2 6]
- International Leadership: Positioning the UK as a trusted provider of operational models and data within global space-weather frameworks. This included active collaboration with initiatives led by the European Space Agency (ESA), NOAA, and NASA, as well as engagement with coordination mechanisms such as the ICAO space-weather advisory system and the International Space Environment Service (ISES).[11]

The SWIMMR programme has the following high-level objectives, each of which includes a number of lower-level objectives:

- Mitigate the potential radiation hazards of space weather to satellites and aviation operations
- Mitigate potential space weather effects on communication and global positioning
- Mitigate the potential risks of space weather to electric power distribution

In addition to this, the project has the following overarching objectives:

- Establish a world leading UK system for space weather modelling and forecasting
- Position the UK as a global leader in monitoring and mitigating effects of space weather
- Develop a framework for supporting the transition of models and data sets from research in the academic community to operational use for space weather forecasting by MOSWOC.
- Produce an updated space weather impact assessment study, building on the Royal Academy of Engineering report of 2013

The SWIMMR programme was also designed to support the key objectives set out by the UKRI Strategic Priorities Fund (SPF), an £830 million investment which has delivered 34 multidisciplinary and interdisciplinary research programmes across two waves. In line with these objectives, SWIMMR aimed to:

- Increase high-quality multidisciplinary and interdisciplinary research and innovation: The programme brought together expertise from space physics, engineering, data science, and operational forecasting to deliver an integrated national capability.
- Ensure UKRI investment links up effectively with government research and innovation priorities: SWIMMR was explicitly aligned with UK government priorities set out in the National Space Strategy (2021) and the National Severe Space Weather Preparedness Strategy (2021). It addresses top-tier risks identified in the UK National Risk Register and supports resilience objectives for critical infrastructure sectors, including aviation, energy, and telecommunications. The programme also aims to improve Met Office operational capability, ensuring that UKRI investment translated into tangible improvements in national forecasting services.
- Respond to strategic priorities and opportunities: Severe space weather represents a systemic risk with global implications. SWIMMR responds to this challenge by delivering new models, sensors, and operational tools that position the UK as a trusted contributor to international space-weather framework. The programme also leveraged UK strengths in research and innovation to ensure that national capability remains competitive and globally relevant.

2.3 Projects

SWIMMR was delivered as a coordinated portfolio of 11 connected projects, jointly led by the Science and Technology Facilities Council (STFC) and the Natural Environment Research Council (NERC).

As of the date of this evaluation, final reconciliation is expected to extend into the new financial year. Preliminary estimates indicate an underspend of approximately £350k, representing 1.75% of the overall programme budget. This figure may reduce by year-end.[17]

The projects involved collaboration across academic institutions, national laboratories, and industry partners. Academic consortia led the development of forecasting models. National laboratories and research institutes such as the Rutherford Appleton Laboratory (RAL) and the British Geological Survey (BGS) contributed infrastructure and technical capabilities for instrumentation, testing, and data integration.

Six Industry partners provided expertise in hardware integration, software engineering, and technical studies. Organisations including BJSS, CACI Ltd., Starion UK, and D-Orbit were involved in sensor design and deployment, digital platform development, and the delivery of operational tools. Engagement with the Met Office Space Weather Operations Centre supported the alignment of models, data streams, and visualisation tools with operational forecasting requirements.

[17] The cost totals are based on STFC's internal financial information and are subject to any assumptions or approximations STFC may have implemented.

2.3.1 STFC-led Projects (S1–S6)

These projects focused on instrumentation, test facilities, and enabling infrastructure.

S1 Space and airborne radiation monitoring - Ended Summer 2025

Led by STFC RAL Space in collaboration with D-Orbit/TAS, CVUT Prague, and the University of Surrey, with data delivered to the UK Met Office. The project was supported by a £5.7 million budget.

S1 Mini focused on the design and development of miniaturised instrumentation and sensors for multi-platform spacecraft applications. *S1 Trusted* aimed to deploy UK-developed radiation monitors on spaceborne and airborne platforms, including aircraft and balloons, to deliver operational data streams to the Met Office Space Weather Operations Centre (MOSWOC), enhancing national monitoring capabilities.

Expected deliverable: A step-change in UK radiation monitoring capability, providing trusted, real-time datasets to underpin forecasting, validation of radiation models, and risk assessment for satellites and aviation.

S2 Testing facilities for radiation resilience (STFC) – Ended Spring 2024

Delivered by STFC via the ChipIr beamline at the ISIS Neutron and Muon Source (£655k), S2 upgraded the UK's national neutron testing capability for components and systems. The project extended radiation effects testing to better characterise the impact of major solar particle events on ground-based electronics, while improving accessibility and uptake of the facility by academia, industry, and critical-infrastructure operators.

Expected deliverable: Enhanced national capacity to qualify and harden electronics against radiation effects, supporting resilience in safety-critical and mission-critical applications.

S3 Research-to-Operations platform for model migration – Ended Late 2024

Led by STFC RAL Space in partnership with the Met Office, CACI, and BJSS, S3 was allocated £920k to establish a cloud-based R2O platform to provide a repeatable, containerised pathway for transitioning academic space-weather models into operations. With API-driven data feeds to enable real-time testing and integration, the platform was designed to accelerate model onboarding into MOSWOC pre-operational and simulated environments.

Expected deliverable: A scalable, cost-effective integration route that reduces time-to-operations, improves interoperability and collaboration, and de-risks the transition from research to forecasting.

S4 Solar wind empirical ensemble package – Ended Late 2024

Led by Aberystwyth University with the Universities of Reading and Durham (£450k), S4 delivered a coronal and solar-wind modelling suite alongside coronal mass ejection tools to enhance operational readiness at the Met Office. The suite aimed to improve the timeliness and accuracy of solar-wind and CME forecasts, supporting downstream models and decision tools used in operational contexts.

Expected deliverable: A strengthened solar-wind prediction capability that feeds operational workflows and improves preparedness for disruptive solar events.

S5 Ground-based neutron monitoring network – Ended Early 2025

Led by Lancaster University with AEA Harwell and Merrion Systems (£1.4 million), S5 designed, built, and deployed new UK neutron monitors with real-time data feeds for operations. These sensors augment the national ability to detect solar energetic particle (SEP) events and ground-level enhancements, providing critical inputs to radiation risk assessments and operational alerts.

Expected deliverable: A UK-anchored, real-time ground network that improves situational awareness and validates radiation models.

S6 Space-weather impact study – Ended May 2024

Delivered by Starion UK (formerly Rhea-UK) with Know.Space and the University of Northumbria (£300k), S6 updated the national evidence base on space-weather impacts and benefits across sectors, building on prior national assessments. By synthesising new data, modelling outputs, and stakeholder input from across SWIMMR, the project aimed to inform risk owners, policymakers, and operators.

Expected deliverable: A current, authoritative assessment to guide policy, investment, and resilience planning.

2.3.2 NERC-led Projects (N1–N5)

These projects concentrated on advancing model development in support of operational forecasting. Areas of focus included:

N1 Satellite radiation risk forecast – Ended September 2024

Led by the British Antarctic Survey (BAS) with the Universities of Sheffield, UCL, and Northumbria (£1.9 million), N1 developed real-time radiation risk forecasts for multi-orbit satellites. Leveraging in-situ and proxy observations, the project aimed to provide actionable risk products for satellite operators across LEO, MEO, and GEO regimes.

Expected deliverable: An operationally relevant, real-time radiation risk outputs to support mission planning, anomaly investigation, and protection strategies.

N2 Radiation modelling for aviation – Ended Summer 2024

Led by the University of Surrey with BGS, MSSL (UCL), and University of Central Lancashire (£1.6 million), N2 delivered the MAIRE+ nowcast and MAIRE-R research models for atmospheric radiation affecting aviation. These models quantify exposure risks to crew and passengers during disturbed solar conditions and support operational decision-making on routes and altitudes.

Expected deliverable: An evidence-based capability for aviation radiation risk assessment, suitable for integration with operational centres and regulatory contexts.

N3 & N5 Assimilative modelling of the ionosphere and thermosphere – Ended Late 2024

Jointly led by the University of Birmingham with partners Bath, Lancaster, Leicester, Leeds, and Southampton (£3.1 million), N3/N5 delivered new models and tools for ionospheric and thermospheric forecasting. The work addressed GNSS and HF communication performance and satellite drag, enhancing predictions that underpin navigation, timing, and space operations.

Expected deliverable: Improved forecasting skill and products for communications and orbit operations, with clear pathways toward operational use.

N4 Ground-effects forecasting (GICs) – Ended Late 2024

Led by the British Geological Survey (BGS) with BAS, UCL, and Imperial College London (£2 million), N4 produced nowcast and forecast models for geomagnetically induced currents (GICs) that affect the UK power grid, pipelines, and rail. The project also delivered an improved UK ground-conductivity model, a key input for accurate GIC estimation.

The programme was originally scheduled as a five-year initiative commencing in 2020, with most projects targeting completion by March 2024. All five NERC-led projects (N1–N5) began on 1 June 2020, while STFC-led projects (S1–S6) were initiated in parallel through a combination of internal delivery and external procurements. By end of 2024, six projects (S2, S3, S4, S6, N2, N4) had reached formal close-out, while others required extensions to complete deployment. Notably, S1 (space and airborne radiation monitors) and S5 (ground-based neutron monitors) continued into 2025 to finalise sensor installations and data interfaces.

Expected deliverable: Operationally meaningful GIC risk information to support infrastructure operators' preparedness and response.

3 Main findings

The main findings are organised into the five impact areas, aligned with the evaluation questions: scientific advancement, industry growth, collaboration, the UK's global reputation, and security and resilience. This chapter examines each area in turn, analysing SWIMMR's impact and influence.

3.1 Scientific advancement

The extent to which SWIMMR has contributed to strengthening the UK's scientific and technical foundations is evaluated in this section. The scientific advancement evaluation questions assessed are:

Evaluation questions
Q1: How has SWIMMR contributed to the development of new transferable modelling and hardware deployment capabilities?
Q2: How has the SWIMMR programme contributed to advancing scientific research and improving understanding of space weather phenomena (including empirical data, monitoring, and forecast capabilities)?
Q3: To what extent has the SWIMMR programme advanced the research to operations (R2O) ecosystem? and supported the research to operations to research (R202) ecosystem?
Q4: To what extent have the benefits and innovations of the SWIMMR programme generated spillover effects in other fields and industries?
Q5: How has the SWIMMR programme facilitated the generation of intellectual property (IP) and patent applications?

3.1.1 Key findings

- Operational modelling capability: SWIMMR contributed to advancing five domain-specific models, radiation belts, ionosphere–thermosphere dynamics, solar wind propagation, aviation radiation, and geomagnetically induced currents, from research prototypes to pre-operational readiness at the Met Office. This progression substantially strengthened the UK's ability to conduct sovereign forecasting and reduced dependence on international models.
  Evidence: Stakeholder interviews confirm these models are already supporting test forecasting; full operational integration is planned for 2026.
  Future implication: Deployment to Met Office environments is expected to deliver validated real-time forecasting capability.

- New measurement infrastructure: The programme established a multi-layer measurement system combining miniaturised radiation sensors, airborne and balloon instruments, and upgraded neutron monitors. This infrastructure expanded the UK's empirical data collection

capacity and filled long-standing gaps in monitoring solar, magnetospheric, and atmospheric phenomena.
Evidence: Early use of these datasets has enabled model verification and supported controlled operational trials at MOSWOC.
Future implication: Integrating airborne sensors into live forecasting workflows would enhance aviation radiation assessment and safety compliance.

- Enhanced scientific knowledge: SWIMMR delivered 188 publications (≈15% of all UK space-weather publications, 2020–2025) with an average FWCI of 1.01, indicating global-average impact for an applied, operationally focused programme. Five papers achieved exceptional influence (FWCI up to 16.6), shaping international understanding of ionospheric dynamics and radiation risk. While outputs were critical for model validation and operational readiness, overall UK publication growth was modest (168 to 205 annually), suggesting possible displacement rather than net expansion.
  Evidence: Bibliometric patterns and interview data indicate increased publications and citations in SWIMMR-related research areas, signalling early-stage knowledge advancement.
  Future implication: Ongoing use of these datasets will strengthen predictive modelling and support UK participation in international research collaborations.

- Established Research-to-Operations (R20) pathway: A cloud-based integration platform created a repeatable pathway for transitioning academic models to operational contexts. This infrastructure improved transparency, accelerated R2O processes, and supported coordinated development between the Met Office and researchers.
  Evidence: Stakeholders describe emerging Research-to-Operations-to-Research practices, although systematic feedback loops have not yet been fully institutionalised.
  Future implication: Formalising feedback mechanisms would accelerate iterative improvements and enhance operational relevance.

- Spillover potential: Upgrades to ChipIr and NILE, alongside sensor innovations, created foundations for applications in aerospace, defence, high-reliability electronics, and telecommunications.
  Evidence: While commercial adoption is currently limited, early interest from industry partners suggests credible potential for future spillovers.
  Future implication: Targeted industry engagement and clearer articulation of use-cases will be needed to convert technical advances into measurable economic impact.

- Collective impact over IP: SWIMMR emphasised shared capability development rather than competitive IP generation. Resulting IP was either retained by academic institutions or transferred to the Met Office to support operational capability.
  Evidence: Stakeholders noted that this approach facilitated collaboration and integration but may constrain direct commercial revenue.
  Future implication: Future programmes could consider balanced IP frameworks that safeguard national resilience while enabling commercial pathways.

3.1.2 Q1: Development of new transferable modelling and hardware deployment capabilities

3.1.2.1 Modelling capabilities

All models delivered under SWIMMR introduced capabilities that were either new or significantly improved compared to what previously existed in the UK. Prior to SWIMMR, most models operated at low to mid-range application usability levels (AUL), limiting their relevance for operational use.[18] Across the five models, starting AULs averaged 3.6 (range 1–6) and rose to 7.8 (range 6–9), marking a decisive shift from research-grade tools to near-operational systems (Figure 4). Four of the five models achieved an AUL of at least 8, corresponding to 'prototype ready for validation' and 'validated by partner organisation', with the aviation radiation model (Project N2) showing the largest gain (from 1 to 8). This convergence toward higher usability and robustness demonstrates substantial progress in readiness for real-world integration.

The consistent rise in AULs highlights success in bridging the gap between concept and application, elevating UK modelling capability to deliver practical value across sectors such as aviation, satellite operations, and infrastructure resilience. Collectively, these improvements strengthen national resilience to space weather risks and reinforce the UK's position as a credible contributor to international forecasting efforts.

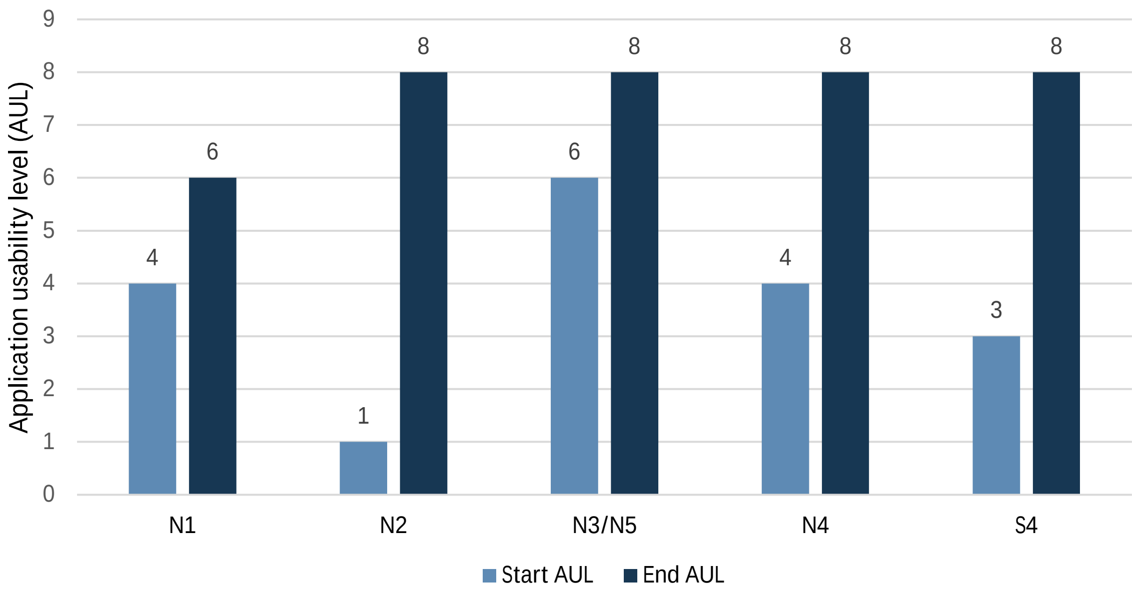

Figure 4. AUL at the start and end of the SWIMMR programme

These models have been delivered to the Met Office at AUL 7 and 8, and have been successfully implemented either on the Met Office's Pre-operational AWS Research to Operations Portal or on its pre-operational High-Performance Computing (HPC) platform. This marks a significant milestone in their transition from research to operational environments.

[18] This metric quantifies the progress of applications from a scale of 1 (basic research) to 9 (approved for on demand use). [Application Usability Levels: A Framework for Tracking Project Product Progress - NASA Technical Reports Server (NTRS)]

At the point of this evaluation, all models are progressing through this pathway, but none have yet achieved full service acceptance. The first models expected to reach full operational status are the ionosphere and thermosphere models (SWIMMR N3 & N5), scheduled to enter the Met Office's Operational Suite in January–February 2026. The full suite is anticipated to be operational by September 2026, representing a complete transition from prototype to embedded capability.

In the meantime, MOSWOC forecasters have received training and are actively incorporating model outputs into internal guidance and forecasting workflows. While these outputs are not yet available to external users, they are enhancing internal decision-making and forecast quality. This impact, though currently less visible, will become increasingly apparent as models transition into full operations and outputs are made publicly available.

In addition to reaching the programme objective, greater impact will materialise post-programme, as models transition into full operational use, inform forecasting decisions, and deliver value to external users. The programme has therefore laid the foundation for impact, with tangible benefits expected to emerge progressively through 2026.

Survey responses indicate that SWIMMR accelerated the transition of space weather models from academic research to near-operational use. One respondent described the programme as having 'rapidly pulled forward academic research into operations,' while another noted that it 'transformed research models into operational models' and enhanced the Met Office's forecasting capability through collaboration with academia. These accounts suggest that, although full operational deployment is scheduled for 2026, SWIMMR has already delivered a measurable uplift in technical readiness and institutional capability, laying the groundwork for sustained impact.

Table 4 provides an overview of the five key modelling projects delivered under SWIMMR, highlighting their purpose, starting AUL, and the level achieved by the end of the programme.

Table 4. Summary of model development and AUL progression

Project	Model Name	Short Description	Starting AUL	Ending AUL	Status at MOSWOC
N1	Radiation Belt Model (BAS-RBM)	Real-time electron belt model providing satellite radiation risk indicators for multiple orbits; previously unattainable through UK-owned models.	4	6	Two main models delivered; Electron belt (BAS-RBM) running on pre-operationally, but proton belt (BAS-PRO) implementation has been problematic.

Project	Model Name	Short Description	Starting AUL	Ending AUL	Status at MOSWOC
N2	Aviation radiation model (MAIRE+)	Novel UK radiation model feeding real-time information providing alerts for aircraft, passengers and crew; pre-operational at Met Office;	1	8	Already being used pre-operationally
N3/N5	Data assimilation model for ionosphere and thermosphere (AENeAS)	Assimilative ionosphere–thermosphere model for GNSS/HF communications; satellite drag and collision mitigation; Used internally at the Met Office ;Deployment at the Met Office high-performance computer (HPC) planned for 2026.	6	8	Delivered to MOSWOC, New strategy to deploy on HPC required instead of the AWS cloud platform.
N4	GIC forecasting system (GORGON)	GIC nowcast/forecast enabling real-time assessment of geomagnetically induced currents (GICs) on UK grid, pipelines, rail; integrated magnetic field variation measures, ground conductivity model and high-voltage power grid model to estimate flow of geo-magnetic currents. Model is available to the Met Office for improved internal forecasting and nowcasting.	4	8	GORGON model running pre-operationally on Met Office MONSOON system
S4	Solar wind suite (DUMFRIC + HUXt, PFSS-HUXt pipeline)	Optimise and transition existing solar wind propagation forecasting models, DUMFRIC (inner boundary) and HUXt (solar wind) to operational forecasting tools for the Met Office; Improve arrival time prediction of CMEs.	3	8	Almost all elements successfully delivered to MOSWOC

3.1.2.1 Hardware capabilities

The programme delivered advancements in technology readiness across six hardware developments. The programme funded critical assets such as the NILE low-energy neutron source and upgrades to ChipIr, establishing new ground-based testing capability for radiation effects on electronics. These facilities provide a strategic platform for future research and industry engagement, positioning the UK as a leader in space-weather resilience testing. Hardware projects delivered operational impact: the UK now has its first neutron monitors since the 1970s, attracting unexpected international interest in their design. Spaceborne and airborne radiation sensors were successfully launched and validated, setting a precedent for commercial adoption, OneWeb has committed to flying its own monitors, demonstrating spillover effects. The Met Office confirmed that 40 space-based sensors and 2 ground-based neutron monitors were now feeding data to MOSWOC – hardware capabilities that did not exist in the UK prior to the SWIMMR programme.[19]

Collectively, the technologies moved from an average starting point of around Technology Readiness Levels (TRLs) 3–4 to TRL 7–9 for its most mature components (Figure 5). The ground-based neutron monitors (S5) achieved the largest numerical increase, moving from TRL 4 to TRL 9, a five-level jump from early prototype to fully operational systems now deployed in the UK. Equally significant in operational terms, the Trusted sensors project (S1) advanced from TRL 6 to TRL 9, completing the critical transition from pre-operational validation to full deployment on aircraft and space platforms—an achievement that directly enables real-world monitoring. By contrast, the Mini-sensor developments (LEES, SURF, Hardpix) progressed more modestly, from TRL 1–3 to TRL 3–4, reflecting early-stage maturation and laying the groundwork for future exploitation. Facility upgrades, including the ChipIr enhancement and co-funded NILE capability at RAL Space, were not assigned TRLs but represent essential infrastructure for downstream testing and validation.

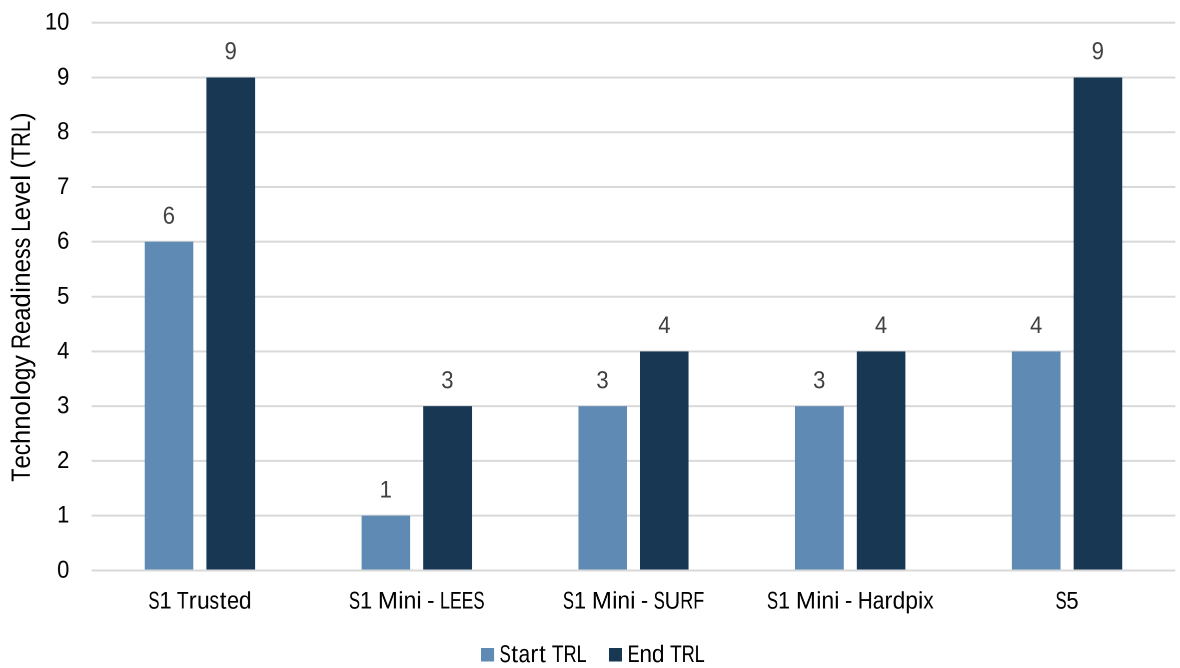

Figure 5. TRL at the start and end of the SWIMMR programme

19 Survey. Met Office. Baseline before after analysis.

Table 5 lists the new hardware or facility enabled by SWIMMR projects along with their TRL progression.

Table 5. Summary of hardware development and TRL progression

Project	Hardware/facility developed	Short Description	Starting TRL	Ending TRL
S1 Trusted	Space and airborne radiation monitoring sensors	Produced and deployed space borne and airborne sensors to fly on aircraft and further developed for use on balloons.	6	9
S1 Mini	Low-energy electron sensor (LEES)	Measurement of low energy electrons	1	3
S1 Mini	SURF	Measurement of surface and internal charging	3	4
S1 Mini	High-energy electron/proton sensor (Hardpix)	Measurement of high energy electrons and protons	3	4
S2	Upgrade to ChipIr facility. Co-funded NILE.	New irradiation testing capability (NILE) at the ISIS Neutron and Muon Source to simulate space weather radiation effects on electronics for ground-based testing	n/a	n/a
S5	Ground-based neutron monitors	Developed new modern UK neutron monitors with improved electronics and efficiency	4	9

Survey responses reflect a consensus that SWIMMR delivered meaningful advances in hardware capability, with respondents highlighting both technical innovation and sector relevance. The development of the NILE facility and enhancements to ChipIr were cited as key successes. The implementation and subsequent adoption of a ground-based neutron monitor, tested via ChipIr and now in use at Rome University, was described as the latest technology in this area, underscoring the international recognition and transferability of SWIMMR-supported hardware outputs.

Some objectives were partially achieved (at the point of this evaluation) or delayed. In Project S1, miniaturised sensor development and aircraft integration progressed more slowly than planned due to underestimated complexity, evolving requirements, and Covid-related disruptions. The team also faced constraints in securing affordable space launch options, though two launches were ultimately achieved. In Project S2, uptake from new users of subsidised testing at ChipIr was lower than anticipated, reflecting timing challenges and limited industry readiness during and immediately after the Covid-19 pandemic, despite successful delivery of facility upgrades and the co-funded NILE source. Project S5 encountered significant design changes midstream, shifting from Boron-Coated Straw detectors to Helium-3 tubes, which increased resource demands and delayed deployment approvals.

Although external disruptions such as COVID-19 were largely beyond the programme's control, their negative impacts were limited due to proactive measures taken by the programme. These included early engagement with platform providers (S1), clearer specification of technical requirements for miniaturised instruments (S1), proactive user engagement to drive facility utilisation (S2), and contingency planning for integration and approval processes (S5).

3.1.3 Q2: Advancing scientific research and improving our understanding of space weather phenomena

3.1.3.1 Advancing scientific research

UK space weather research has been published at a steady rate over the past decade, with annual outputs ranging from 154 to 186 publications between 2015 and 2019. These publications represent the wider UK space weather research community, which serves as a comparison group for assessing the specific contribution of the SWIMMR programme.

Figure 6 shows the number of UK-affiliated research articles and reviews on space weather topics indexed in Scopus between 2015 and 2025, distinguishing overall UK outputs from those specifically linked to SWIMMR from 2020 onwards. Between 2020 and 2025, SWIMMR generated 188 academic journal articles across 39 distinct journals, representing approximately 15% of all UK space-weather publications during this period.[20] While these outputs are significant, the broader trend shows that average annual UK publications rose only modestly, from 168 per year (2015–2019) to 205 per year (2020–2025). This suggests that SWIMMR's contribution was concentrated within programme-linked outputs rather than driving a large systemic increase, indicating some potential displacement of effort from other research streams.

Crucially, these publications were not solely academic exercises; they directly underpinned the development and validation of operational models for the Met Office, including radiation belt forecasting, ionosphere–thermosphere assimilation, and aviation radiation risk tools. In other words, SWIMMR's research outputs were instrumental in transitioning models from concept to pre-operational readiness, bridging the gap between scientific knowledge creation and real-world forecasting capability.

[20] ResearchFish publications data extract. 'Journal articles' only.

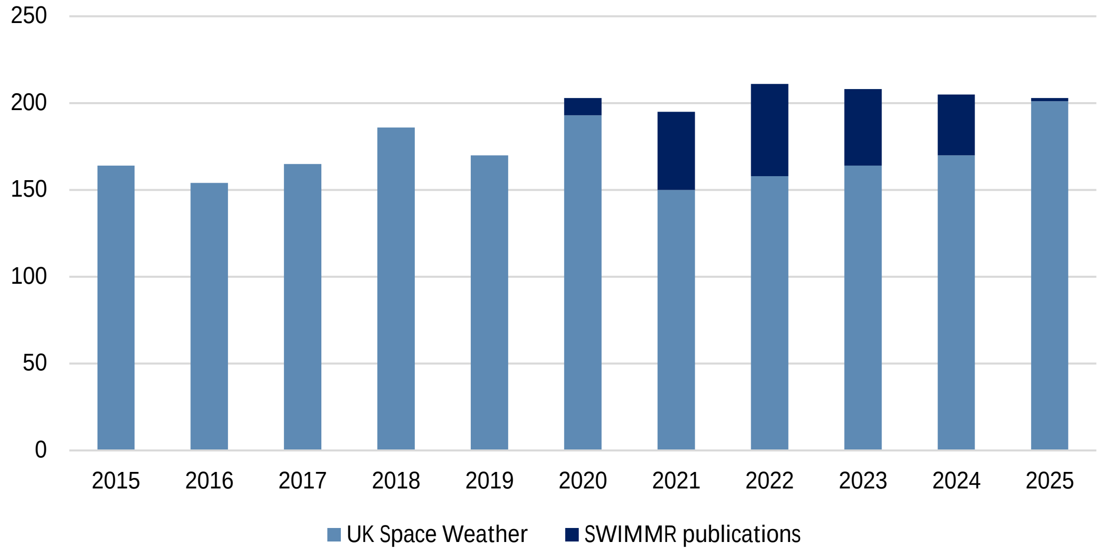

Figure 6. Annual UK space weather research publications (2015–2025)

The majority of SWIMMR publications were produced by Project N1, which focuses on satellite radiation forecasting through the BAS-RBM radiation belt model. N1 alone produced 78 publications, representing the largest share of outputs and highlighting its pivotal role in advancing radiation belt modelling for operational forecasting and satellite safety. This reflects the strategic importance of radiation environment prediction for mitigating spacecraft risks and supporting resilient space operations.

Project N3/N5 delivered 35 publications through ionosphere-thermosphere modelling, enhancing understanding of upper-atmospheric dynamics. Other packages, such as N4 (31 publications) and N2 (26 publications), provided valuable contributions. Figure 7 highlights the research outputs across SWIMMR projects.

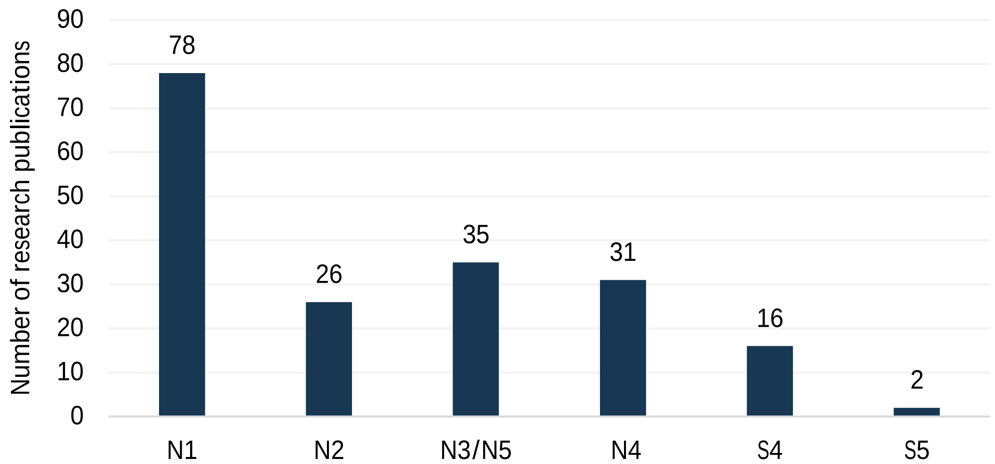

Figure 7. SWIMMR research outputs (number of publications) by project

Assessing SWIMMR's impact on the wider body of scientific knowledge requires examining both the volume and influence of its research outputs. Since publications began emerging in 2020, the programme has generated a growing corpus of peer-reviewed work that has received an average of 9.9 citations per publication and achieved a Field-Weighted Citation Impact (FWCI) of 1.01.[21] An FWCI at this level indicates that SWIMMR papers are cited at roughly the global average for comparable research, this reflects a relatively new programme operating within an applied, instrumentation and forecasting-focused field.[22]

However, five key publications have attracted a total of 382 citations, performing substantially above global citation norms. The average FWCI across these publications is 6.31, driven by two exceptionally high-impact papers:

- Themens et al. (2022), analysing global ionospheric responses to the Tonga eruption, has an FWCI of 16.64, indicating citations over sixteen times the global average for comparable research.[23]
- Whitman et al. (2023), a large international review of solar energetic particle prediction models, shows an FWCI of 4.19, reflecting sustained global relevance.[24]
- Chen et al. (2022), examining ducted chorus wave dynamics and associated electron microbursts, has an FWCI of 4.04, reflecting strong international influence in magnetospheric physics.[25]
- Hapgood et al. (2021), developing UK reasonable worst-case space-weather scenarios, has an FWCI of 3.61, indicating citation levels more than three times the global average for comparable operational research.[26]
- Zhang et al. (2023), presenting a zero-shot machine-learning approach for intelligent fault detection, has an FWCI of 3.07, demonstrating above-average global impact in applied AI and engineering research.[27]

By comparison, the International Comparison of the UK Research Base 2025 shows that UK performance in the physical sciences, including areas strongly supported by STFC, achieves citation impacts well above the world average, reflecting the field's high levels of international

[21] SciVal data extract: FWCI, year range: 2020-2024

[22] https://helpcenter.pure.elsevier.com/en_US/data-sources-and-integrations/field-weighted-citation-impact-fwci-metrics

[23] Themens, D. R., Watson, C., Žagar, N., Vasylkevych, S., Elvidge, S., McCaffrey, A., ... & Jayachandran, P. T. (2022). Global propagation of ionospheric disturbances associated with the 2022 Tonga volcanic eruption. *Geophysical Research Letters*, *49*(7), e2022GL098158.

[24] Whitman, K., Egeland, R., Richardson, I. G., Allison, C., Quinn, P., Barzilla, J., ... & Hosseinzadeh, P. (2023). Review of solar energetic particle prediction models. *Advances in Space Research*, *72*(12), 5161-5242.

[25] Chen, L., Zhang, X. J., Artemyev, A., Angelopoulos, V., Tsai, E., Wilkins, C., & Horne, R. B. (2022). Ducted chorus waves cause sub-relativistic and relativistic electron microbursts. *Geophysical Research Letters*, *49*(5), e2021GL097559.

[26] Hapgood, M., Angling, M. J., Attrill, G., Bisi, M., Cannon, P. S., Dyer, C., ... & Willis, M. (2021). Development of space weather reasonable worst-case scenarios for the UK national risk assessment.

[27] Zhang, S., Wei, H. L., & Ding, J. (2023). An effective zero-shot learning approach for intelligent fault detection using 1D CNN. *Applied Intelligence*, *53*(12), 16041-16058.

collaboration and long citation horizons. At the national level, the UK's FWCI is consistently reported at approximately 1.5–1.6, driven by mature, highly collaborative research fields.[28]

These benchmarks, however, reflect different programme types and structural characteristics: STFC outputs often stem from large-scale, high-impact physics collaborations, while SWIMMR is a targeted, time-limited translational R&D investment designed primarily to strengthen UK operational space-weather capability. Viewed through this lens, it is expected that the programme's average FWCI sits below comparable programmes.

Nonetheless, at least five SWIMMR-linked publications are achieving significant global impact, each with an FWCI well above the world average. These high-performing outputs demonstrate that the programme is producing work of international scientific relevance, despite its applied orientation and relatively short citation window. Taken together, these results indicate that while SWIMMR's average citation performance reflects the nature of the programme, its most influential publications are already shaping global understanding of space-weather phenomena.

3.1.3.2 Improved understanding of space weather phenomena

Participants responding to the evaluation survey were unanimous in recognising SWIMMR's contribution to advancing UK space weather knowledge.[29] The collected data on project outputs indicate that the models and instruments developed under SWIMMR have measurably strengthened the UK space-weather knowledge base. The programme delivered new and improved datasets, enhanced magnetometer networks, and advanced ionospheric and radiation-belt models, enabling more accurate monitoring, simulation, and forecasting of space weather phenomena. Early applications of these tools in operational contexts, such as the Met Office forecasting services and BGS geomagnetic storm monitoring, demonstrate improvements in situational awareness for radiation hazards, ionospheric disturbances, and geomagnetic storms. Collectively, the outputs provide a more integrated and accessible capability for both scientific research and operational decision-making, which in future is expected to support further peer-reviewed publications and the validation of models against real-world observations.

SWIMMR funding has been critical in accelerating the development and integration of models and instrumentation that would not have been feasible through standard research grants alone. By coordinating complementary projects, the programme enabled the creation of a cohesive UK capability in space weather, which in turn improved understanding of key phenomena by linking research outputs directly to operational applications. This integration allowed scientists to test hypotheses at scale, validate models against real-time data, and generate insights into solar-terrestrial interactions that were previously unattainable. Funding facilitated investments in hardware deployment, high-resolution datasets, and modelling expertise, producing outputs that have enriched the scientific literature and enhanced practical forecasting tools.

28 International comparison of the UK research base, 2025 - GOV.UK

29 Survey.

The programme's support also catalysed collaboration beyond pre-existing levels between national research organisations, universities, and government organisations, evidenced by the larger collaboration numbers post SWIMMR programme as highlighted in section 3.3. Subject to full operational integration in 2026, these collaborations and early adoptions are expected to translate into tangible improvements in monitoring, forecasting, and risk management for satellite operators, aviation, and power grid stakeholders.

Case Study 1 focuses on N1, the BAS Radiation Belt Model (BAS-RBM), a flagship SWIMMR project that established the UK's first operational, multi-orbit capability for forecasting high-energy electron dynamics. The sections that follow provide a summary of each relevant SWIMMR project, highlighting their principal contributions to the scientific understanding of space-weather phenomena. For each project, outputs are described in terms of new models, instrumentation, datasets, and methodological advances, alongside their impact on monitoring, simulation, and forecasting capabilities. This project-level overview demonstrates how the coordinated SWIMMR programme collectively strengthened the UK space-weather knowledge base, supported operational applications, and enhanced the broader research community's ability to interpret and respond to radiation hazards, ionospheric disturbances, and geomagnetic storms.

3.1.4 Case Study 1: BAS Radiation Belt Model (BAS-RBM, N1)

Overview

The BAS Radiation Belt Model (BAS-RBM) represents a major advancement in UK-owned space-weather science, establishing a domestic capability to forecast high-energy electron dynamics across multiple orbital regimes. Prior to SWIMMR, the UK had no operational models capable of simulating radiation belt behaviour beyond geostationary orbit. BAS-RBM now provides real-time simulations for geostationary (GEO), medium Earth orbit (MEO), and the slot region, critical zones for satellites such as GPS, Galileo, and O3b. The project lead highlighted:

> "We put in a forecasting system for a whole range of orbits which nobody else has done… so not just geostationary, but medium Earth orbit where GPS and Galileo fly, also slot region orbit, where O3b fly."[30]

Scientific contribution

BAS-RBM integrates six distinct wave diffusion models, enabling improved understanding and forecasting of electron flux variability during geomagnetic storms. This has directly contributed to knowledge of radiation belt dynamics, storm-time acceleration, and loss mechanisms. Peer-reviewed outputs have disseminated these findings within the space physics community, providing a foundation for subsequent research on particle acceleration and space-environment processes.

> "This new model is enabling us to do much more sophisticated things to better understand the environment."[31]

Validation against satellite and ground-based observations has confirmed the model's accuracy, ensuring both scientific credibility and operational relevance.

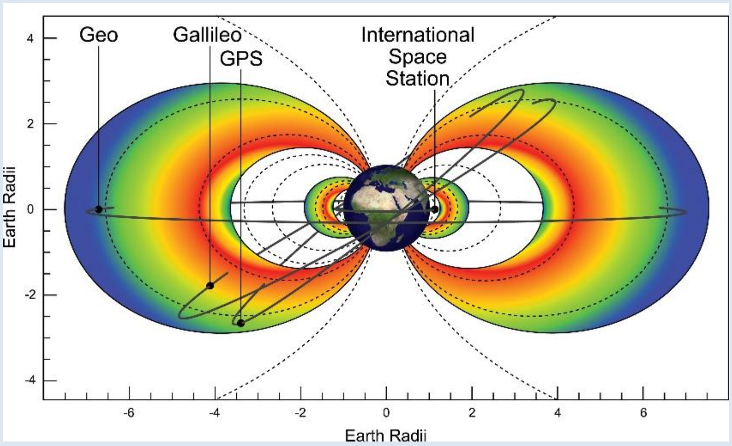

Figure 8. Satellite orbits and the van Allen radiation belts showing structure of Earth's radiation belts and the position of various satellite orbits relative to Earth. Source: British Antarctic Survey

Operational impact

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30 Interview. Project PIs.

31 Interview. Met Office.

A key innovation of the project was the integration of BAS-RBM with ESA's DICTAT model, widely used to assess internal charging risks on satellites. This coupling produces real-time radiation risk indicators via a simple red–amber–green alert system, translating complex particle flux outputs into actionable guidance for satellite operators. By bridging the gap between environmental modelling and engineering risk assessment, BAS-RBM allows operators to anticipate periods of high radiation and protect sensitive satellite systems, enhancing mission resilience and planning.

Added value of SWIMMR funding

SWIMMR funding supported access to high-quality observations, computational resources, and expertise, enabling the iterative development, validation, and operational integration of BAS-RBM. The programme transformed what would have been a research prototype into pre-operational, UK-owned tool that delivers both scientific insights and practical operational benefits. Without SWIMMR funding, the UK would have lacked the resources and coordination to develop a domestic, multi-orbit radiation-belt model. The UK would have continued to rely on foreign models and datasets for satellite risk assessment, limiting both scientific advancement and operational autonomy. Progress in understanding storm-time electron dynamics and integrating these insights into real-time risk alerts would have been delayed, and the UK would not have established a fully operational capability capable of informing satellite mission planning, engineering design, and hazard mitigation.

Key achievements

- First UK-owned model to simulate radiation-belt behaviour across GEO, MEO, and slot regions.
- Integration of six wave diffusion models, advancing understanding of storm-time electron dynamics.
- Coupling with ESA DICTAT to produce real-time operational risk alerts.
- Documented in peer-reviewed publications, strengthening international scientific knowledge.
- Provides actionable insights for satellite mission planning, engineering design, and operational decision-making.

Conclusion

BAS-RBM highlights how SWIMMR has strengthened the UK's space-weather capability. By combining scientific innovation, technological sophistication, and operational application, the project has delivered a unique UK asset that advances fundamental understanding of radiation-belt dynamics while providing benefits for satellite operators. It demonstrates how strategic funding can transform a capability gap into a world-class scientific and operational resource.

N2 - Radiation modelling for aviation

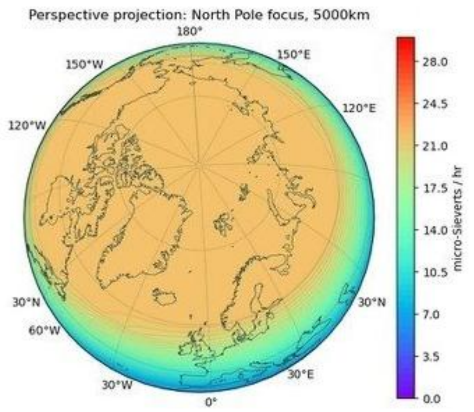


Figure 9. Radiation intensity map. Orange areas represent higher radiation levels. Blue-green areas indicate lower radiation levels.

The N2 project delivered the UK's first comprehensive aviation radiation model, MAIRE+, and a complementary research model, MAIRE-R, significantly advancing UK capability in atmospheric radiation monitoring and forecasting.

MAIRE+ is the UK's first model able to estimate radiation levels on aircraft in real time. It combines data from monitoring stations and airborne sensors to show how radiation levels change during normal operations and during solar events. Although the new UK neutron-monitor network was not yet providing data during the project, MAIRE+ was successfully tested using international measurements, showing it is reliable and ready for future integration with UK-owned sensors.

MAIRE-R builds on this by exploring more experimental and longer-term scientific questions, such as radiation conditions at very high altitudes (up to 100 km) and how radiation levels change during major solar events. This work supports future needs in high-altitude aviation and early space-tourism activities and helps deepen UK understanding of how radiation behaves in the upper atmosphere.

> "On the modelling side there's been a very large step forward here… before this project, the UK did not have a viable radiation model. This has now been developed and is installed at the Met Office and is working in a pre-operational form at the AUL 8 level." [32]

Both MAIRE+ and MAIRE-R have been transferred to the Met Office, where MAIRE+ is operational in pre-production form and MAIRE-R continues to support research and development. By delivering validated models, integrating observational data, and expanding the altitude and temporal scope of radiation modelling, the N2 project has made a substantial contribution to the UK space-weather knowledge base while enabling actionable outputs for aviation safety and operational planning.

[32] Interview. Project PIs.

N3/N5 - Ionosphere and thermosphere modelling

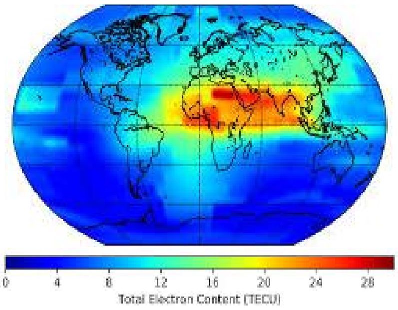


Figure 10. AENeAS model: Showing Total Electron Content (TEC) in the Earth's ionosphere

Before SWIMMR, the UK did not have a single system capable of jointly modelling the ionosphere and thermosphere, even though these layers interact strongly. The N3 and N5 projects were therefore combined to create AENeAS, an integrated model that blends a physics-based background with real observations to generate the most accurate possible picture of current upper-atmospheric conditions. Early validation against independent datasets showed that AENeAS improves estimates of ionospheric absorption, scintillation, and rapid changes that affect the reliability of GPS and radio communications.

For the N3 component, the model provides better indications of when and where GPS signals may weaken or fluctuate, supporting navigation and timing services. For N5, AENeAS offers improved estimates of atmospheric drag on satellites, reducing uncertainty in orbit predictions and helping lower collision risk. By producing a more complete view of how the upper atmosphere behaves during disturbed conditions, AENeAS strengthens the UK's scientific understanding of ionosphere–thermosphere coupling while delivering practical benefits for satellite tracking and communication resilience. It also provides a strong foundation for future work on geomagnetic-storm impacts and emerging space-traffic management needs.

N4 – Ground effects (GIC) forecasting

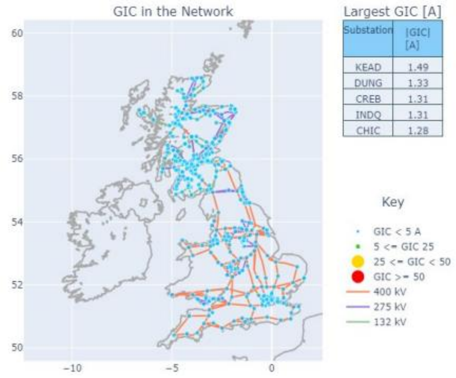


Figure 11. Nowcast assessment of GIC in the UK power grid.

The N4 project focused on a long-standing challenge in UK space-weather science: understanding how disturbances in the Earth's magnetic field translate into electrical currents that affect ground-based infrastructure. Prior to SWIMMR, available models were limited in scope and not suitable for operational forecasting. N4 addressed this by developing the UK's first end-to-end system for nowcasting and forecasting geomagnetically induced currents (GICs).

> "We went from a fairly academic set of models and have turned that into a very robust set of models that produce magnetic field products...14 of them every 5 minutes, so it's been a very successful project."[33]

The project delivered a suite of advanced models that blend improved magnetic-field monitoring, new magnetotelluric survey data, and four machine-learning approaches. It also expanded the UK's magnetometer network, strengthening the observational evidence needed to validate forecasts. Together, these developments now enable the production of 14 magnetic-field and geoelectric products every five minutes, providing timely estimates of ground-level impacts for the first time.

The enhanced capability offers more accurate forecasts of sudden storm commencements and better insight into how geomagnetic activity interacts with the UK's ground conductivity. These models are now used internally at the Met Office to assess risks to power grids, pipelines, and rail systems. Real-time GIC maps produced by N4 help operators identify where transformers or other assets may be under stress during severe space-weather events, enabling preventative action and improving infrastructure resilience. This shift from experimental tools to operationally relevant forecasting demonstrates the scientific and practical value delivered through N4. This also reinforces key SPF objectives by ensuring UKRI investment is effectively aligned with government research and innovation priorities, while responding to strategic national resilience and infrastructure opportunities.

[33] Interview. Project PIs.

S4 - Solar Wind Modelling Suite

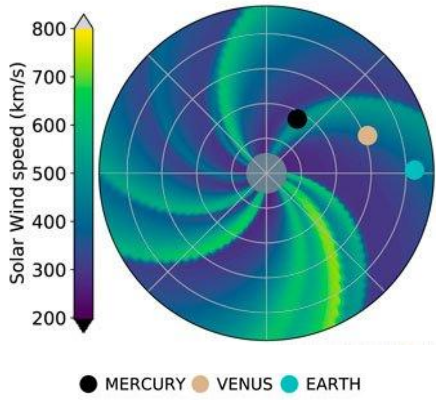


Figure 12. Solar wind speed distribution chart

The S4 project focused on advancing the performance of key solar-wind propagation models used to predict the arrival of coronal mass ejections (CMEs), primarily DUMFRIC and HUXt. Rather than developing new systems, the project strengthened and extended the capabilities of existing models to better meet MOSWOC's operational requirements.

The work delivered tangible scientific and operational gains. Improvements in computational efficiency and ensemble modelling allowed forecasters to quantify uncertainty more robustly and generate faster, higher-fidelity predictions of CME arrival times and effectiveness. These enhancements have improved MOSWOC's ability to anticipate the onset and severity of geomagnetic storms, supporting better decision-making for sectors dependent on space-weather alerts.

Beyond immediate operational benefits, the upgraded modelling framework provides a scalable platform for future scientific improvements, such as integration with higher-resolution solar wind inputs or advanced ensemble schemes, ensuring the capability continues to evolve with emerging research and forecasting needs.

S1 Mini and Trusted – Miniaturised sensors and space and airborne radiation sensors

Figure 13. Miniaturised instruments

Figure 14. Airborne space weather monitor

S1 Mini and S1 Trusted advanced the UK's capability to monitor radiation hazards in both space and aviation domains by developing next-generation particle detection instruments. S1 Mini focused on sensor miniaturisation and enhanced onboard processing to characterise high-energy protons and electrons, particles known to degrade satellite components and interfere with aircraft electronics. By reducing power consumption and data-transfer demands, the project produced instruments suitable for hosted payloads with tight resource constraints. Although not yet feeding operational systems, the prototypes significantly increased technological readiness for future missions and expanded the UK's sensor design expertise.

S1 Trusted transitioned this capability into operational use, deploying radiation sensors on spacecraft and aircraft at altitudes up to 1,200 km, substantially higher than typical low-Earth-orbit missions. This provided access to a region of near-Earth space where observational coverage has historically been sparse. The resulting measurements created a unique dataset, repeatedly highlighted by stakeholders as a significant scientific contribution:

> "I think it's developed understanding considerably. There was very little data coming from the altitudes around 1200km's before we started this. So [now] we've got unique data from that altitude." [34]

These observations have been incorporated into Met Office modelling systems, improving characterisation of particle populations, energy spectra, and variability across orbital regimes. This enriched understanding has strengthened SWIMMR's modelling programmes, supported more accurate radiation-environment forecasts, and laid the foundations for future operational radiation-monitoring missions. By improving both measurement quality and environmental coverage, S1 has enhanced the resilience of UK space- and aviation-dependent infrastructure.

[34] Interview. Project PIs.

S5 – Ground based neutron monitors

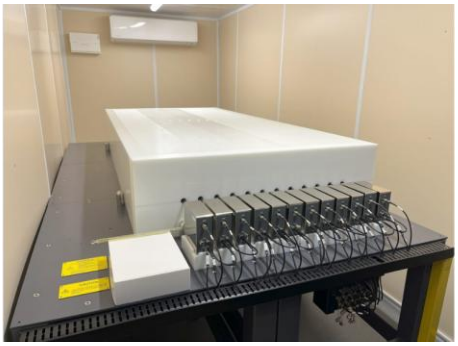


Figure 15. The 4-NM-2023 neutron monitor installed at the Met office

S5 restored a long-absent national capability by developing and deploying a new generation of neutron monitors to measure secondary cosmic rays at ground level. The flagship instrument, 4-NM-2023, was installed at the Met Office site in Camborne, while compact monitors in Lerwick and Lancaster created the UK's first real-time surface radiation-monitoring network in decades. These instruments track neutron count rates, an essential indicator of both background galactic cosmic ray levels and sudden increases during extreme solar events such as ground-level enhancements (GLEs). Their measurements provide early evidence of radiation changes that can affect aviation, satellites, and ground-based systems.

The redesigned monitors represent a significant technological upgrade: they are smaller, lighter, and safer, replacing boron trifluoride (BF_3) detectors with helium-3 sensors and incorporating modern electronics for continuous, high-quality data output. This capability now feeds directly into operational modelling systems, including the N2 MAIRE+ aviation radiation model, and supports the international neutron monitor network, enhancing global situational awareness of radiation hazards.

The recent coordinated launch of radiation monitors from Camborne, Lerwick, and De Bilt marks an important scientific milestone, bringing together outputs from S1, S5, and N2. By synchronising balloon-borne particle measurements with ground-based neutron observations, SWIMMR has established a vertically integrated radiation-monitoring system spanning the surface to the upper atmosphere. This combined dataset will enable rigorous validation and calibration of MAIRE+, improve estimates of radiation exposure across atmospheric layers, and offer new insights into how solar energetic particle events evolve as they propagate downward.[35]

This integrated monitoring approach represents a step-change in the UK's ability to characterise and forecast radiation hazards. The resulting data will be valuable for scientific research, aviation, satellite operators, defence, and critical national infrastructure, all of which depend on accurate assessments of space weather–driven radiation risks.

[35] https://www.metoffice.gov.uk/about-us/news-and-media/media-centre/weather-and-climate-news/2025/leap-forward-for-space-weather-monitoring

S2 – Testing facilities for radiation resilience

Figure 16. NILE test facility at ISIS

The S2 project delivered a critical new capability for space-weather research with the NILE testing facility at the ChipIr ISIS Neutron and Muon Source. NILE provides controlled neutron-radiation testing for both academic and industrial users, enabling systematic evaluation of electronic components under conditions representative of space-weather events. This allows researchers and industry to distinguish the effects of solar energetic particle events from routine cosmic-ray backgrounds, supporting more accurate assessments of system vulnerability.

A key scientific contribution of NILE has been demonstrating that space-weather, driven neutron surges can cause simultaneous, unexpected disruptions in electronic systems, phenomena previously considered rare. This insight has informed design and risk-modelling strategies in sectors such as internet infrastructure, power electronics, and other critical technologies, revealing vulnerabilities that were not apparent under conventional testing.

The facility has engaged two main user groups: organisations with some awareness of radiation effects but limited understanding of space-weather risks, and organisations with little or no prior knowledge of these hazards. Since its upgrade, NILE has supported approximately 32 users, 25 of whom were new to the facility, illustrating growing demand for space-weather resilience testing.[36] By combining novel experimental capability with active user engagement, S2 has strengthened UK scientific understanding of space-weather effects on electronics while providing a national asset that informs design, mitigation, and preparedness across multiple industries.

[36] Survey.

3.1.5 Q3: Advancing the research to operations (R2O) and research to operations to research (R202) ecosystems?

The SWIMMR programme has strengthened the UK's space-weather capability by accelerating the transition of research models into operational readiness. Multiple scientific models, covering ionospheric and thermospheric dynamics, aviation radiation, and ground-induced currents, have moved into pre-operational use at the Met Office, filling critical gaps in forecasting services. These models are already informing internal Met Office workstreams and are on track to become fully operational by late 2026.

SWIMMR's impact extends beyond technical integration, catalysing a cultural shift across the UK space-weather research community. Operational thinking is now embedded into academic practice, with researchers designing models and facilities with usability and operational deployment in mind. Internationally, SWIMMR has been recognised as a benchmark for effective research-to-operations transition, cited by NOAA and NASA as a model to emulate. While the feedback loop from operations back to research (R2O2R) is still at an early stage, SWIMMR has laid the foundation for a sustainable, iterative R2O ecosystem.

Assessing Research-to-Operations (R2O) quantitatively was challenging due to varied project maturity levels and diverse transition pathways, which made consistent measurement of "integration into operations" difficult. With models still in prototype or validation phases, the evaluation relied primarily on qualitative evidence from surveys and interviews to capture perceived effectiveness and progress.

3.1.5.1 Effectiveness and efficiency of research to operations

SWIMMR became a catalyst for moving academic models into operational readiness. A key enabler was the S3 project, which developed a cloud-based platform on Amazon Web Services (AWS), allowing partners to run models in real time under conditions that mimic operational systems, a capability that did not exist prior to SWIMMR. This infrastructure accelerated the R2O process and enabled models across the programme to be tested and evaluated under real-world parameters.

> *"The technology introduced by this cloud computing platform meant that the process of research-to-operations was much smoother and could go faster."* [37]

A Met Office respondent noted that international organisations often take up to six years to transition a single model into operational use. By contrast, SWIMMR has enabled the UK to integrate multiple models in a fraction of that time, thanks to the AWS-based platform developed under Project S3. This platform allows models to run on Met Office infrastructure early, giving scientists and technical teams direct access for testing and refinement. As a result, processes that typically span years can now be completed in around six months per model, demonstrating SWIMMR's effectiveness in accelerating Research-to-Operations. This rapid progress has drawn

[37] Interview. Met Office.

significant interest from international partners and prompted requests for collaboration and knowledge sharing.

> "To put it into context, our international counterparts spent six years transitioning one model from research into operations. We're going to try and do that with six models inside two years, and this is only possible because of SWIMMR's AWS platform."[38]

Furthermore, Interviewees consistently highlighted SWIMMR's success in closing the gap between academic research and operational forecasting. Previously, models were often developed in isolation, with limited pathways for integration into operational systems. SWIMMR addressed this by introducing structured processes, technical infrastructure, and collaborative mechanisms that enabled smoother transitions. Survey data in Figure 17 indicates that SWIMMR primarily supported R2O progress through new collaborations (42%), complemented by the introduction of new tools (31%) and processes (27%). This demonstrates a balanced approach combining technical, procedural, and organisational enablers.

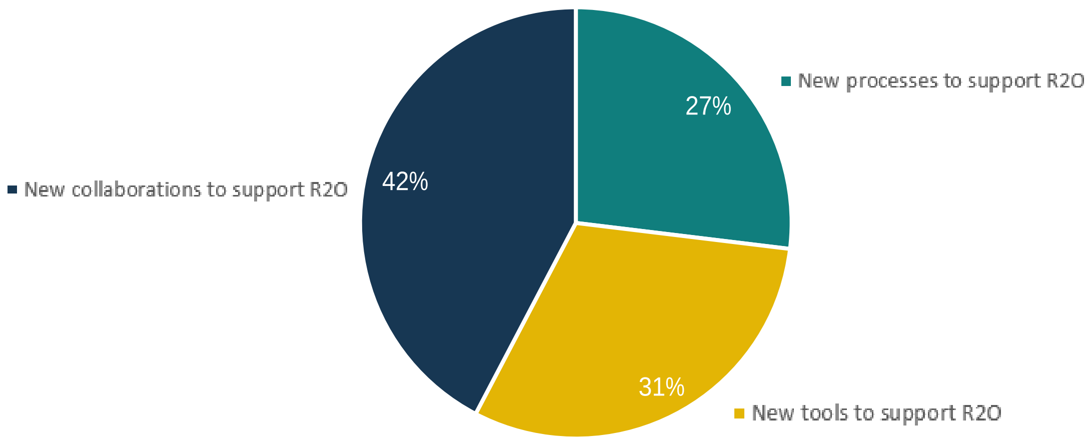


Figure 17. Percentage of survey respondents indicating how SWIMMR helped to support R20 progress. Respondents were allowed to select more than one response. Results based on a total of 14 respondents.

3.1.5.2 Cultural shift to operational thinking

Beyond technical infrastructure, SWIMMR has instigated a cultural shift within the research community. Researchers now design models with operational deployment in mind from day one, considering usability, reliability, and real-world application. This change in mindset was highlighted in interviews:

> "It has substantially changed the way I think of my research and how I do research. Everything I do now, I think operations… and I realise now when I interact with other

[38] Interview. Met Office.

> academics in the field, how clueless I was before and they may still be, as far as operations go."[39]
>
> "We've learned a lot over the last few years in terms of how to make these kinds of systems [AWS] work, and the tools that you need to support that."[40]
>
> "We designed ChipIr to do exactly that job [move from research to operations], which is to solve the real world problems in reliability…by providing a testing capability that enables companies to directly solve these problems."[41]

This cultural shift lays the foundation for a sustainable, iterative R2O2R cycle. By embedding operational thinking from the outset, future model transitions will be faster, more cost-effective, and less resource-intensive, reducing the need for extensive retrofitting or redesign. Models will be purpose-built for deployment, ensuring they are robust, scalable, and aligned with end-user needs.

3.1.5.3 Early-stage R2O2R development

The research-to-operations-to-research (R2O2R) cycle is emerging, with early progress in establishing feedback loops. The Met Office stakeholders highlighted that the process has been initiated through R2O and is gradually gaining momentum. Forecasters at the Met Office are beginning to provide input on required visualisations and model outputs, informing model refinement and future research priorities:

> "O2R is being kick started by the R20, it's sort of developing a bit more life of its own now."[42]
>
> "We're already making the outputs available to our forecasters to look at and provide any feedback."[43]

Although still limited, this early-stage feedback demonstrates that pre-operational testing can guide research and model improvement. Further effort is required to fully realise the R2O2R cycle, ensuring that outputs are exploited by end users such as industry and system operators. Importantly, SWIMMR's primary focus was to equip the Met Office for research-to-operations transition; the emergence of R2O2R represents a valuable additional outcome, laying the groundwork for a fully integrated, iterative space-weather capability.

3.1.5.4 R2O in context and the value of SWIMMR

The concepts of R2O and R2O2R are well established in operational science internationally, particularly in meteorology, space weather, and climate science. For example, the NOAA Space Weather Prediction Center (SWPC) in the United States routinely transitions academic research into operational forecasting models, while also incorporating forecaster feedback to guide further

39 Interview. Project PIs.

40 Interview. Project PIs

41 Interview. Project PIs

42 Interview. Met Office

43 Interview. Met Office.

research. Similarly, NASA and ESA heliophysics programmes employ structured R2O pathways to ensure that new instruments and models can support operational forecasting and space mission planning. Meteorological agencies such as the UK Met Office, ECMWF, and JMA also formally track R2O outcomes, ensuring research outputs inform routine operational services.

Despite these precedents, SWIMMR represents a unique UK-led effort in systematically embedding R2O and the early stages of R2O2R across a multi-project programme. Its structured approach enabled the efficient transition of diverse models into pre-operational use at the Met Office. Beyond technical integration, SWIMMR has driven a cultural shift, encouraging researchers to design models with operational usability in mind and establishing the foundations for iterative feedback loops between research and operations.

The value of SWIMMR lies in this combination of scientific innovation, operational integration, and cultural change. By providing dedicated infrastructure, collaborative mechanisms, and a coordinated programme structure, SWIMMR accelerated R2O transitions that would otherwise have been fragmented and slow. Furthermore, it positioned the UK as a credible contributor to international space-weather efforts, enabling domestic control over operational capabilities and providing a model that could inform other national R2O initiatives.

Case study 2 illustrates how SWIMMR accelerated R2O progress, establishing technical infrastructure, processes, and collaborative mechanisms that enabled scientific models to move from the research environment into pre-operational use. It highlights both the technical achievements and the cultural shift within the UK space weather community toward designing research outputs with operational deployment in mind.

3.1.6 Case Study 2: Research to operation (R20) progress at MOSWOC

Overview

The SWIMMR programme significantly advanced the UK's space-weather research-to-operations capability by enabling academic models to be transitioned into pre-operational use at the MOSWOC. Prior to SWIMMR, academic models were typically delivered in isolation, requiring the Met Office to adapt and integrate them manually, slowing uptake and limiting operational relevance. Through SWIMMR, models covering the ionosphere, thermosphere, radiation belts, aviation radiation, and ground-induced currents were systematically integrated, filling critical gaps in forecasting services.

Role of S3 – Enabling operational Transition

A key enabler was the S3 project, which developed a cloud-based platform on Amazon Web Services (AWS) to host models in a pre-operational environment. This infrastructure allowed academic partners to test and run their models in real-time, simulating operational conditions:

> "Previously, we couldn't do this at all. Partners would typically develop something offline, hand us the code, and we'd have to figure out how to use it, but this [SWIMMR] really joined up the gap between research and operations."[44]

S3 streamlined collaborative development, facilitated model validation, and accelerated integration timelines. It allowed strategic planning across SWIMMR projects, enabling parallel development of models to address the most critical operational gaps efficiently.

Operational Impact

- Improved understanding of operational requirements: Academic partners gained insight into operational standards, coding practices, and documentation, improving model readiness for live forecasting.
- Collaborative model development: The AWS platform fostered iterative refinement, with researchers able to adjust models directly while supported by Met Office staff. This collaborative environment strengthened both model performance and scientific understanding.
- Filling capability gaps: SWIMMR addressed critical gaps across the Sun–Earth system.
  - Improved nowcasting of ionospheric and thermospheric conditions
  - Enhanced radiation belt forecasting
  - Introduction of aviation radiation and geomagnetically induced current (GIC) models
- Pre-operational outputs and early feedback loops (R2O2R): Models running on the platform are producing real-time outputs for forecasters, enabling early operational feedback to guide future research and model refinement.

[44] Interview. Met Office.

"We've assigned one of our forecasters to each of the SWIMMR models… they engage with the academic partners to provide feedback."[45]

- Efficiency gains: By providing a shared technical infrastructure, SWIMMR reduced time spent on setup and troubleshooting, allowing staff to focus on model improvement and scientific analysis.

Model Progression

All SWIMMR models have reached Application Usability Level (AUL) 7–8, defined as "prototype ready for validation or validated by partner organisation," and are running pre-operationally. Full operationalisation is planned according to the following timeline:

- Jan–Feb 2026: N3 & N5 (ionosphere/thermosphere)
- Mar–Apr 2026: N2 (aviation radiation risk)
- Mid-2026: N4 (ground effects/GIC) & N1 (radiation belt)
- Sep 2026: S4 (solar wind/CME)

By September 2026, all models are expected to be fully operational, providing a comprehensive UK-owned space-weather forecasting suite.

The value of SWIMMR

Without SWIMMR funding, R2O progress in the UK would have been significantly slower. Academic models may have been developed in isolation, but there would have been limited infrastructure, coordination, or collaborative mechanisms to transition them into operational use. Critical gaps in forecasting, ionosphere/thermosphere, radiation belts, aviation radiation, and GICs, would likely have persisted, leaving MOSWOC reliant on fragmented or international data sources. The cultural shift toward operationally aware research would have been delayed, and the foundations for a sustainable R2O2R cycle would not have been established, slowing both scientific progress and the delivery of actionable space-weather services. SWIMMR delivered both technical and cultural impact:

- Technical: Cloud-based platform, pre-operational models, improved forecasting capabilities, accelerated integration timelines.
- Cultural: Operational thinking embedded in academic research, early R2O2R feedback mechanisms, collaborative practices across institutions.
- Strategic: Enabled prioritisation of modelling gaps, coordinated development, and faster delivery of UK-owned operational capability.

Key Achievements

- First UK programme systematically transitioning space-weather research models into pre-operational use.

[45] Interview. Met Office.

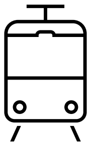
- Integrated multiple models into a scalable cloud-based infrastructure, reducing deployment times.
- Strengthened operational forecasting and scientific understanding across multiple domains.
- Established early R2O2R feedback loops, supporting iterative research refinement.
- Provided a roadmap for full operationalisation, creating a sustainable UK-led space-weather capability.

Conclusion
This example demonstrates how SWIMMR transformed research outputs into near operational tools. By providing infrastructure, coordination, and culture change, the programme has accelerated scientific impact, enhanced operational capability, and laid the foundation for sustainable iterative R2O2R practices.

3.1.7 Q4: Spillover effects in other fields and industries

While SWIMMR's core objectives focused on aviation, satellite navigation, communications, and power distribution, its advances in instrumentation, modelling, and radiation monitoring show potential for wider cross-disciplinary applications. This evaluation considers impacts beyond these target sectors, defining a cross-disciplinary application as any field where SWIMMR knowledge, tools, or methods are being applied or creating new use cases. Evidence points to emerging spillovers in four areas: rail, electronics and control systems, internet infrastructure, and nuclear.

Rail



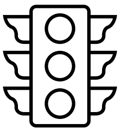
Potential Impact: Electrified rail networks are vulnerable to geomagnetically induced currents (GICs), which can affect signalling and control systems. SWIMMR's modelling of ground-level magnetic fields and GICs offers a framework for assessing and mitigating these risks.

Evidence: A follow-on NERC Pushing the Frontiers grant was awarded to study the UK rail network's exposure to GICs, reflecting recognition of space weather as a transport resilience issue.

> "We received a NERC 'Pushing the Frontiers' grant to study the entire electrified rail network in the UK for geomagnetically induced currents in rail."[46]

Status: Early-stage, emerging influence, with structured research underway.

Electronics and control systems

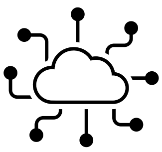


Potential Impact: Radiation resilience is increasingly important for safety-critical electronics, including automotive, industrial control, and medical devices. SWIMMR's testing and modelling capabilities enable companies to assess vulnerability and improve reliability.

Evidence: Industry partners, including high-power semiconductor developers like STMicroelectronics, have engaged with ChipIr testing facilities to explore neutron effects and strengthen system resilience.

Status: Operational engagement with private sector underway; influence on design and testing practices is emerging.

Internet infrastructure



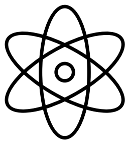
Potential Impact: Digital infrastructure, including routers and data centres, can be disrupted by extreme space weather. SWIMMR outputs provide tools for assessing and mitigating such risks.

[46] Interview. Project PIs.

Evidence: Two major global internet hardware providers, Cisco Systems and Arista, participated in ChipIr testing to evaluate network vulnerabilities and adapt their systems.

Status: Demonstrates early cross-sector awareness and application potential.

Nuclear



Potential Impact: Nuclear facilities require robust systems capable of withstanding radiation surges. SWIMMR's radiation modelling and monitoring tools offer data that could inform safety assessments and operational planning.

Evidence: Stakeholder consultations indicate industry interest in SWIMMR outputs:

> "We have had meetings with people in that sector [nuclear] who are interested in the outputs from the SWIMMR programme."[47]

Status: Engagement is preliminary but highlights potential for future adoption.

SWIMMR's advances in modelling, instrumentation, and radiation monitoring have begun to influence a range of sectors beyond its original scope. Although many spillover effects are still emerging, the programme demonstrates clear potential to inform risk assessment, infrastructure resilience, and operational planning in rail, electronics, internet, and nuclear domains. As SWIMMR models and instruments become fully operational, these cross-sector impacts are expected to strengthen, highlighting the broader societal and economic value of the programme.

3.1.8 Q5: Facilitating the generation of intellectual property (IP) and patent applications

Although formal IP protection was not a stated objective, several projects generated intellectual assets with future value:

- N4 (Geomagnetically Induced Currents modelling): Developed IP on representing high-voltage power grids; retained by the British Geological Survey, with foreground IP licensed to the Met Office for operational use.
- N1 & N2 (Radiation belt and aviation radiation models): Produced software tools and analytical methods retained within academic institutions.
- S1 (Radiation sensors): Enhanced existing IP through miniaturisation and improved sensor processing.
- S2 (ChipIr neutron testing facility): Enabled private companies to generate internal IP through use of the facility.

Survey responses confirmed that five SWIMMR projects produced outputs considered IP, demonstrating that innovative tools and methods emerged despite the absence of formal patenting. One project lead explained:

[47] Interview. Project PIs.

> "The N2 model we've generated, the IP is a set of IP that is now within the university. In principle, we could license that IP to other people or develop it further ourselves and so on." [48]

3.1.8.1 Collective innovation and operational integration

SWIMMR deliberately maintained simple IP management to encourage collaboration and reduce legal complexity. By allowing IP to remain with the originating institution while supporting its operational deployment, the programme enabled models, instruments, and testing facilities to be used effectively by the Met Office and academic partners.

This approach meant that innovation was directly translated into national capability, rather than being restricted by commercial or proprietary concerns. As an interviewee noted.

> "We don't tend to do patents in academia because we're not really an engineering organisation. We tend to produce research for either commercial or open research and that is then provided to the clients or the public." [49]

SWIMMR's focus on shared outputs, documentation, and operational usability created fertile ground for future innovation and potential commercial exploitation while maintaining public value.

While formal patents were not pursued, SWIMMR successfully fostered innovation through collective knowledge creation, shared resources, and operationally focused development. The programme generated intellectual assets, software, analytical tools, instrumentation advances, and research methods, that strengthen UK space-weather capability and hold potential for future licensing or commercialisation. By emphasising capability development and collaborative knowledge transfer over proprietary ownership, SWIMMR achieved its strategic objectives and laid the groundwork for sustained innovation.

48 Interview. Project PIs.

49 Interview. Project PIs.

3.2 Industry growth

This section evaluates SWIMMR's impact on boosting the growth of the space weather industry. This was examined through the evaluation question:

Evaluation question
Q6: To what extent has the SWIMMR programme contributed to economic growth?

3.2.1 Key findings

- Employment and skills development: SWIMMR created and safeguarded around 40 high-skilled roles across academia and the Met Office, including research scientists, physicists, postdoctoral researchers, software and instrument engineers, and operational specialists. These figures represent gross jobs, not formally adjusted for deadweight or displacement, though survey evidence indicates high additionality, suggesting most roles would not have existed without SWIMMR. These positions strengthened UK capability in modelling, instrumentation, and forecasting while reducing reliance on overseas expertise through targeted training and on-the-job development.
  Evidence: Project records and survey responses confirm that SWIMMR-supported staff played critical roles in model integration, instrument maintenance, and the development of forecasting workflows at MOSWOC.
  Future implication: Continued investment in specialist roles will be essential to maintain sovereign forecasting capability and retain the skilled workforce underpinning the UK's space-weather resilience.

- Commercial opportunities and industry engagement: The programme enabled emerging commercial activity through enhanced testing facilities, most notably ChipIr and the NILE neutron-testing facility, which now provide unique UK capabilities for assessing electronic and aerospace system resilience under simulated space-weather conditions. These facilities have attracted major international firms willing to pay premium daily rates for access, demonstrating credible early market demand.
  Evidence: Engagements with companies such as Cisco, Arista, STMicroelectronics, Boeing, and Honeywell indicate that SWIMMR outputs are already supporting revenue-generating services and informing resilience improvements in high-reliability sectors.
  Future implication: Broader commercial uptake and structured technology-transfer pathways could accelerate the emergence of a UK space-weather services market.

- Follow-on investment and economic momentum: The programme leveraged approximately £0.60 in additional funding for every £1 invested, through follow-on grants, contracts, and international collaborations. SWIMMR outputs also strengthened the Met Office's case for increased core funding, enabling expansion of its space-weather team and accelerating the integration of academic models into operational systems.
  Evidence: ESA contracts awarded to SWIMMR partners and new Met Office investment demonstrate clear downstream economic effects linked to programme outputs.
  Future implication: As forecasting capability improves, SWIMMR-generated infrastructure and

models could materially reduce potential economic losses from severe space-weather events and stimulate further demand for UK-developed tools, software, and consultancy services.

3.2.2 Employment and skills development

One of the most immediate impacts of SWIMMR has been in the creation and safeguarding of high-skilled employment. Across the suite of projects (S1–S6 and N1–N5), the programme generated or protected approximately 40 roles, including eight positions at the Met Office.[50] These figures represent gross jobs, not formally adjusted for deadweight or displacement, though survey evidence indicates high additionality, suggesting most roles would not have existed without SWIMMR. These roles span research scientists, physicists, postdoctoral researchers, software and instrument engineers, and technical specialists. The academic projects focused on advancing modelling and instrumentation, employing postdoctoral and PhD researchers (30%) and physicists (22%), reflecting the programme's strong emphasis on developing expertise in space physics and computational modelling. A breakdown of the job roles created by SWIMMR are presented in Figure 18.

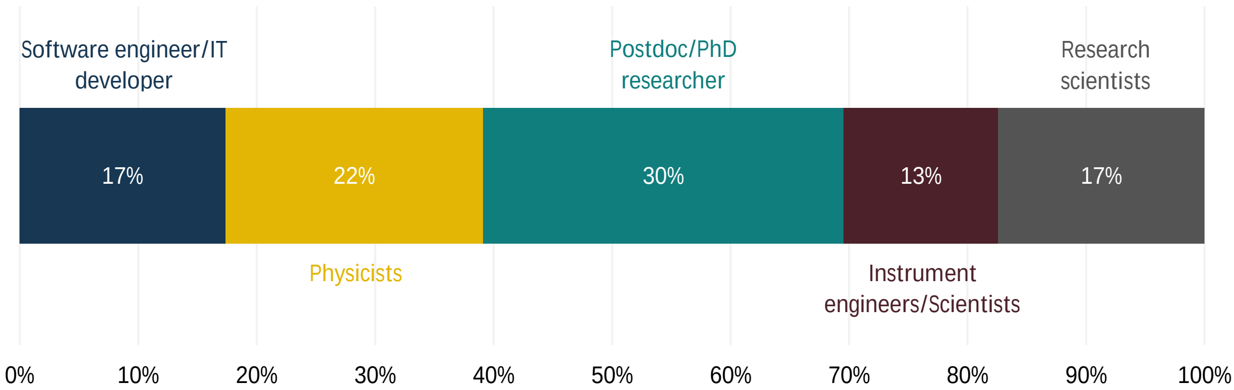


Figure 18. Type of job roles created and/or supported across all core SWIMMR projects led by academia/research organisations (percentages based on interviewees who responded to follow-up questions on the job type/role created or supported).

At the Met Office, roles focused on operational integration, with research scientists and software engineers managing model data, validating outputs, and refining parameters. Technical service specialists maintained and troubleshot instruments, while project managers coordinated the progression of SWIMMR initiatives. Beyond recruitment, SWIMMR supported upskilling through on-the-job training and targeted courses, ensuring that expertise remained in the UK and reducing reliance on overseas talent. By investing in a high-skilled workforce, the programme strengthened the UK's knowledge-based economy and reinforced its global standing in emerging sectors such as space weather services and resilience technologies.

50 Total jobs created and/or supported figure. Interview and survey responses synthesised and cross-evaluated by project.

3.2.3 Commercial opportunities and industry engagement

Although SWIMMR was not originally conceived as a commercialisation programme, it has opened doors to economic and industrial engagement. Facilities established or enhanced through SWIMMR, such as ChipIr and the NILE testing facility at ISIS, now provide unique capabilities for testing electronic systems under simulated space weather conditions. These services, previously unavailable in the UK, have attracted companies willing to pay large amounts of money per day for access, including major international players such as Cisco, Arista and STMicroelectronics.

> "We cost about [commercially sensitive amount] a day to operate with us. The fact they're willing to spend that kind of money to look at the resilience of their systems means they are undoubtedly generating important value within the business."[51]

The programme's models, instrumentation, and facilities have allowed industry partners to test and improve the resilience of electronic systems, aircraft components, and network infrastructure against radiation and space weather effects. These collaborations illustrate how SWIMMR outputs are beginning to translate into revenue-generating activities and form the basis for future licensing, technology transfer, and commercial contracts. The programme has, in effect, started to transition space weather research from a purely scientific endeavour into a sector with genuine commercial potential.

3.2.4 Follow on investment and economic momentum

For every £1 invested in SWIMMR, approximately £0.60 of additional funding has been attracted through follow-on grants, contracts, and international collaborations.[52] ESA, for example, awarded multiple contracts to SWIMMR partners for work related to grid resilience, autonomous vehicles, and socio-economic impact assessment of space weather events.

The programme's outputs have supported the Met Office in securing increased core funding to expand its space weather team and infrastructure, enabling integration of academic models into operational use. This additional capacity strengthens national forecasting and resilience and generates future demand for tools, software, and consultancy services, stimulating UK-based technology providers and creating further economic activity.

Extreme space weather events in the UK could cost the economy an estimated £50 billion in a single year.[53] SWIMMR-enabled forecasting and modelling capabilities improve preparedness and mitigation, reducing potential economic losses and supporting resilience across critical infrastructure sectors.

Collectively, these outcomes demonstrate how strategically targeted public investment can generate a virtuous cycle, producing research outputs that drive innovation, economic growth, and sector development.

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51 Interview. Project PIs.

52 ResearchFish further funding data extract. Funding leverage ratio calculation.

53 https://www.lloyds.com/insights/futureset/futureset-insights/systemic-risk-scenarios/extreme-space-weather/economic-impact

3.3 Collaboration

This section assesses how the SWIMMR programme strengthened collaboration across the UK space weather sector and the extent to which it fostered alignment between academia, research organisations, government bodies, industry, and international partners. The analysis addresses the following evaluation question:

Evaluation question
Q7: To what extent has the SWIMMR programme improved collaboration both nationally and internationally, and how has it fostered closer alignment between academia, industry, and end users?

3.3.1 Key findings

- Strengthened cross sector collaboration: The programme substantially improved collaboration across the UK space-weather ecosystem, bringing together universities, research organisations, the Met Office, government bodies, and emerging industry partners. SWIMMR's mission-led structure created shared objectives and delivery mechanisms that enabled joint infrastructure use, knowledge exchange, and coordinated problem-solving that would not have occurred otherwise. However, industry engagement remains in early development. While SWIMMR successfully initiated contact with private companies, broader commercial adoption awaits full operational deployment of models and services.
  Evidence: Of 42 collaborations across SWIMMR projects, 29 were newly formed, with notable growth in cross-sector links.
  Future implication: Maintaining these networks will be essential for future operational model deployment, commercialisation pathways, and a more integrated national space-weather capability.

- New and sustained national and international partnerships: The programme generated 43 new domestic collaborations and 28 new international partnerships spanning universities, national research agencies, operational bodies, and private companies. Many of these relationships have continued beyond SWIMMR's end date, creating a more connected and opportunity-rich UK space-weather community.
  Evidence: Partnerships with organisations such as NASA, Natural Resources Canada, the University of Nagoya, ESA, and multiple European neutron-monitor groups supported data access, instrumentation development, and operational tool integration.
  Future implication: These partnerships provide a foundation for future joint missions, shared observation networks, and internationally aligned operational forecasting capabilities.

- Enhanced academia–Government integration: SWIMMR deepened relationships between academic institutions and operational agencies, most notably the Met Office, through structured consortia that pooled complementary expertise. This alignment was critical for delivering models, datasets, and forecasting tools that met operational standards.
  Evidence: Several projects included the Met Office as a delivery partner, with regular joint meetings, shared development environments, and coordinated Research-to-Operations

processes that improved scientific robustness and operational relevance.
Future implication: Embedding structured Research-to-Operations-to-Research cycles will strengthen model performance, accelerate operational adoption, and maintain alignment between research capability and national resilience needs.

3.3.2 Strengthened academia, research, and government relationships

SWIMMR played a critical role in deepening links between UK universities, research organisations, and operational bodies. By structuring consortia to combine complementary expertise, the programme enhanced shared infrastructure and strategic alignment, which was essential for delivering outputs such as models, datasets, and forecasting tools. This approach has successfully met SPF objectives of increasing high-quality multidisciplinary and interdisciplinary research and innovation in the UK.

Analysis by organisation type shows that, of 42 distinct collaborations captured across SWIMMR projects, 13 were pre-existing, primarily academia–research (9) and academia–academia (2), with one research–research and one academia–government link.[54] The majority (29) were newly formed, reflecting the programme's proactive role in fostering connections across the ecosystem. Notably, cross-sector collaborations included academia–government (1), academia–industry (2), industry–industry (2), and industry–government (3), demonstrating SWIMMR's success in linking previously unconnected sectors (Figure 19).

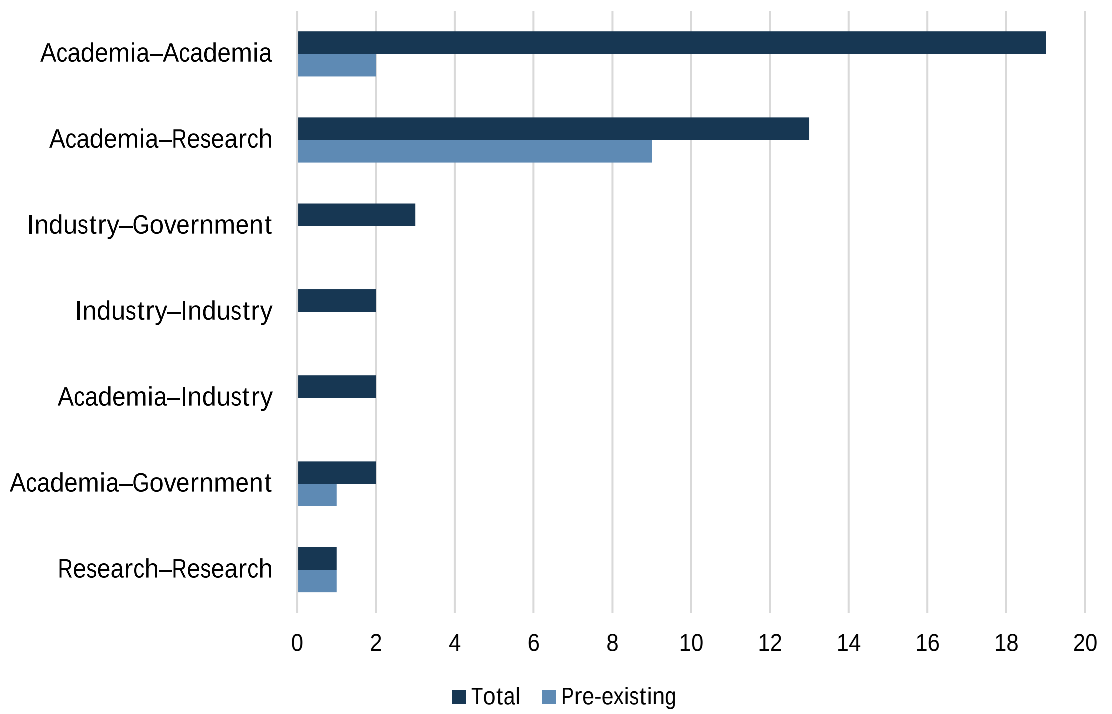

Figure 19: Collaborations before and during SWIMMR

[54] Data sources include: SciVal, Scopus, ReseachFish, Google Scholar.

The programme's joint requirements and objectives necessitated a highly collaborative approach. Consortia were established for each project, with six projects engaging universities and research institutions from the outset, and four projects including industry partners alongside academic and research bodies. The Met Office was a key partner across nearly all projects, providing operational expertise, supporting the transfer and testing of models and instruments, and facilitating knowledge exchange through regular engagement. SWIMMR acted as a conduit for academic researchers to engage with operational teams and research institutes on real-world challenges, ensuring outputs were scientifically robust and operationally relevant.

A notable example is the N1 project, led by the British Antarctic Survey (BAS), which brought together Imperial College London, University of Reading, Northumbria University, University of Sheffield, the Met Office, and a private industry consultant. The consortium exemplifies SWIMMR's ability to create cross-sector engagement. As one participant noted:

> "It worked really really well. It was a very friendly atmosphere. It was open sharing of data and the Met Office were really good in bringing a wider community."[55]

The Met Office played a central role in convening stakeholders and maintaining regular meetings, which facilitated knowledge exchange and helped initiate new relationships with defence organisations, including Dstl and the Ministry of Defence (MOD):

> "Engagement with the MOD is important. We tried to engage with them for many years in years gone by, and now it feels like they really are engaged, which is really good."[56]

All SWIMMR projects involved a mix of organisation types, promoting shared learning and creating a connected ecosystem of academia, research organisations, and government. This close-knit network is expected to enhance the UK's credibility in space weather science and operations, support operational innovation, and underpin future joint initiatives.

However, engagement with industry remains at an early stage. While SWIMMR has initiated partnerships with private companies, further investment and targeted efforts are needed to accelerate the translation of research outputs into commercial applications. Operational uptake by industry is still nascent, pending full model deployment and service-level agreements. As one advisory member reflected:

> "Within the space weather community, it's had a significant impact. Outside of that bubble, however, I think its impact has been minimal."[57]

Future programmes could build on SWIMMR's achievements by embedding more structured industry engagement, focusing on pathways for commercialisation, and strengthening public awareness of UK capabilities in space weather resilience.

55 Interview.Project PIs

56 Interview. Project PIs

57 Interview. Advisory board member.

3.3.3 External collaborations

A key strength of the SWIMMR programme was its ability to build partnerships beyond core project teams. It established 33 new external collaborations involving academic institutions, operational agencies, international research organisations, and private sector partners, delivering both scientific and operational benefits. Notably, 28 of these collaborations were international, underscoring SWIMMR's strong global reach and influence.[58]

- Scope and diversity of collaborations: SWIMMR fostered collaborations across several countries, including the United Kingdom, United States, Canada, New Zealand, Italy, Finland, Netherlands and Switzerland. Partners included universities (e.g., University of Oulu, University of Arizona, University of Otago), national research agencies (e.g., NASA, Natural Resources Canada), operational bodies (e.g., Met Office, Royal Netherlands Meteorological Institute,), and private companies (e.g., Mirion Technologies, Hybrid Instruments, Surrey Satellite Technology Ltd).

  Most collaborations were academic–academic or academic–operational in nature, with a smaller number involving private sector organisations. Collaborations typically involved small, focused consortia of two to four partners, allowing clear coordination, knowledge exchange, and alignment with programme objectives.

- Contributions and resource sharing: External partners contributed in a variety of ways, often through in-kind support including:

  - Access to data and instrumentation (e.g., ground-based magnetometers, neutron monitors, radiation measurements).
  - Expertise in model development, simulation, and operational procedures.
  - Support for technical notes, mission concept studies, and instrumentation design.

  Formal financial contributions were limited but strategically targeted to support operationalisation or instrumentation development. Examples include EUR 65,000 from SSTL and GBP 20,000 from Mirion Technologies. As part of wider resource sharing and collaboration, the University of Rome Tor Vergata has acted as an early academic user of our neutron monitoring capability. A monitor has been installed and is now operating at their Rome site, and discussions are continuing on broader applications, including potential deployment aboard an ocean-going vessel through the Italian Ministry of Defence.

- Scientific and operational outcomes: External collaborations have generated tangible outputs and impacts, including:

  - Publications in preparation or submitted to high-impact journals.
  - Conference presentations and technical notes on instrumentation and mission concepts.

[58] ResearchFish

- Improved operational capability for space weather forecasting, radiation belt simulations, geomagnetically induced current (GIC) modelling, and cosmic radiation monitoring.
- Enhanced research-to-operations (R2O) transition, exemplified by the integration of academic models into Met Office operational systems.

In several cases, collaborations enabled unique datasets or facilities, such as the commissioning of new neutron monitors in the UK and Italy, access to extreme space weather testing facilities, and joint studies with international agencies.

- Strategic value: Respondents highlighted that external collaborations:
  - Strengthened the UK space weather community through sustained international engagement.
  - Facilitated skill and knowledge transfer between academia, operational agencies, and industry.
  - Provided a mechanism for translating research into operational or near-operational tools, often more rapidly than comparable international programmes.
  - Demonstrated that relatively modest in-kind and financial inputs can leverage substantial scientific and operational impact.

These impacts are illustrated by specific SWIMMR projects, below, that leveraged external partnerships to deliver tangible outcomes:

S5 – Advancing Instrumentation and global knowledge sharing

The University of Lancaster-led S5 project exemplifies how SWIMMR facilitated both industry engagement and international academic collaboration. Through a competitive tender, Mirion Technologies was selected to supply instrumentation meeting rigorous operational standards, including full documentation, CE marking, and lifetime quality assurance. As one team member noted:

> "I learnt more about industry in putting together something that's got a lifetime quality record, extremely well documented ... so that we can get it on to the Met Office site."[59]

Beyond industry collaboration, S5 strengthened ties with the European neutron monitor network, including partners in Finland, Greece, Belgium, Hawaii, and South Africa. These relationships advanced technical innovation, shared design standards, and enabled interoperability across global monitoring systems. Key benefits included access to high-quality, compliant instrumentation, knowledge exchange across an international academic network, and enhanced UK capability in cosmic radiation monitoring.

[59] Interview. Project PIs.

N4 - Driving operational Innovation through ESA and Japan partnerships

The N4 project demonstrated SWIMMR's capacity to translate research outputs into operational solutions with international impact. Led by the British Geological Survey, the project established strategic partnerships with the University of Nagoya (Japan) and Geosphere Austria. UK-developed technology, including a real-time GIC nowcasting system, was incorporated into a European Space Agency (ESA) initiative, highlighting the attractiveness of UK capability on the international stage. As one respondent reflected:

> "On the back of this project, we've built partnerships with University of Nagoya [in Japan]. We've also taken the technology, and we're using it for a European Space Agency project."[60]

These collaborations accelerated the development of operational forecasting tools, enabled technology transfer, and strengthened the UK's strategic influence in international space weather monitoring.

N3/N5 – Strengthening global government and defence engagement

SWIMMR enabled UK universities to expand beyond academic-only collaborations into high-level partnerships with international government and defence organisations. The N3/N5 project provided opportunities for the University of Birmingham and other UK institutions to engage with the US Space Weather Prediction Center, US Air Force Research Laboratory, US Naval Research Laboratory, the Australian Bureau of Meteorology, and Australia's Defence Science and Technology Group. Industry engagement also expanded, including collaboration with Orion (USA).

> "SWIMMR was key for me personally... moving from just being a university to having strong collaborations with industry and government, but also in other countries."[61]

These collaborations enhanced UK operational credibility, provided access to critical global datasets, and optimised resources by building on data agreements already established by the UK Met Office and NOAA. They also demonstrated the strategic value of SWIMMR in targeting collaborations to maximise efficiency, reduce duplication, and generate impact across multiple operational domains.

Summary of impact

Collectively, these examples illustrate SWIMMR's contribution to international collaboration, industry engagement, and operational innovation. They highlight the programme's ability to:

- Deliver high-quality, operationally relevant outputs.
- Build strategic international partnerships.
- Enhance UK technical capability and global reputation.

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60 Interview. Project PIs.

61 Interview. Project PIs.

- Support knowledge exchange and technology transfer across academia, industry, and government

Overall, the external collaborations have reinforced SWIMMR's impact beyond its immediate project teams, underpinning both the programme's scientific achievements and its operational relevance. They provide a model for future interdisciplinary, mission-led programmes where small-scale, high-value partnerships can deliver measurable outcomes.

3.4 UK's global reputation

This section examines the impact of the SWIMMR programme on the UK's international standing and sovereign capability in space weather research. International reputation is shaped by several external factors, including pre-existing scientific capability, long-standing collaborations, and broader investment in the UK space sector. Accordingly, the analysis clearly identifies credible contribution and where attribution can be evidenced. The analyses answer's the evaluation question:

Evaluation question
Q8: How has the SWIMMR programme enhanced the UK's position as a leader in space weather research?

3.4.1 Key findings

- Increase in international recognition: SWIMMR has raised the UK's visibility within the global space-weather community, particularly through its research-to-operations (R2O) advances and integrated programme structure. International agencies have taken renewed interest in UK approaches, and stakeholders consistently report greater recognition at major conferences and technical forums.
  Evidence: Interviewees described UK Research-to-Operations processes being referenced positively by NASA, NOAA, and ESA; UK-hosted events saw up to one-third international attendance; and partners reported being impressed by UK capability delivered on comparatively modest budgets.
  Future implication: Demonstrated operational performance of SWIMMR-supported tools will be essential for converting this growing recognition into sustained international leadership.

- Enhanced sovereign capability: The programme has materially increased the UK's ability to generate and use its own space-weather data, models, and testing capabilities. These assets reduce dependency on overseas missions and datasets and provide credible pathways to long-term scientific and operational independence.
  Evidence: SWIMMR delivered new UK-owned models, unique airborne and high-altitude datasets, and Europe's only neutron ground-level testing facility. Survey findings show 90% agreement that the UK's sovereign capability has improved due to assets that stakeholders reported would not exist without SWIMMR.
  Future implication: Continued investment is required to maintain and scale these capabilities, especially in observational coverage and operational integration, to secure enduring sovereignty.

- Emerging leadership potential, contingent on operational validation: Stakeholders view the UK as increasingly competitive with leading nations, sometimes ahead in specific technical areas, but emphasise that international leadership ultimately depends on proving operational performance at scale.
  Evidence: Interviewees cited the UK as being on a level playing field with the United States in

certain model domains, but also stressed the need for validation demonstrating superiority over existing Met Office tools.
Future Implication: Full R2O transition and performance verification will determine the UK's credibility as a global leader and shape future influence in international standards, missions, and resilience frameworks.

3.4.2 International recognition and attention

SWIMMR's international recognition has been a notable strength of the programme. Around 60% of its research publications (122) involved international collaboration, reflecting strong global engagement and the ability to connect UK expertise with leading scientists worldwide.[62] These collaborations have fostered knowledge exchange and strengthened the scientific community. Prior to SWIMMR, the UK was regarded as competent but behind leading nations in operational space-weather capability. Interview evidence suggests the programme has shifted this perception, with many stakeholders now viewing the UK as operating on par with the United States in key technical areas, particularly where SWIMMR accelerated Research-to-Operations transitions.

> "I think we're seen as at least at least on a level playing field with the United States and arguably in some areas ahead of the United States, which is a great place to be."[63]

International agencies have shown interest in the UK's approach to integrating academic research into operational systems. Several interviewees reported that UK R2O processes were highlighted at international conferences as examples of effective programme management and alignment between research and operations. This interest has resulted in requests for knowledge-sharing sessions and expanded international engagement. UK-hosted space weather events have experienced increased international participation, with some annual meetings attracting roughly one third overseas attendees. Stakeholders attribute this to a perception that UK research groups offer a comparatively integrated R2O model and a collaborative national structure.

> "Space weather seminars have morphed into an annual space weather meeting, last year we had about 200 attendees, a third of them were international attendees, because they see it's quite unique we are so research to operations focused"[64]
>
> "I am often asked [by US partners] how we deliver so much for so little [Funding]... So to go from where we were to an operational thing, most people don't understand how it's possible."[65]
>
> "I've presented results in international conferences with some top US members there and they are interested, they are impressed."[66]

62 ResearchFish geographical collaborations data extract.
63 Interview. Met Office.
64 Interview. Met Office.
65 Interview. Project PIs.
66 Interview. Project PIs.

Despite these positive indications, several respondents emphasised that sustained demonstration of operational accuracy and performance will be required before the UK can fully consolidate its international reputation. The forthcoming validation of SWIMMR-supported models and instruments is therefore seen as an important next step.

> "I feel the work we've done has been very valuable, but we need to show that it's working in operations and that it actually is more effective than the tools the Met Office currently use."[67]

While stakeholders widely credited SWIMMR with improving the UK's international profile, the evaluation recognises several important contextual factors that limit the strength of causal attribution. The UK entered the programme with an already well-established academic reputation in space weather, meaning that some international attention would likely have occurred regardless of SWIMMR. Similarly, rising global interest in space weather as a field may explain part of the increased participation at UK-hosted events, independent of programme activities. In addition, the UK's long-term reputation will ultimately depend on sustained operational performance and the successful validation of SWIMMR-supported tools over time. Taken together, these factors suggest that SWIMMR made a meaningful contribution to enhanced international standing, but was not the sole driver of change.

3.4.3 Sovereign capability and global influence

Survey evidence indicates broad agreement that SWIMMR strengthened the UK's global standing (90% of respondents either agreed or strongly agreed). Interviews reinforce this perception. Attribution of impact in this area is clearer because the programme delivered tangible and unique national assets, including new models, datasets, and Europe's only neutron ground-level testing facility. Stakeholders highlighted that SWIMMR-supported tools, particularly in radiation belt modelling, ionosphere–thermosphere modelling, aviation radiation exposure, and new ground-based neutron and airborne measurement systems, have expanded the UK's capacity to generate national data and reduce reliance on external missions. Some sensors provide unique datasets (e.g., above 1,200 km altitude), offering opportunities for scientific leadership.

The establishment of Europe's only neutron ground-level testing facility was regarded as a significant step in strengthening UK sovereignty. Stakeholders viewed this capability as strategically important for supporting industry and future mission development.

These mechanisms form a plausible causal pathway between SWIMMR delivery and perceived increases in UK stature and independence. However, gaps remain. Stakeholders identified limited observational coverage across parts of the space environment and the need for continued investment to maintain and scale operational capability. While SWIMMR has created a strong foundation, long-term influence will depend on follow-on programmes, continued integration within the Met Office, and the extent to which new capabilities are embedded in international standards and collaborations.

[67] Interview. Project PIs.

3.5 Security and resilience

This section assesses the extent to which the SWIMMR programme has enhanced the ability of government and industry to apply adaptation and mitigation measures for space weather, and the degree to which the programme has contributed to reducing health and safety risks across three critical domains. These domains, aviation, communications and global positioning, and electricity networks, were central to SWIMMR's design, reflecting sectors where space weather impacts pose material operational and safety risks.

SWIMMR primarily sought to mitigate risks by improving forecasting, modelling, and monitoring capabilities, focused particularly on integrating new systems into the Met Office Space Weather Operations Centre (MOSWOC) as the principal end user. However, benefits and early engagement have extended beyond the Met Office. The Met Office will supply outputs from SWIMMR models, to the National Space Operations Centre, jointly led by the UK Space Agency and MoD Space Command, to support their role in safeguarding the UK's space assets. Government departments, commercial operators, and industrial stakeholders are beginning to recognise the value of SWIMMR outputs, and several interviewees noted that the programme has stimulated strategic conversations across aviation, satellite operations, and energy. Nonetheless, much of this impact remains prospective: operational adoption is emerging, not yet embedded, and translation into formal policy and organisation-wide mitigation measures is still developing.

The following sections examine progress to date, the early response from government and industry, and emerging evidence of potential health and safety benefits across the three mitigation domains. The analysis addresses two evaluation questions:

Evaluation question
Q9: How has the SWIMMR programme increased the ability of industry and government to apply adaptation and mitigation measures for space weather?
Q10: How has the SWIMMR programme contributed to reducing health and safety risks associated with space weather events?

3.5.1 Key findings

- Increased awareness of space weather risks: SWIMMR has raised awareness of space weather impacts among government and industry, stimulating strategic discussion and framing space weather as a material risk for critical sectors.
  Evidence: References to SWIMMR appear in the 2021 Severe Space Weather Preparedness Strategy, the National Space Strategy, and the Defence Space Strategy. Interviews indicate that stakeholders are more informed and engaged, though adoption of formal mitigation measures remains limited.
  Future Implication: Demonstrating quantifiable value and integrating outputs into standard operational and policy frameworks will be essential to translate awareness into practical, system-wide mitigation.
- Translation into policy and operational adoption is emerging: While SWIMMR has provided scientifically robust tools and evidence, widespread embedding into government policy and

industry practice remains limited due to event rarity, unclear standards, and challenges in quantifying operational and economic risk.
Evidence: Stakeholders consistently note that outputs inform internal planning and strategy, but operational adoption across government and commercial sectors is uneven. S6 project updates refreshed national evidence but were not fully endorsed, limiting policy impact.
Future implication: Strengthening risk quantification, demonstrating value, and aligning outputs with decision-making needs will be crucial to convert SWIMMR capabilities into actionable mitigation measures across sectors.

- Critical infrastructure resilience: SWIMMR has enhanced UK resilience across aviation, satellite systems, and the power grid. High-altitude radiation sensors, balloon instruments, and ionosphere–thermosphere models support operational decision-making for polar routes, improving safety and informing flight planning. GNSS, satellite health, and collision-avoidance modelling has increased situational awareness during space weather events, while UK-specific GIC forecasting tools estimate transformer risk and guide grid planning.
  Evidence: Sensors and models successfully informed the May 2024 storm response; NESO and airlines are engaging with outputs, and ICAO engagement is underway.
  Future implication: Full operational integration will reduce health and safety risks, strengthen satellite and aviation resilience, and inform critical infrastructure management.

3.5.2 Industry and government response to space weather event adaptation and mitigation measures

Translation of SWIMMR outputs into formal government policy and industry-wide mitigation measures remains at an early stage. Interviewees acknowledged that SWIMMR has raised the profile of space weather as a national risk and stimulated more informed discussions across strategic and operational communities. However, several systemic factors constrain adoption:

- Event rarity reduces perceived urgency. As one project lead noted, severe events are so infrequent that organisations "*have a million other better things to worry about*."
- Lack of clear standards makes it difficult for organisations to justify investment or benchmark risk.
- Challenges in quantifying risk impede business cases for resilience measures.
- Commercial sensitivities limit visibility of internal mitigation practices.

The result is an environment in which awareness is rising, technical capability is maturing, but organisational adoption is still emerging.

3.5.2.1 Government

Government adoption of space weather mitigation measures influenced by SWIMMR remains limited, though awareness and strategic recognition have clearly increased. Interviewees reported that SWIMMR helped inform aspects of national risk planning, including updates to the 2021 Severe Space Weather Preparedness Strategy, which references SWIMMR and assigns obligations to the Met Office to incorporate programme outputs into national capability. Space weather is also now reflected in the National Space Strategy and the Defence Space Strategy, signalling that it is recognised as a material risk.

However, interviewees emphasised that these developments cannot be attributed solely to SWIMMR:

> "I wouldn't say that SWIMMR influenced that strategy [2021 Severe Space Weather Preparedness Strategy] being published. I think it would have happened whether SWIMMR was there or not, but it certainly influenced some of the content of that."[68]

A broader barrier relates to the lack of clarity around risk quantification. One project lead explained that uncertainty persists over whether a severe event would cause sudden catastrophic failure or a gradual degradation of systems, an ambiguity that complicates investment decisions and preparedness planning. Although departments are increasingly aware of space weather, interviewees described engagement among critical national infrastructure operators as slow and uneven. Comparisons were drawn to New Zealand, where space weather is treated with greater urgency and clearer expectations for resilience planning.

Overall, evidence points to growing strategic attention, but limited operational follow-through, with SWIMMR contributing to the enabling environment rather than driving specific policy changes.

3.5.2.2 Assessment of the S6 project

The S6 project, commissioned to update the Royal Academy of Engineering's 2013 assessment of space weather impacts, was intended to refresh the evidence base underpinning resilience planning across government and critical national infrastructure. Given the significant scientific and technological advances over the past decade, as well as changes to UK infrastructure, operating models, and dependencies on satellite-based services, the decision to update the 2013 report was well-founded. Interviewees noted that the 2013 assessment remained highly influential but was increasingly outdated, particularly in its treatment of GNSS vulnerabilities, data-centre risks, and the evolving electricity system. On this basis, commissioning an updated study was justified and aligned with the programme's aim of strengthening the national evidence base.

The updated analysis generated new insights and a broader sectoral assessment, drawing on improved datasets, more sophisticated modelling capabilities, and stakeholder engagement across the space, communications, transport, and energy sectors. These enhancements provided a more contemporary picture of UK exposure to severe space weather events and identified areas where existing resilience measures were insufficient. From an analytical standpoint, the project improved the granularity and relevance of the evidence available to government.

However, the value of the investment was constrained by limitations in the report's precision and clarity, issues that ultimately prevented the Space Environment Impacts Expert Group (SEIEG)

68 Interview. Met Office.

from endorsing it. SEIEG members felt that the assessment did not fully resolve key uncertainties (such as the likely scale and timing of system degradation across sectors), and that some recommendations were not actionable given current risk-assessment standards. As a result, the report's ability to shape government policy was reduced, and its intended influence on national resilience planning was not fully realised.

Despite this, the work was not without benefit. Stakeholders indicated that the updated report contributed to internal discussions on critical national infrastructure exposure, supported more informed dialogue between technical experts and policymakers, and provided a platform for subsequent analytical work commissioned by NESO and other agencies. In this sense, the S6 project offered partial value: it refreshed an outdated evidence base and triggered further analytical activity, even if it did not achieve the level of policy traction originally intended.

Overall, the update can be considered justified in principle and directionally useful, but the shortcomings that prevented endorsement limited its strategic impact. Future updates of national space weather assessments may need stronger methodological rigour, clearer quantification of risk, and more explicit alignment with government decision-making needs to maximise the value of such investment.

3.5.2.3 Industry

Industry engagement with SWIMMR outputs has generally been more immediate than governmental uptake, reflecting the operational relevance of many project deliverables. Aviation stakeholders, in particular, have benefited from early access to radiation monitoring and improved forecasting tools. Satellite operators and power network companies also stand to gain, though direct evidence of systematic operational uptake remains inconclusive.

Stakeholders repeatedly highlighted the difficulty of quantifying risk in commercially meaningful terms as a key barrier to adoption. One project lead summarised this challenge:

> "… until somebody cracks the actual risk and can quantify it properly rather than just in a hand-wavy sort of way ... I don't think it can be taken seriously by people in industry."[69]

Another emphasised the importance of demonstrating value before organisations switch from legacy systems:

> "You have to think about the value of changing over from an old system that 'works'… it's not a technical challenge as much as it's a commercial challenge."[70]

Commercial confidentiality also restricts visibility of how companies use SWIMMR outputs internally. Some operators consider their mitigation strategies proprietary and are reluctant to share them, making it difficult to assess the extent of practical uptake. Other interviewees noted that for many companies, space weather remains a relatively low priority due to its infrequency:

[69] Interview. Project PIs

[70] Interview. Project PIs

> "A lot of these industries are sceptical there is an impact… [severe events] happen so rarely that they've got a million other better things to worry about."[71]

In summary, SWIMMR has generated tools with clear operational relevance, but widespread adoption is likely to depend on demonstrating quantifiable value, establishing clear standards, and reducing uncertainty around risk.

3.5.3 Reducing health and safety risks associated with space weather in aviation, communications, and power grid domains

SWIMMR sought to mitigate health and safety risks associated with space weather across three domains:

- Aviation: reducing radiation hazards and communication failures
- Communications and global positioning: reducing GNSS degradation and satellite disruption
- Electric power grids: reducing GIC-induced transformer stress and blackout risk

Evidence indicates that the aviation sector has seen the earliest and clearest benefits, while satellite operations and power networks show promising but still developing engagement.

3.5.3.1 Aviation

Aviation is the sector showing the most tangible and immediate application of SWIMMR outputs. Project leads confirmed that radiation sensors developed under SWIMMR are now deployed on commercial aircraft and integrated into the Met Office's operational systems. These tools have strengthened operational decision-making for high-altitude and polar routes, where radiation exposure and communication disruptions are most acute.

The Met Office highlighted strengthened engagement with the International Civil Aviation Organization (ICAO), which sets global standards for flight safety and radiation alerts. Enhanced measurement and modelling capability is expected to shape future ICAO discussions on thresholds and response protocols. While operational integration is at an early stage, SWIMMR has clearly improved the evidence base and provided practical tools for managing risks in live environments.

Case study 3, below, examines how SWIMMR-derived tools are being adopted by airlines and incorporated into Met Office operations, and how these developments are shaping engagement with international regulatory bodies.

[71] Interview. Project PIs

3.5.3.2 Case study 3: Risk mitigation in aviation

This case study assesses the impact of SWIMMR outputs on the aviation sector, focusing on two key risk areas: radiation exposure and disruption to flight communications. Aviation provides an early example of tangible application because of its well-defined operational requirements, high sensitivity to space weather events, and international regulatory oversight. The evaluation considers how SWIMMR's radiation sensors, high-altitude measurements, and ionosphere-thermosphere modelling have contributed to operational decision-making, situational awareness, and resilience in live aviation contexts.

Radiation monitoring

Objective addressed: Mitigate the potential radiation hazards of space weather to aviation operations.

The SWIMMR programme significantly enhanced aviation radiation measurement capabilities. Fourteen aviation sensors and ten high-altitude balloon sensors were deployed, operating with two UK commercial airlines, one international airline, and select Royal Air Force platforms. These instruments provide real-time measurements of particle type and energy levels at cruising altitudes, enabling more accurate assessment of cumulative radiation exposure for passengers and crew, particularly on high-latitude and polar routes.

The benefits to the aviation industry include:

- Improved understanding of cumulative radiation exposure along critical flight paths.
- Enhanced risk assessment for aircraft electronics susceptible to particle-induced malfunctions.
- Provision of actionable data for operational decisions, including re-routing or adjusting flight altitudes during heightened space weather activity.

As one project lead highlighted:

> "On the instrumentation front for aviation, there's a lot of interest in the instruments we've built and international interest from Boeing, amongst others."[72]

By providing high-resolution, real-time radiation data, SWIMMR supports more informed operational planning, contributing to passenger and crew safety, protecting avionics systems, and strengthening the UK's capability to deliver internationally recognised space weather services. While full integration into airline operational protocols is ongoing, the evidence indicates a clear contribution to the sector's preparedness and resilience.

Flight communications and air traffic control

Objective addressed: Mitigate the potential space weather effects on communication and global positioning.

Reliable communication between aircraft and air traffic control is essential for safe operations, particularly on transoceanic and polar routes where high-frequency (HF) radio remains the

[72] Interview. Project PIs.

primary method of contact. Severe space weather events can disrupt HF signals by altering ionospheric conditions, limiting reliable communication. SWIMMR's ionosphere-thermosphere modelling provides forecasts of HF communication performance, enabling the Met Office to issue alerts and support route planning for flights operating above 82 degrees North, where HF communication is mandatory.

The benefits for aviation operators include:

- Improved situational awareness, distinguishing space weather-related communication disruptions from other operational issues.
- Enhanced operational planning, allowing flight paths or altitudes to be adjusted in anticipation of HF signal degradation.
- Strengthened safety, reducing the risk of losing contact with aircraft in remote polar regions.

As the Met Office noted:

> "The ionosphere-thermosphere modelling capability now allows us to develop downstream applications like communication maps for air traffic control and establish effective communication frequencies"[73]

This capability represents a significant advance in aviation resilience. Although operational integration is at an early stage, SWIMMR's outputs are informing international discussions with the International Civil Aviation Organization (ICAO) on thresholds for radiation alerts and communication protocols, reinforcing the UK's role as a provider of critical space weather services.

Assessment

SWIMMR's aviation-focused outputs demonstrate early and tangible benefits by strengthening operational decision-making, situational awareness, and safety in high-risk flight environments. The deployment of radiation and balloon sensors provides credible, real-time data, while ionosphere-thermosphere modelling supports proactive management of HF communication risks.

However, full attribution to SWIMMR is moderated by the nascent stage of operational integration. Evidence of realised outcomes, such as confirmed flight path adjustments or avoidance of HF-related incidents, remains limited, and economic benefits, including cost savings or efficiency gains, are not yet quantifiable. Nevertheless, the programme has clearly enhanced the evidence base, facilitated engagement with key stakeholders, and laid the foundation for future operationalisation and international collaboration.

[73] Interview. Met Office.

3.5.3.3 Communications and global positioning

Space weather can significantly disrupt satellite-based communication systems and degrade the accuracy of global navigation satellite services (GNSS), creating operational risks for sectors that depend on precise positioning and uninterrupted connectivity. The SWIMMR programme addressed these challenges through advances in ionospheric and thermosphere modelling, radiation belt forecasting, and tools to support satellite health and orbit management.

- GNSS, GPS precision and reduction of satellite collisions: SWIMMR's ionosphere–thermosphere models provide a more accurate characterisation of atmospheric conditions that affect GNSS performance. These improvements are crucial for navigation, emergency services, and infrastructure requiring precise timing. Interviewees reported that the enhanced modelling capability improves situational awareness of when positioning errors may occur.

  The improved thermosphere modelling also supports collision avoidance by reducing orbital prediction errors. However, this capability is not yet operationally integrated. As one project lead stated:

  > "We are not yet at the point where MOSWOC… are using the SWIMMR models in their operational planning. That's what I'm hoping to see in the next 6 to 12 months"[74]

- Satellite health and radiation risks: SWIMMR's radiation belt model provides early warnings of increased radiation levels, enabling satellite operators to take protective measures. During the May 2024 storm, the model accurately identified elevated risk in medium Earth orbit and slot region satellites, critical for GNSS and communications—allowing operators to focus monitoring and adjust operations.

  > "We forecast the risk red, amber, green for satellite charging."[75]

  Companies such as Space DOTS are engaging with SWIMMR data to strengthen commercial space weather risk assessment services. Overall, SWIMMR has introduced highly relevant capabilities, though operational adoption is still emerging.

3.5.3.4 Electric power grids

Space weather can induce geomagnetically induced currents (GICs) that stress transformers and increase the risk of power outages. Prior to SWIMMR, the UK lacked robust UK-specific modelling. SWIMMR filled this gap through new GIC tools tailored to British grid infrastructure.

- GIC modelling capability: The new models combine ground conductivity data with geomagnetic measurements to forecast GICs at individual substations. As one project lead described:

[74] Interview. Project PIs.

[75] Interview. Project PIs.

> "Now we have a model for the power grid of United Kingdom, that actually gives you at nodes of the power grid, an estimate of the ground induced current they can expect."[76]

This capability was successfully validated during the May 2024 storm, which triggered transformer alarms in locations identified by the model as high-risk. Although the storm did not require reactive mitigation measures, it demonstrated the accuracy and operational value of the model.

- Early engagement from NESO: The National Electricity System Operator (NESO) has shown significant interest in SWIMMR outputs and has commissioned follow-on research with SWIMMR partners and the Met Office:

> "On the back of it [SWIMMR], NESO has commissioned further research… to look at the effects of extreme space weather on the power grid and give them policy ideas for future research."[77]

While direct mitigation measures (e.g., reconfiguration protocols, hardware changes) have not yet materialised, SWIMMR is informing strategic planning and priority-setting for monitoring infrastructure.

Case study 4 discusses how SWIMMR's modelling and forecasting tools are being applied to understand and mitigate these risks, supporting resilience planning and informing discussions with operators such as the National Electricity System Operator (NESO).

[76] Interview. Met Office.

[77] Interview. Project PIs.

3.5.3.5 Case study 4: Risk mitigation in electric power grids

This case study assesses the impact of SWIMMR on the UK electricity sector, focusing on mitigating the risks posed by space weather events to the national power grid. Severe geomagnetic storms can induce geomagnetically induced currents (GICs) in the Earth's surface, stressing transformers and other critical infrastructure, and potentially causing regional power outages. The evaluation examines how SWIMMR's modelling, measurement, and forecasting tools have strengthened situational awareness, informed resilience planning, and contributed to decision-making within both industry and government.

Geomagnetically Induced Current (GIC) modelling

Objective addressed: Mitigate the potential risks of space weather to electric power distribution.

SWIMMR delivered a UK-specific capability for GIC modelling, combining geomagnetic field measurements with detailed geoelectric data derived from the N4 project. Over 2021–2024, the N4 project conducted 53 new magnetotelluric (MT) measurements and integrated 17 legacy datasets to produce a comprehensive geoelectric model of Britain. The analysis revealed significant regional variations in conductivity, including a highly resistive zone in West Yorkshire and a conductive zone in Cheshire, challenging prior assumptions about grid vulnerability.

When combined with geomagnetic data, this model demonstrated that areas around Bradford were more susceptible to GICs than previously recognised. Earlier NESO advice had prioritised peripheral nodes such as Norfolk and Cornwall for monitoring. SWIMMR's insights enabled NESO to refocus sensor deployment to areas of greatest vulnerability, improving the evidence base for operational decision-making and resilience planning.

This integration of geophysical measurements and geomagnetic monitoring represents a step change in national capability, enhancing the accuracy of forecasts and supporting evidence-based resilience strategies.

Operational validation and early use

During the May 2024 geomagnetic storm, SWIMMR's GIC model correctly identified high-risk substations where transformers triggered alarms, validating the forecasting capability. Although the event did not require active mitigation, it demonstrated the practical utility of the model for operational planning and risk assessment. Figure 20 indicates the outputs of the model at the time of the storm.

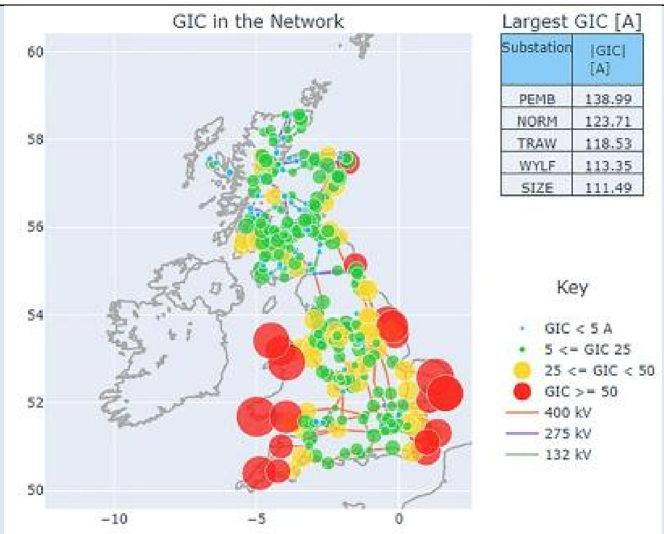

Figure 20. Map of the nowcast of geomagnetically induced current (GIC) (in amperes) in the Great Britain high voltage grid during the May 2024 geomagnetic storm.[78]

The National Electricity System Operator (NESO) has since commissioned further research with SWIMMR partners and the Met Office to explore extreme space weather effects on the grid and to develop evidence-based recommendations for future policy and monitoring strategies.

Benefits for the electricity sector:

- Improved situational awareness: Grid operators can identify substations at risk during geomagnetic storms and take preventive action to protect critical infrastructure.
- Evidence-based resilience planning: Forecasts inform investment decisions, monitoring strategies, and prioritisation of protective measures across the network.
- Enhanced collaboration: SWIMMR outputs have strengthened engagement between the Met Office, National Electricity System Operator (NESO), and industry stakeholders, facilitating knowledge sharing and coordinated planning.

Assessment

SWIMMR's GIC modelling capability represents a substantial advancement in national resilience to space weather. While direct mitigation measures have not yet been widely implemented, the programme has clearly improved understanding of risk, informed operational planning, and provided a robust evidence base for future investment and monitoring strategies.

Attribution to SWIMMR is strong in terms of capability development, technical innovation, and decision-relevant insights. Full operational impact is still prospective, pending widespread integration into routine grid operations, but the programme has already contributed to strategic preparedness, improved situational awareness, and strengthened the UK's position as a leader in space weather risk management.

[78] Reproduced from Beggan et al. (2025) under the CC BY 4.0 licence. © 2025 British Geological Survey (UKRI)

3.6 Additionality of SWIMMR support

Survey evidence provides a clear indication that SWIMMR funding was instrumental in enabling activities that would otherwise have been significantly constrained (Figure 21). While the total eligible population comprised 48 individuals involved in programme delivery and governance, 20 respondents answered the additionality questions. Although results are unweighted, the achieved sample provides informative coverage of project, management, and governance perspectives. With 20 responses from a population of 48, the survey carries an estimated margin of error of approximately ±17 at the 95% confidence level, meaning findings should be interpreted as directionally robust rather than statistically definitive.

When asked whether alternative sources of funding would have enabled delivery of similar outcomes, the overwhelming majority disagreed: 95% of respondents (19 of 20) indicated that comparable activities could not have been supported through other routes, with nearly half selecting *strongly disagree*. This strongly suggests that alternative funding streams were either unavailable or insufficient to support the same level of technical development and operational progress.

Similarly, 55% of respondents (11 of 20) reported that the UK's space-weather monitoring and forecasting capabilities would *not* have improved at all in the absence of SWIMMR support. Perceptions of funding adequacy further reinforce this view: 55% (11 of 20) agreed that the level of funding was appropriate for the objectives, although 20% (4 of 20) expressed reservations, indicating that additional resources may have strengthened delivery.

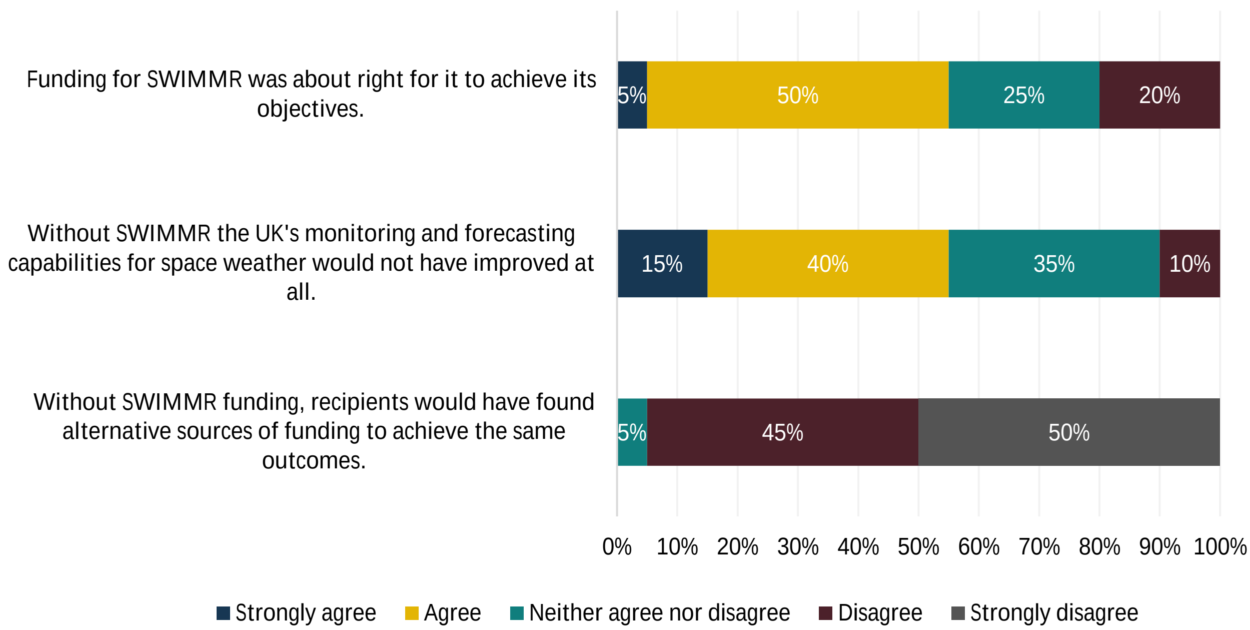

Figure 21. Survey responses to questions regarding the additionality of the SWIMMR programme

Taken together, the unweighted survey findings demonstrate clear programme additionality. SWIMMR funding played a pivotal enabling role, supporting advances in modelling, instrumentation, operational readiness, and scientific capability, with little evidence of displacement from alternative sources.

These survey results are used as triangulating evidence to strengthen confidence in the findings derived from qualitative interviews, programme documentation, and bibliometric analysis. Given the sample size and associated margin of error, the survey provides *directional insight* into stakeholder perceptions and the relative strength of programme mechanisms. It is not used to draw statistical conclusions, but rather to validate themes emerging from other evidence sources, identify areas of consensus or divergence across stakeholder groups, and corroborate the additionality and contribution pathways set out in the evaluation's theory of change.

3.7 Conclusions and lessons learned

3.7.1 Conclusions

The SWIMMR programme has delivered a substantive uplift in the UK's space-weather capability and met the intent of its mission-led design. Evidence gathered through a theory-based, mixed-methods evaluation, drawing on programme records, bibliometrics, surveys, interviews, and case studies, indicates that these outcomes were largely additional and would not have occurred, or would have progressed significantly more slowly, without SWIMMR funding.

3.7.1.1 Advanced operational capability

Five domain models progressed to pre-operational use at the Met Office, achieving AUL7–8 and establishing a defined pathway to full operationalisation through 2026. Survey evidence and interviews consistently show that these transitions were dependent on SWIMMR investment, given limited alternative funding routes and the absence of equivalent capability development elsewhere. This represents a decisive shift from research prototypes toward operational systems and reduces reliance on non-UK assets.

3.7.1.2 Measurement infrastructure rebuilt and extended

Measurement infrastructure was rebuilt and extended in ways that would not have been feasible under existing departmental or research budgets. The establishment of a multi-tiered observation base, including spaceborne and airborne radiation sensors, a modernised neutron-monitor network, and upgraded resilience-testing facilities (ChipIr/NILE), directly enabled the creation of unique datasets for validation and operational decision-making, particularly in aviation radiation, GNSS performance, and GIC risk assessment. Stakeholders reported that without SWIMMR, this instrumentation would not have been replaced or upgraded at comparable scale or speed.

3.7.1.3 Research-to-Operations (R2O) process accelerated and embedded

Research-to-Operations pathways were accelerated and institutionalised through a cloud-based integration platform and structured engagement with the Met Office. Interviews highlight that SWIMMR funding removed key technical and organisational barriers, enabling a repeatable route from academic code to operational environments and establishing early R2O2R feedback loops with forecasters. Without SWIMMR, these pathways would likely have remained ad hoc and significantly slower.

3.7.1.4 Knowledge creation and intellectual property

SWIMMR's investments increased UK space-weather research outputs by 15% between 2020 and 2025 and generated new datasets across space, air, and ground platforms, enhancing understanding of radiation environments, ionospheric variability, and solar-wind behaviour. The programme prioritised shared capability over competitive intellectual property generation, fostering collaboration and operational integration while limiting direct commercial revenue. This approach has established a foundation for both resilience and potential future commercialisation.

3.7.1.5 Wider benefits and economic momentum

SWIMMR supported the creation and safeguarding of approximately 40 high-skill roles across academia and the Met Office, with survey evidence indicating strong additionality. Industry engagement through ChipIr and NILE increased materially, attracting companies such as Cisco, Boeing, Honeywell, and STMicroelectronics. Early spillovers into sectors including rail, electronics, and telecommunications appear linked to the new infrastructure and datasets. For every £1 invested in SWIMMR, approximately £0.60 of additional funding was leveraged through grants, contracts, and collaborations, strengthening the Met Office's case for increased core funding and accelerating operational adoption of academic models.

3.7.1.6 Cross-sector and international integration

SWIMMR enhanced collaboration across the UK space-weather ecosystem, establishing 29 new domestic partnerships and 43 domestic and 33 international collaborations with organisations including NASA, the European Space Agency, Natural Resources Canada, and the University of Nagoya. Structured consortia ensured alignment between academia and operational users, while international engagement elevated the UK's visibility and credibility within the global space-weather community.

3.7.1.7 Sovereign capability and resilience

The programme delivered UK-owned models, unique airborne and high-altitude datasets, and Europe's only neutron ground-level testing facility, reducing dependence on overseas resources. Sensors and models have supported critical infrastructure, including aviation, satellite systems, GNSS, and the power grid, enhancing situational awareness and operational decision-making, as demonstrated during the May 2024 storm. SWIMMR also raised awareness of space-weather risks among government and industry, informing strategic discussion and framing space weather as a material risk for national resilience.

3.7.1.8 Impact realisation is staged and contingent

While outputs and near-term outcomes are well evidenced and largely attributable to the programme, longer-term effects, service acceptance, business adoption, and policy influence, will depend on continued operational integration, sustained instrumentation maintenance, and funding continuity. Attribution for these future impacts remains uncertain due to concurrent international developments; the evaluation therefore applies contribution analysis with transparent assumptions and triangulation.

Overall, the evidence indicates that SWIMMR has delivered outcomes that were largely additional and has established a strong foundation for UK leadership in space-weather forecasting and resilience. Its mission-led structure, small consortia, clear scopes, and alignment with operational users proved effective and offer a replicable model for future initiatives in resilience, climate, and other R2O domains.

The strength of the evidence supporting these conclusions reflects the depth, quality, and triangulation achieved across multiple sources, including surveys, interviews, bibliometric analysis, programme records, and case studies. Table 6 summarises the strength of evidence obtained for each evaluation question, providing a clear foundation for interpreting findings and drawing lessons for programme design and policy.

Table 6. A breakdown of evidence strength by evaluation question

Impact area	Evaluation question	Strength of evidence
Scientific advancement	Q1. How has SWIMMR contributed to the development of new transferable modelling and hardware deployment capabilities?	Strong quantitative and qualitative evidence; clear attribution
	Q2. How has the SWIMMR programme contributed to advancing scientific research and improving understanding of space weather phenomena?	Strong bibliometric and qualitative evidence; robust triangulation
	Q3. To what extent has SWIMMR strengthened the Research-to-Operations (R2O) ecosystem and supported the Research-to-Operations-to-Research (R2O2R) feedback loop?	Good qualitative evidence; supported by operational records
	Q4. To what extent have SWIMMR's innovations generated spillover effects in other fields and industries?	Moderate qualitative evidence; early-stage impacts
	Q5. How has the SWIMMR programme facilitated the generation of intellectual property (IP) and patent applications?	Limited evidence; qualitative only
Industry growth	Q6. To what extent has SWIMMR contributed to economic growth and commercial opportunities in the UK space sector?	Moderate evidence; attribution plausible but contingent on future uptake
Collaboration	Q7. To what extent has SWIMMR improved collaboration—both nationally and internationally and fostered closer alignment between academia, industry, and operational end users?	Strong qualitative evidence; supported by bibliometric trends
UK global reputation	Q8. How has SWIMMR enhanced the United Kingdom's position as a global leader in space weather research and forecasting?	Good bibliometric and qualitative evidence; attribution challenging
Security and resilience	Q9. How has SWIMMR contributed to reducing health and safety risks associated with space weather events?	Indicative qualitative evidence; operational impacts emerging

Impact area	Evaluation question	Strength of evidence
	Q10. How has the SWIMMR programme increased the ability of government and industry to apply adaptation and mitigation measures for space weather hazards?	Good qualitative evidence; contingent on full operationalisation

The utility of the evaluation questions can be categorised as follows:

- Q1 and Q2 provide the strongest evidence base, combining quantitative, bibliometric, and qualitative sources to assess SWIMMR's contributions to modelling, hardware deployment, and scientific advancement.
- Q3 and Q7 elucidate the mechanisms of capability building, focusing on Research-to-Operations pathways and collaboration across academia, industry, and operational end users.
- Q4, Q5 and Q6 explore complementary impacts, including spillovers, intellectual property generation, and early-stage economic and commercial effects.
- Q8, Q9 and Q10 examine broader system-level outcomes, such as global positioning, health and safety risk reduction, and resilience measures, where evidence is emerging but attribution remains challenging.

3.7.2 The extent to which the SWIMMR programme has met its objectives

The evaluation evidence collected provides an assessment of SWIMMR's delivery against its high-level objectives. Table 7 summarises this assessment.

Table 7. SWIMMR programme achievement against objectives

SWIMMR Objective	Assessment	Justification
OBJ 1: Mitigate the potential radiation hazards of space weather to satellites and aviation operations	Objective largely met	Delivered radiation belt and aviation radiation models (AUL 7–8) and airborne sensors; full operationalisation due 2026
OBJ 2: Mitigate potential space weather effects on communication and global positioning	Objective partially met	Developed ionosphere–thermosphere models and GNSS resilience tools; integration with Met Office planned for 2026
OBJ 3: Mitigate the potential risks of space weather to electric power distribution	Objective largely met	Produced UK-specific GIC forecasting system and ground conductivity model; validated during May 2024 storm
OBJ 4: Establish a world-leading UK system for space weather modelling and forecasting	Objective partially met	Five domain models transitioned to pre-operational

		use; full operational suite expected by late 2026
OBJ 5: Position the UK as a global leader in monitoring and mitigating effects of space weather	Objective partially met	Raised UK's international profile and delivered unique sovereign assets; sustained leadership contingent on validation
OBJ 6: Develop a framework for supporting the transition of models and datasets from research to operational use	Objective met	Cloud-based R2O platform established; accelerated model migration and initiated early R2O2R feedback loops
OBJ 7: Produce an updated space weather impact assessment study	Objective partially met	Delivered updated impact study (S6); improved evidence base but limited policy traction due to endorsement challenges

SWIMMR has substantially advanced UK space-weather capability, meeting or largely meeting most technical and operational objectives. Core achievements include pre-operational models, new measurement infrastructure, and a repeatable Research-to-Operations pathway. However, full impact realisation is staged, with several objectives, such as global leadership and systemic risk mitigation, dependent on operational integration and sustained funding beyond 2025.

3.7.3 Lessons learned

The lessons learned and successes presented here are based on survey and interview questions focused on barriers, challenges, and reflections on what worked well. This means the evidence spans issues broader than the impact areas covered in the main findings, touching on programme design, governance, operational requirements, collaboration, technical readiness, and sustainability. In several cases, the points raised reflect the experience of only a small number of respondents, and wording is calibrated accordingly. Collectively, however, they offer useful considerations for future research-to-operations programmes.

- Requirements and operational alignment: A recurring theme was the need for early and detailed operational requirements capture. Several respondents noted that initial ambiguity in Met Office specifications around what constitutes 'operational readiness' created alignment challenges later in delivery, requiring additional work to adapt academic models to operational environments. This directly relates to findings showing that five domain-specific models progressed to pre-operational use and that early SWIMMR funding removed barriers to Research-to-Operations pathways, highlighting the importance of clear operational specifications from the outset. Future programmes would benefit from Phase-0 feasibility studies, user story mapping, and structured engagement with operational teams before full funding is committed. These steps can reduce uncertainty, improve scoping accuracy, and align deliverables with the type of datasets and operational outputs SWIMMR successfully delivered, such as aviation radiation and GNSS performance metrics.

- IT, infrastructure and integration: Technical integration presented notable challenges. Parallel development of AWS and Met Office operational environments alongside model build led to late-stage integration work, including adapting models to evolving system configurations. This mirrors the findings on the cloud-based integration platform and R2O2R feedback loops, which were key enablers of operational uptake, showing that early technical alignment is critical. Respondents also reported delays in gaining access to operational platforms, complex licensing processes, and inconsistent onboarding procedures. These issues were not universal but occurred with sufficient frequency to highlight the need for early alignment between technical environments and delivery timelines, streamlined licensing, and clear interface standards to avoid bottlenecks.
- Collaboration and communication: Collaboration within individual projects was almost universally described as positive, with strong intra-consortium relationships and effective problem-solving. This reflects findings that structured consortia and cross-sector engagement enhanced collaboration across academia, the Met Office, and industry, creating 29 new domestic and 76 international partnerships. However, cross-programme integration was more limited, attributed to staggered project start times, funding differences, and COVID-related isolation. Respondents emphasised that structured mechanisms for cross-strand engagement, such as regular technical reviews and shared design artefacts, would have improved integration and reduced duplication. Early and consistent engagement with operational teams was particularly valuable for clarifying expectations and supporting the creation of high-value datasets and operational decision tools.
- Pandemic response: COVID-19 created significant delivery challenges, especially for projects reliant on laboratory access, hardware development, or fieldwork. Despite these challenges, the programme successfully delivered upgraded measurement infrastructure (ChipIr/NILE, neutron monitors, radiation sensors), demonstrating resilience in operationalisation. Respondents noted that pandemic conditions accelerated adoption of digital collaboration tools, which ultimately strengthened programme-wide communication and inclusivity. Virtual engagement enabled more frequent interactions across geographically dispersed partners. Future programmes should retain these practices while reintroducing in-person technical integration where necessary for complex system testing and operational onboarding.
- Funding continuity and sustainability: The absence of assured follow-on funding was identified as a critical risk. Respondents expressed concern that without continued investment, the momentum and capability built through SWIMMR could be lost, particularly in embedding operational models, maintaining instrument networks, and sustaining academic–operational relationships. This lesson is grounded in findings on impact realisation, follow-on investment (£0.60 leveraged per £1 invested), and the contingent nature of long-term operational, commercial, and policy impacts. Future programmes should incorporate multi-year envelope

planning and bridge funding mechanisms from inception to ensure continuity and protect long-term benefits.

- End-user alignment and culture: SWIMMR's mission-driven approach required a cultural shift for some academic partners, moving from open-ended research toward operationally relevant development. This is consistent with findings that structured R2O pathways, shared IP frameworks, and early engagement with operational users facilitated the transition from academic models to operational systems. This transition was generally viewed positively and was supported by clear success criteria and ongoing dialogue with end users. Respondents stressed that grounding deliverables in real-world use cases and operational constraints is essential for ensuring outputs are both scientifically robust and practically useful. Transparent expectations and continuous engagement between researchers and operational stakeholders remain key to sustaining this alignment and maintaining international credibility.

A.1 Stakeholder interviews and surveys

A.1.1 Interviews

Table 8. SWIMMR Stakeholders interviewed, and key projects covered

Organisation	Organisation type	Interviews conducted	Projects covered
British Antarctic Survey	Public Sector Research Establishment	1	N1
British Geological Survey	Public Sector Research Establishment	2	N4
University of Surrey	Academia	1	N2
University of Lancaster	Academia	1	S5
University of Birmingham	Academia	1	N3/N5
University of Aberystwyth	Academia	1	S4
STFC/RAL Space/ISIS Neutron and Muon Source (ChipIr)	Public Sector Research Establishment	3	S1 Trusted, S1 Mini and S2
Met Office	Government	4	S3
Starion Group (formerly Rhea)	Industry	1	S6
RethinkPNT	Industry	1	-
Department for Science, Innovation and Technology	Government	1	-

A.1.2 Survey sample

Survey responses included Principal Investigators (PIs) for 9 of the 11 SWIMMR projects. No survey data were received for projects N3/N5; however, information for these was obtained through interviews.

Table 9. Number of SWIMMR survey responses by project or organisation

Project or organisation	Response count in sample	Population count
N1	1	4
N2	1	3
N3/N5	0	1
N4	3	4
S1	2	5
S2	1	1
S3	1	2
S4	1	3
S5	2	3
S6	1	5
Met Office	2	4
SWIMMR management or Strategic Advisory Group	6	13

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