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Evidence Synthesis

The May 2024 geomagnetic storm: UK experience and perspective

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The May 2024 geomagnetic storm was the largest for over 20 years. The storm was categorized as a 'low-level' G5, where G5 is the highest on the National Oceanic and Atmospheric Administration (NOAA) scale for geomagnetic storms, yet the individual solar eruptive events were not particularly severe, and the observed impacts were relatively minor. The impacts

Cite this article: Horne RB *et al*. 2026 The May 2024 geomagnetic storm: UK experience and perspective. *R. Soc. Open Sci.* **13**: 251943.
https://doi.org/10.1098/rsos.251943

Received: 9 October 2025
Accepted: 17 February 2026

Subject Category:
Science, Society and Policy

Subject Areas:
plasma physics, geophysics

Keywords:
space weather, geomagnetic storm, science policy

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THE ROYAL SOCIETY
PUBLISHING

that were observed were due to the combined and sustained effect of five successive earthward-directed coronal mass ejections (CMEs) which drove the storm. The event exposed the weakness of the current storm classification system which does not discriminate between low impact and high impact G5 events; it exercised the UK Met Office forecasting system, communications and UK preparedness; and it highlighted key areas that need to be addressed, particularly relating to national power supplies, space traffic management, aviation, forecasting and data gaps. Here, we set out what happened, record some of the key impacts, discuss what went well and what needs to be improved. We make 14 recommendations relevant to four government departments, so that the UK can be better prepared for a low-probability, high-impact space weather event described in the reasonable worst-case scenario that informs the national risk register.

1. Introduction

The geomagnetic storm that took place in May 2024 was the largest for over 20 years. It was a space weather event where the impacts on UK critical national infrastructure were relatively minor, but an event that proved to be an important test of UK preparedness. The purpose of this article is to set out what happened, record some of the key impacts, discuss what went well and what needs to be improved.

The paper makes 14 recommendations for policymakers so that the UK can be better prepared for a low-probability, high-impact space weather event in the future. The recommendations are summarized first before continuing with more detailed description.

The recommendations are made in the context of the Royal Academy of Engineering Report [1] and the reasonable worst-case environment [2,3] and are grouped together according to their relevance to government departments: Department for Science, Innovation and Technology (DSIT); Department for Energy Security and Net Zero (DESNZ); Department for Transport (DfT) and Ministry of Defence (MOD).

1.1. Summary of recommendations

1.1.1. Electricity grid (DESNZ)

(1) The National Energy System Operator for Great Britain (NESO), electricity distribution network operators (DNOs) and electricity generators should work together to determine the level and duration of geomagnetically induced currents (GICs) which should not be exceeded for each transformer type on the Great Britain (GB) power grid. Such information can then be used to optimize mitigation plans and reduce GICs to regions most at risk in order to ensure an uninterrupted supply of electricity.

We also make three recommendations from the May 2024 storm where work may already be under consideration:

(2) NESO, DNOs and electricity generators should deploy instruments to measure GICs at transformers on the GB grid in regions that are most at risk. There are multiple similarities between space weather impacts on the UK and New Zealand, but the UK has a more complex grid. It is therefore recommended that the number of measurements should at least be comparable to that deployed in New Zealand (80–100). The GIC data should be recorded and archived so that the impact of low-probability, but high-impact events can be properly assessed, and the information exploited to refine preparedness plans.

(3) NESO, DNOs and electricity generators should work together to test and verify models of GICs through each transformer on the GB grid so that models are properly representative of the UK. Such models can then be used to assess GICs during low probability but high impact events.

(4) NESO, DNOs and electricity generators should engage with operators in New Zealand to develop a robust mitigation plan that would reduce GICs to the transformers most at risk while

maintaining grid stability. The plan should include consideration of blocking capacitors and the switching of circuits, facilitated by modelling studies.

1.1.2. National Space Operations Centre (DSIT and MOD)

(5) Research should be undertaken to reduce the number of unnecessary collision avoidance manoeuvres due to space weather events by a factor of two or more. This could be done by significant improvements to the accuracy of atmospheric models used in orbit predictions, and more testing and verification of the models.

(6) Research should be undertaken to assess the number of spacecraft and the amount of space debris that will permit spacecraft to operate safely in low Earth orbit (LEO) during a low probability, but high impact space weather event. This should include an assessment of tipping points, where one collision produces a shower of debris that causes more collisions, and so on, in a cascade known as the Kessler syndrome that would render LEO unusable. Such analysis would provide policy makers with the information they need to review mitigation methods such as the time to de-orbit spacecraft, and orbit slot allocations, and help ensure the safe operation of satellites and satellite services during severe space weather events. The impact of space weather on satellite collisions should be considered for the national risk register.

1.1.3. Satellite operators (DSIT and MOD)

(7) Users of satellite services that need to operate through a severe space weather event should challenge satellite operators to assess the vulnerability of their satellite fleet to a solar energetic particle event as large as the 1972 or 1956 events, so that robust mitigation measures can be put in place.

1.1.4. Aviation (DfT)

(8) Airborne radiation measurements should be commenced with the UK 'SAIRA' monitors (developed under the SWIMMR programme [4]) as soon as possible in preparation for the next ground level event (GLE) so that robust mitigation measures can be put in place to protect aircraft, passengers and crew. These measurements should be maintained in continuous and ideally expanded operation.

(9) To protect aviation from harmful levels of particle radiation, the Met Office should develop a system of warnings based on real-time measurements of high-energy particles that can cause radiation increases down to aviation altitudes (and to the ground). Real-time measurements will provide the reliability that operators need to take mitigating action.

1.1.5. Forecasting (DSIT, MOD)

(10) As mitigation measures depend critically on accurate forecasts, research should be undertaken to improve our capability to predict the emission of coronal mass ejections (CMEs) from the Sun, the time of CME arrival at Earth, the direction of the associated interplanetary magnetic field and the severity of the resulting geomagnetic storms. We recommend a scientific goal of achieving a reliable forecast of the severity of a geomagnetic storm with 2–3 h warning. A predictive capability also needs to be developed for solar energetic particle events. A variety of different approaches should be employed, including artificial intelligence (AI) and machine learning, where appropriate, and the forecasts should be tested and verified in line with good practice using separate, independent and unbiased datasets for training, testing and validation.

(11) The Met Office should continue to make operational the models delivered to it during the SWIMMR programme. This requires close collaboration with the academic community since this is where the expertise resides. Closer collaboration will focus the research community on

operational requirements, enable updates and refinements to the models, and efficiently close the loop on research-to-operations-to-research.

(12) Data from geostationary Earth orbit (GEO), medium Earth orbit (MEO) and LEO satellites should be used to test and verify radiation belt models to help ensure the safe operation of satellites in all orbits, particularly equatorial orbits between 1300 km and 20 200 km where there are no *in situ* data.

(13) The UK should work to ensure the future availability of observational space weather data needed for forecasting. A key example here is the UK-led ESA Vigil mission which will provide earlier observations of potentially dangerous activity as it develops on the Sun and improved observations of CMEs in transit from the Sun to the Earth. Thus, continued support for the development of Vigil, and of the data systems needed to exploit Vigil data, is a critical step towards improved space weather forecasts, especially improved estimates of the time of arrival of CMEs at the Earth.

1.1.6. Working together (DSIT, MOD, DESNZ, DfT)

(14) The UK should encourage operators of infrastructures affected by space weather to reach out to technical experts, engineers and scientists in academia and beyond when they need advice. Our ability to mitigate the adverse impacts of space weather depends fundamentally on our understanding of how space weather environments interact with each of those infrastructures and how those interactions can disrupt infrastructure operations. Thus, we need processes that enable ideas to flow between science, engineering and operations, while protecting any confidential information associated with particular infrastructure.

2. The solar and geomagnetic storms of May 2024

Between 7 and 11 May 2024, five M-class solar flares, eight X-class solar flares and seven halo CMEs were emitted from active region AR 3664 on the Sun (figure 1). This active region was characterized by a large group of sunspots, comparable in size to the sunspot region that led to the 1859 Carrington event [5]. Observations showed that the CMEs were directed towards the Earth, and at least one had a speed greater than 1000 km s^{-1} which suggested there could be a large geomagnetic storm when it reached the Earth [6]. The fastest CME on 9 May 2024 was associated with an X2.2 solar flare. For comparison, the Carrington Event of 1859 was associated with a CME travelling at twice the speed and a much larger X-class flare with an estimated magnitude between X15 and X80 [7]. (The solar flare classification scheme uses an exponential scale, so the 1859 event was much more powerful than the May 2024 event.)

The UK Met Office issued an ‘Informal Briefing’ at 11.17 UT on Friday 10 May and subsequently forecast a low-level G5 magnetic storm, which is the highest category possible (Met Office warnings are available from [8]). The arrival of the first CME was recorded by magnetometers at Hartland, Devon, at 17.07 UT on the 10 May and was followed by the arrival of more CMEs and the start of an unusually sustained geomagnetic storm. The CMEs ‘pushed’ the outer boundary of the Earth’s magnetic field inside geostationary orbit, exposing satellites in that orbit to the solar wind and enhanced levels of charged particle radiation. More details on the timeline of events are given in appendix A.

At around 21.00 UT on the 10 May 2024, there was a *decrease* in the number of cosmic rays striking the atmosphere. This was caused by the arrival of the CMEs and was detected by ground-based monitors (see data statement) including two recently developed UK-based neutron monitors: one at the University of Surrey (based on soil moisture sensors) and one at Lancaster University [9] (based on other techniques) which were undergoing final testing at the time of the storm. At 02.05 UT on the 11 May, a ground level radiation enhancement (GLE), numbered 74 internationally, was recorded by the Oulu neutron monitor (see data statement) and lasted for a few hours. A GLE occurs when a solar energetic particle (SEP) event (also known as a radiation storm) occurs with sufficiently high energy particles to penetrate the Earth’s magnetic field and cause radiation increases at the ground. In this case, the GLE was caused by a burst of high-energy particles with GeV energies associated with an X5 flare from AR3664 when it was near the western limb of the Sun. The particles penetrated the

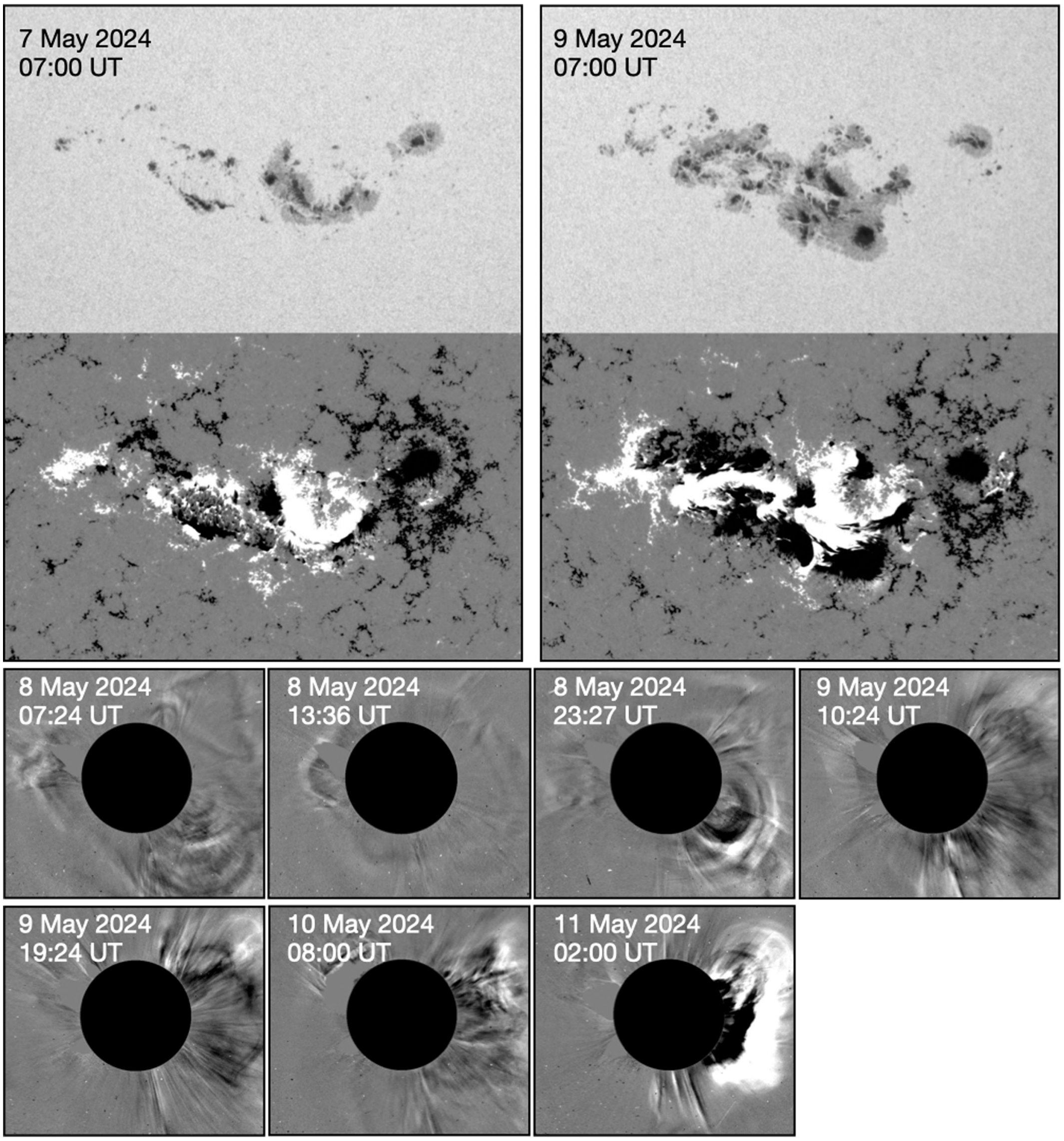

Figure 1. Solar observations of NOAA active regions 13 664/13 668 on 7 and 9 May 2024 (top row) in visible light continuum and line of sight magnetic field data. White (black) regions represent magnetic field directed toward (away from) the observer. Bottom two rows show the seven halo and partial halo CMEs as observed in coronagraph data. The coronagraph images are difference images and show change in intensity as compared with the previous image. Images courtesy of the NASA SDO AIA and SOHO LASCO teams, and jHelioviewer.

atmosphere at high latitudes and triggered warnings from ground-based monitors around the world [10,11].

The geomagnetic storm developed into an extended period of sustained disruption caused by the multiple CMEs. The Dst index, which is a well-known measure of the strength of a magnetic storm (separate to the Kp index), fell to a minimum value of –412 nT on 11 May 2024, making this the sixth largest geomagnetic storm since 1957, and comparable to the Halloween storm of October 2003 (Dst = −383 nT) and the storm of November 2003 (Dst = −422 nT). The May 2024 storm was nowhere near as large as the 1859 Carrington event, for which the best estimates suggest Dst lay between −1100 nT and −750 nT [12]. Subsequent analysis has shown that the May storm was a 1 in 12.5 year event [13], whereas the Carrington event was a 1 in 100 year event.

The coincidence of a severe magnetic storm and a GLE is unusual but not unknown. In this case, the GLE was small, but the coincidence of a severe geomagnetic storm and a severe GLE has the potential to drive impacts much greater than the sum of the two separately, as observed in May 1967 [14].

The purpose of this article is to set out what happened during the May 2024 geomagnetic storm and its impact on electricity supplies, satellites, aviation, global navigation satellite signals (GNSS) and transport which are part of the UK critical national infrastructure. Impacts on the infrastructure relating to Northern Ireland and the Republic of Ireland are given in [15]. The paper here highlights the importance of accurate forecasting for mitigating the impacts of space weather and identifies some of the most important areas where more research is needed. The paper records what went well and what needs to be improved and makes several recommendations so that the UK can be better prepared to withstand a low probability, high impact space weather event in the future.

3. Impacts of the May 2024 storm

Only the key impacts are listed in this article. It is likely that many more minor impacts were not reported, for fear of adverse publicity or owing to a lack of diagnostics that take into account the disruption due to space weather.

3.1. Impacts on the electricity grid

One of the most important risks posed by space weather to the power grid comes from GICs which flow through the power transmission network during geomagnetic storms [1]. If GICs become large (typically over 50 Amps per phase), or moderately large and continue for a sustained period, they can affect the operational stability of the electricity supply and cause damage to transformers on the grid.

This report focuses on the operation of the power grid in England, Scotland and Wales, which falls under the responsibility of NESO, and which is referred to here as the GB grid. The operation of the power grid in Northern Ireland falls under the responsibility of EirGrid, which is the system operator for both the Republic of Ireland and Northern Ireland. The impact of the storm on the Irish power grid has already been reported elsewhere [15].

NESO activated their mitigation plan once the storm reached G5. The plan includes the suspension of any maintenance work and a call for more generating capacity to deal with any increased reactive power demand caused by the storm.

The only GIC measurements on the GB grid are undertaken by Scottish Power at three locations: Torness, Neilston and Strathaven. The largest measured GIC during the storm was 14 A at Strathaven, which is not particularly large. There were no reported problems.

The auroral oval expanded across the UK to lower latitudes, and so the largest GICs would be expected to occur farther south. However, there is no equipment at present to measure GICs in England or Wales, and we must rely on models and the assumptions made in those models to get an estimate of the GICs. The model used to calculate GICs on the GB grid was developed by the British Geological Survey (BGS) and delivered to the Met Office as part of the SWIMMR programme [16].

The maximum GIC calculated using the BGS model was 68 A and occurred at the substation at Landulph, Cornwall, at 22.30 UT on the 10th of May [16] (see also figure 2). There were five substations where the GIC was 50 A or more, and these were in coastal areas of Wales, Cornwall and East Anglia. The model also estimated long sustained periods of high GIC of more than 15 A at several substations. While these values did not cause grid instability or a regional power outage in the UK, work has yet to be done to establish what level of GIC would cause an outage.

To calculate GICs, the BGS model makes several important assumptions. For example, the model includes only the 400 and 275 kV transmission lines in England and Wales as managed by NESO, but not the lower voltages (132 kV, 66 V) in the distribution network. It also makes assumptions about the electrical resistance of the lines, transformers and earthing points. The model provides the GIC at substation level (nodes) where there may be several transformers and assumes that the current through each transformer is split equally. This may not be true; it depends on the design of the transformer. The model needs to be verified experimentally against measurements of GICs in England and Wales to ensure that it is properly representative of the national grid. As stated previously, there are currently no measurements of GICs made at all in England or Wales.

Measurements of harmonic distortion from the Strathaven station revealed high even harmonics, indicating AC waveform distortion and the presence of GICs (which repeatedly rose over 10 A). High harmonics could be a useful source of data on transformer stress and GICs across the UK [17], but this needs more analysis.

It is useful to contrast what happened on the electricity grid in New Zealand for the same event so that we can learn from their experience. Like the UK, New Zealand is an island nation surrounded

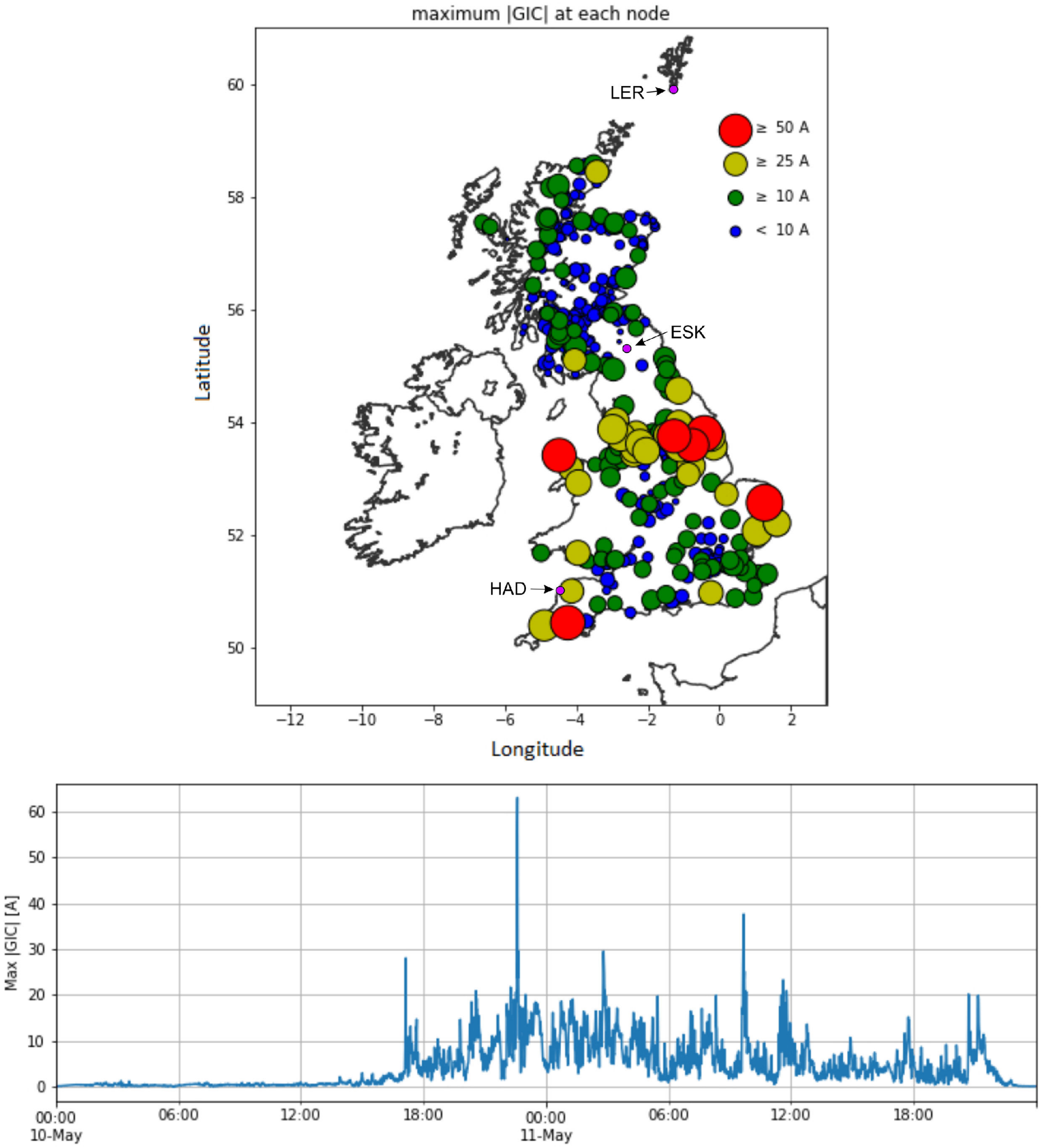

Figure 2. Top, maximum GIC (in Amperes) at substations during the 10–11 May 2024 geomagnetic storm derived from the BGS model. LER, ESK and HAD refer to magnetic observatories at Lerwick, Eskdalemuir and Hartland. Bottom, overall maximum GIC modelled at any substation in the network throughout the storm. The figure is taken from Lawrence *et al*. [16].

by salt water (which is important when it comes to GICs owing to enhanced electrical conductivity), the geography is similar (North–South rather than East–West) and the magnetic latitude is similar. For example, the magnetic latitude of the capital Wellington in the North Island is almost the same as London, and Dunedin in the South Island is almost the same as Edinburgh.

In New Zealand, the grid operator Transpower developed a mitigation plan in collaboration with the academic community (Prof C. Rodger at the University of Otago) under the Solar Tsunamis project. GICs are measured at over 80 transformer locations, and their computer model has been verified against observations across the country [18]. Their plan says that when a G4 storm is forecast, they should ‘watch and monitor’, and that when the forecast reaches G5, the whole mitigation plan should be enacted. In the May 2024 event, once they had a warning of G4, they decided to implement their mitigation plan for the South Island. Once G5 was in progress, they implemented the plan for the North Island as well [18]. The plan was designed to reduce GICs in the transformers most at risk, and from previous modelling and testing, was able to achieve reductions of up to 50% in some areas. The plan was based on an assessment of the GIC level at which the transformers would be damaged. With the mitigation plan in place, the maximum GIC measured at two transformers at a substation in Dunedin was 113 A and 100 A. The plan worked, and there were no outages or grid instability in New Zealand for the 48 h period while the mitigation was in place.

It is estimated that the GIC could be as high as 605 A (30 times the 20 A threshold considered 'large') on the New Zealand grid for a 1 in 100 year event without mitigation [19], and therefore, as the UK is at a similar geomagnetic latitude to New Zealand, comparable values in the UK could be possible.

As already discussed, there were no power outages on the UK transmission network, no transformers were taken out of service and grid stability was maintained. However, there were other minor impacts and important lessons to learn in readiness for a 1 in 100 years severe event.

The fact that the maximum safe GIC on the GB grid is not known, that there are currently no measurements of GICs in England and Wales at all, that the BGS model needs verification in England and Wales and that the mitigation plan does not include an explicit reduction of GICs on the GB grid as in New Zealand, raises serious concerns. To address these issues, we recommend the following.

Electricity grid (DESNZ):

(1) NESO, electricity DNOs and electricity generators should work together to determine the level and duration of GICs which should not be exceeded for each transformer type on the GB power grid. Such information can then be used to optimize mitigation plans and reduce GICs to regions most at risk in order to ensure uninterrupted supply of electricity.

We also make three recommendations from the May 2024 storm where work may already be under consideration:

(2) NESO, DNOs and electricity generators should deploy instruments to measure GICs at transformers on the UK grid in regions that are most at risk. There are multiple similarities between space weather impacts on the GB grid and New Zealand, but the UK has a more complex grid. It is therefore recommended that the number of measurements should at least be comparable to that deployed in New Zealand (80–100). The GIC data should be recorded and archived so that the impact of low-probability, but high-impact events can be properly assessed, and the information exploited to refine preparedness plans.
(3) NESO, DNOs and electricity generators should work together to test and verify models of GICs through each transformer on the GB grid so that models are properly representative of the UK. Such models can then be used to assess GICs during low probability but high impact events.
(4) NESO, DNOs and electricity generators should engage with operators in New Zealand to develop a robust mitigation plan that would reduce GICs to the transformers most at risk while maintaining grid stability. The plan should include consideration of blocking capacitors and the switching of circuits, facilitated by modelling studies.

3.2. Impacts on satellites in low Earth orbit

One of the main risks to satellites in LEO is collisions with other satellites and with space debris caused by changes in atmospheric drag during geomagnetic storms [20,21]. Another risk is damage to electronic components owing to single event effects (SEEs) [22] as a result of high energy charged particles from SEP events, and satellite charging owing to the Earth's radiation belts and the aurora [23], which can disrupt service and in exceptional cases cause satellite loss. Here we refer to orbits below 2000 km altitude, which includes the Starlink and OneWeb constellations.

The number of satellites in LEO has grown rapidly over the last 6 or 7 years from a few hundred to over 9000. The satellite population is expected to reach over 60 000 by 2030 [24]. The current increase is due mainly to the launch of Starlink, OneWeb and similar large-scale constellations. None of these new spacecraft has encountered a severe space weather event before, operated through a solar maximum or encountered the significant activity associated with the declining phase of the solar cycle in the years following solar maximum.

3.2.1. Satellite drag in low Earth orbit

During the May 2024 storm, one of the most widely reported impacts was the rapid drop in satellite altitude at LEO, by thousands of satellites [25]. In some cases, the increased drag caused satellites to rotate in uncontrolled ways. A well-reported example was NASA's ICESat-2, which uses lidar to monitor the topography of Earth's surface. To do so, the spacecraft must point accurately towards the

Earth. The increased drag disrupted that pointing, a disruption that was quickly detected by on-board monitoring systems that then put the spacecraft into safe mode, stopping operations and protecting the spacecraft until the operations team at NASA could assess the problem and restart operations. This led to a six-week break in service [26]. Over the first three weeks of that break, the satellite's altitude gradually dropped by 3 km, owing to increased drag linked to the unplanned changes in spacecraft orientation. The spacecraft then performed several manoeuvres to restore the required orbit altitude and ground track, using a significant fraction of the remaining fuel on the spacecraft.

The number of satellites performing orbit manoeuvres increased more than tenfold from approximately 300 before the storm to almost 5000 on 11 May [25]. The number returned to 300 by the end of 12 May and then increased to around 1000 for the next few days. By far the majority of these were Starlink satellites which orbit at approximately 550 km altitude. For comparison, there was almost no increase in the number of manoeuvring satellites during the 2003 storm [25].

Satellite manoeuvres were carried out in response to higher atmospheric drag caused by the storm. For example, results from the NRLMSISE-00 model showed that the mass density at 400 km increased by a factor of six near the equator, and at latitudes above 50° N and below 70° S [25]. The increase was due mainly to Joule heating by electrical currents in the upper atmosphere, ion uplift and by electron precipitation associated with the aurora.

Most of the orbit manoeuvres carried out by Starlink were done autonomously using GNSS signals [25]. This is a new dependency on GNSS which has developed over the past 10 years. This means that the satellite manoeuvres were carried out without awareness of the location of other satellites. In an increasingly congested environment, this raises the potential for collisions between two satellites. During the May 2024 storm, ionospheric slant delays affecting GNSS positioning signals resulted in errors of up to 60 m on the ground (see §3.4). Since approximately two-thirds of the ionosphere is above the peak height (above approx. 300 km), the impact on GNSS used by satellites in LEO could be significant. For example, under normal conditions, 65% of the total electron content which affects GNSS lies above 300 km (30% above 400 km, 10% above 550 km and 5% above 750 km). However, during the storm in October 2003, the amount of total electron content above the CHAMP satellite at 400 km increased by 900% owing to the uplift in the ionosphere [27]. We are therefore facing a hitherto unparalleled situation in which tens of thousands of satellites could automatically try to apply 'corrective' manoeuvres based on erroneous, disrupted or even completely unavailable positioning information. Many satellites use only single-frequency GNSS receivers for positioning information, further increasing their vulnerability to uncertainties in positioning information. If a severe space weather event occurs during the orbit-raising stage following launch, when the satellites are located close to each other, the impact of the increased atmospheric drag and imprecise GNSS could be catastrophic [28].

There are over 50 000 pieces of orbiting space debris greater than 10 cm, and over a million larger than 1 cm [29]. Everything over 10 cm is tracked, but even the smaller pieces, such as a fleck of paint, can still write off payloads or disable a satellite on impact owing to the extremely high velocities (7 km s^{-1}) at which the debris moves in LEO in crossing or opposing orbits. Satellite operators take avoiding action if the probability of a collision with a tracked object exceeds 1 in 10 000. Ideally, they receive a warning of a collision 7 days ahead, but as there is an uncertainty in the predictions owing to uncertainties in the atmospheric models and the dynamic variability of the real environment during space weather events, they do not usually act until, at most, 2 days ahead. The large changes in the atmospheric density and increase in the number of manoeuvring satellites in a short timespan made collision analysis much more difficult during the May 2024 storm.

The National Space Operations Centre (NSpOC) warned UK-licensed satellite operators of 2560 potential collision risks in May (figure 3), which is a 35% increase over the previous month [30]. NSpOC also estimated that it took approximately 2 days to be confident about making orbit predictions again. Thus, during the storm, there was a much higher number of collision alerts and potentially a higher risk of collision with other spacecraft and with space debris than ever before. The danger is that in a bigger storm and with an increasingly congested environment, a tipping point would be crossed where one collision produces a shower of debris that causes more collisions and so on, in a cascade known as the Kessler syndrome [31], which would make LEO unusable. While this is of critical importance for satellites, it should also be noted that the International Space Station is in LEO.

Some of the reported civil impacts also affected some military systems and operations. Defence deployed users reported system impacts attributed to the May 2024 events to the UK Space Command 1 Space Operations Squadron (1SOS is part of the NSpOC). These real-world examples are valuable for validating impact predictions and to inform tabletop exercises.

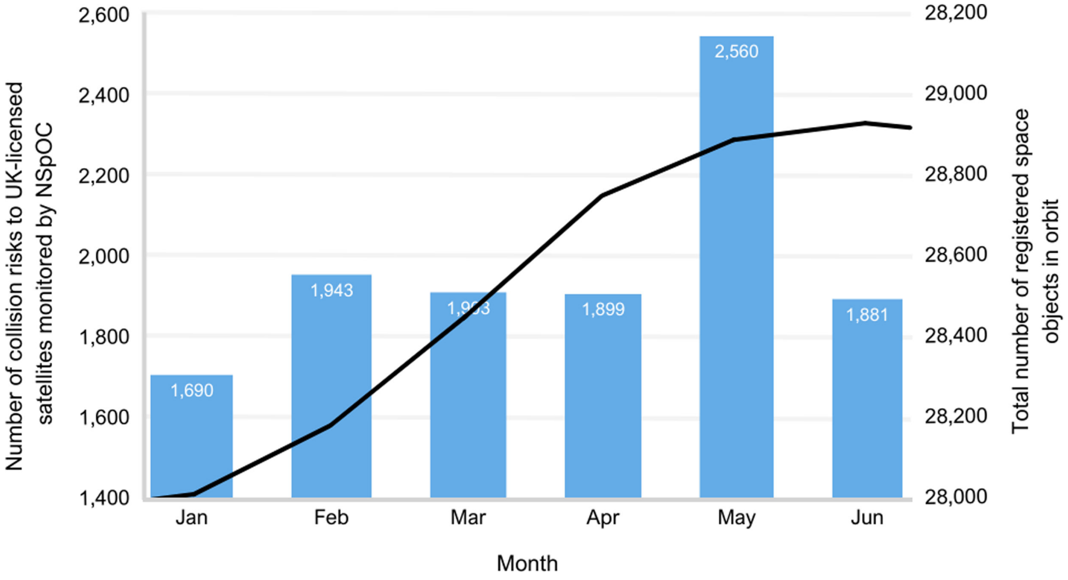

Figure 3. The number of collision risks to UK-licensed satellites (blue) for the first 6 months of 2024.

One benefit of the storm was the early re-entry of space debris at low altitudes. For example, NSpOC reported 156% more objects re-entering the Earth's atmosphere in May than in April, and 56 uncontrolled re-entries were also reported [30]. While some of these re-entries may have been planned already, the huge increase over the previous month indicates that the magnetic storm had an important impact.

The safe operation of satellites in LEO relies heavily on accurate orbit prediction models. The largest uncertainty in the models is due to changes in mass density of the upper atmosphere caused by geomagnetic storms and solar heating effects. We recommend the following.

National Space Operations Centre (DSIT and MOD):

(5) Research should be undertaken to reduce the number of unnecessary collision avoidance manoeuvres owing to space weather events by a factor of two or more. This could be done by significant improvements to the accuracy of atmospheric models used in orbit predictions, and more testing and verification.

(6) Research should be undertaken to assess the number of spacecraft and the amount of space debris that will permit spacecraft to operate safely in LEO during a low probability, but high impact space weather event. This should include an assessment of tipping points, where one collision produces a shower of debris that causes more collisions, and so on, in a cascade known as the Kessler syndrome that would render LEO unusable. Such analysis would provide policy makers with the information they need to review mitigation methods such as the time to de-orbit spacecraft, and orbit slot allocations, and help ensure the safe operation of satellites and satellite services during severe space weather events. The impact of space weather on satellite collisions should be considered for the national risk register.

3.2.2. Ionizing radiation in low Earth orbit

During the May 2024 storm, satellites in high inclination LEO orbits detected a significant increase in ionizing radiation across the South Atlantic Anomaly (SAA) region. The SAA is a region where there is a weakness in the Earth's magnetic field and high energy electrons and protons from the radiation belts penetrate closer to the Earth. The daily average flux of high-energy protons (greater than 9 MeV) increased by a factor of six [32]. As a result, the damage to solar arrays on satellites in LEO is expected to have more than doubled compared to the beginning of the year. Solar array power will continue to degrade until the proton belt has fully decayed, which is estimated to take between 660 and 570 days for 5 and 15 MeV protons, respectively (I Sandberg 2025, personal communication).

The enhanced ionizing radiation in the SAA region was due to a combination of rapid compression of the geomagnetic field caused by the CME (§3.3) and the weak SEP event that took place during the storm. The rapid compression accelerated protons to very high energies, which became trapped in the geomagnetic field and circulated around the Earth as part of the proton radiation belt [33].

There was enhanced electron precipitation associated with the aurora during the storm, which extended to much lower latitudes than usual as the aurora moved towards the equator. This had the potential to cause surface charging of some LEO satellites (including Starlink and OneWeb satellites) along the higher latitude part of their orbits, which would have increased the risk of an electrostatic discharge (ESD) and disruption to service. The weak SEP event that took place during the middle of the storm is likely to have caused an increase in SEEs in electronic components for satellites on high-inclination orbits. Starlink reported ‘very challenging conditions’ with short intermittent outages over a period of hours, but no satellites were lost during the storm [34]. Similarly, Iridium operating in a higher inclination LEO did not report any computer resets or clock instabilities, and its customers experienced no negative service impacts [34].

For comparison, the SEP event that occurred on 4 August 1972 was more than 600 times more intense than that during the May 2024 storm (7×10^4 particles cm^{-2} s^{-1} sr^{-1} [35], compared to 206 particles cm^{-2} s^{-1} sr^{-1} on 11 May). With the growing use of electronic components that are not radiation-hardened, if an event as large as the August 1972 event were to happen again, it is not clear how many satellites in LEO would be affected, or the extent to which satellite services would be disrupted. This is an important concern owing to the growing dependence on LEO satellites for data transfer.

The International Space Station is also in LEO. However, NASA stated that ‘NASA completed a thorough analysis of recent space weather activity and determined it posed no risk to the crew aboard the International Space Station, and no additional precautionary measures are needed’ [36].

3.3. Impacts on satellites in geosynchronous and medium Earth orbit

One of the main risks to satellites in GEO and MEO owing to space weather is internal satellite charging caused by enhancements in the outer electron radiation belt [37]. Another risk is surface charging caused by the injection of low-energy electrons, usually on the night side of the Earth [38]. Satellite charging can lead to an ESD which can damage electronic components, disrupt service and, in exceptional cases, cause satellite loss [39]. Cosmic rays and high-energy ions from a solar energetic particle event can also damage electronic components via SEEs [22].

During the May 2024 storm, one satellite operator with satellites in the so-called ‘slot region’, which lies between the inner and outer electron radiation belts, had to switch to a backup system during the storm. They also had to devote significant staff effort to resolve operational problems. However, there was no interruption to service.

Another operator with satellites at GEO reported an overall decrease in the number of SEEs. This was probably caused by additional magnetic shielding from the CME (known as a Forbush decrease) that deflects the lower energy portion of cosmic rays. It lasted about 2 days.

Another satellite operator reported a reduction in the number of SEEs from satellites in the slot region, and then a slow increase over a period of months.

Data from the GOES geostationary satellites and the British Antarctic Survey radiation belt model [40] (BAS-RBM, delivered to the UK Met Office as part of the SWIMMR programme) showed that during the May 2024 magnetic storm, the outer boundary of the Earth’s magnetic field was ‘pushed’ inside geostationary orbit several times by the Earthward-directed CMEs (figure 4). Thus, satellites in GEO, including Skynet, lost the protection of the Earth’s magnetic field and were fully exposed to the solar wind and to cosmic rays. The inward motion depleted the electron radiation belt at GEO but increased the electron flux at lower altitudes corresponding to MEO where the GPS and Galileo GNSS satellites orbit, and by over four orders of magnitude in the slot region between $L^* = 2$–3 where satellites in lower MEO operate. The slot region is usually devoid of high energy particles, but during the May storm, it became ‘filled-in’. The model also showed that charging currents under 0.5 mm of Al slab shielding on a typical satellite exceeded the NASA recommended guidelines for a period of a few days. Thus, the risk of service disruption was reduced at GEO but increased at lower orbits.

There are no publicly available reports of anomalies for satellites at GEO or, as far as we are aware, at MEO owing to satellite charging, and so it is not clear how many satellites were affected.

Data from low-altitude satellites [32] and the BAS proton radiation belt model (part of the SWIMMR programme) showed that during the storm, there was an increase in the proton flux in the main part of the proton radiation belt and a reduction in the outer part. The reduction in the outer part was probably due to the distortion of the geomagnetic field which released high-energy protons from

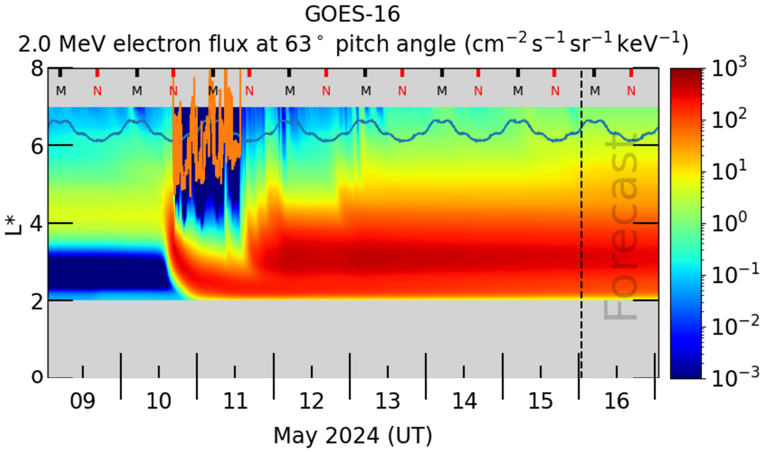

Figure 4. Modelled flux of 2 MeV electrons (colour coded) as a function of L* and time from the BAS radiation belt model. Here, L* is a magnetic coordinate and is approximately equal to distance along the equator from the centre of the Earth, measured in Earth radii, to the magnetic field lines where the radiation belt flux is modelled. The track of the GOES-16 satellite at geostationary orbit is shown by the solid black line near L* = 6.6 and N and M refer to when the satellite is at noon and midnight, respectively. The outer boundary of the geomagnetic field (orange line) was 'pushed' inside geostationary orbit several times between 10 and 11 May 2024. The modelled electron flux in the 'slot region' between L* = 2–3 increased by four orders of magnitude during and after the storm.

trapped orbits encircling the Earth [33]. The outer part of the proton belt subsequently recovered back to its normal level.

The initial reduction and then recovery of the outer part of the proton belt is consistent with the reduction and then increase in SEEs in the slot region reported by satellite operators. As noted in an earlier section, the time scale for the main part of the proton radiation belt to decay is approximately 570–660 days, posing a risk of additional satellite anomalies and solar array degradation for satellites passing through that region over a comparable time scale.

More generally, the enhanced radiation belts increased the radiation dose for some satellites undergoing orbit raising to GEO using electric propulsion. Typically, it can take 200 days or so to reach GEO using electric propulsion, and so an increase in radiation dose is likely to reduce solar array power, increase the risk of anomalies and reduce the expected operational lifetime [41].

The May 2024 storm strongly supports the reasonable worst-case scenario [2,3] in that a 1 in 100 year geomagnetic storm is likely to have more impact on satellites at lower altitudes than GEO (figure 4) owing to the magnetic field compression. Satellite operators can take steps to mitigate the effects of space weather if they have a timely warning. For example, they can re-plan operations such as delaying an orbit manoeuvre or bringing it forward before the storm, as they chose to do for SKYNET 4E on 6 September 2017 [42]. They can delay a software upgrade, have more people ready to deal with incidents and inform their users that the system may become unreliable for a certain period. For this, they need accurate forecasts of the time of arrival for a CME, the direction of the associated interplanetary magnetic field and severity of a geomagnetic storm at least a few hours ahead. At present, the uncertainty in the time of arrival of the CME is approximately ±13 h [43]. For the May 2024 storm, the modelling capability was exceptionally (and temporarily) enhanced owing to the fortuitous location of the STEREO A satellites. At the time, its vantage point off the Sun–Earth line provided the ability to more accurately specify the incoming CMEs. This additional information is not usually available and underlines the critical contribution anticipated from the ESA Vigil mission, scheduled for launch in 2031, which is strongly supported by the UK.

There are no current measurements of the radiation belts for orbits between 1300 km and 20 200 km altitude, such as the slot region where there is a growth in the number of satellites and satellites undergoing orbit raising using electric propulsion. Observations by satellites in LEO can only measure a small fraction of the particles in the equatorial region corresponding to these altitudes, so the true number is unknown. Thus, we must rely on models, such as the BAS-RBM, which require more testing and verification using data from GEO, MEO and LEO to ensure that they are representative of this and all regions.

We recommend the following.

Satellite operators (DSIT and MOD):

(7) Users of satellite services that need to operate through a severe space weather event should challenge satellite operators to assess the vulnerability of their satellite fleet to a solar energetic particle event as large as the 1972 or 1956 event, so that robust mitigation measures can be put in place.

Recommendations related to forecasting are given below under §4.

3.4. Impact on GNSS

GNSSs such as the GPS and Galileo systems work by using the time delay between a signal sent by the satellite and the time it is received by the receiver to estimate the range from each satellite to the receiver. These ranges include the effect of the group delay caused by the ionosphere. The ionospheric delay is estimated by software that derives the receiver position, using either a model or near-real-time data related to ionospheric conditions, as discussed as follows. In severe space weather, it can be challenging to estimate ionospheric delays, and this may result in an error in receiver position. In the following discussion, these position errors are expressed in metres (figure 5).

Basic GNSS systems use a climatological model of the ionosphere to correct for this offset. More capable GNSS systems use a correction signal from a fixed ground-based transmitter (e.g. advanced differential GNSS systems such as real-time kinematics (RTK)), or from a satellite at GEO (space-based augmentation system (SBAS)) to obtain higher accuracy [44]. The main space weather risk to GNSS signals comes from large gradients in the ionosphere that cause an error in the correction signal, and from irregularities that cause scintillations and loss of phase lock by the receivers leading to errors.

During the storm, the ionospheric electron density increased and became much more structured during the late UT hours of 10 May 2024. This caused positioning errors in GNSS receivers. There is a global network of ground-based GNSS receivers that monitor the total electron content between the satellites and the ground. During the height of the storm on the 10th and 11th of May, the ionospheric effects over the UK for an L1 receiver operating at 1575.42 MHz caused a position error typically less than 10 m for the whole period. However, across much of the rest of the world, ionospheric effects were much larger than in the UK, for example, on the 10th of May at 20.00 to 23.00 UT across the American sector, position errors increased to around 60 m (on the GPS L1 signal). These large ionospheric errors in the USA affected precision agriculture. Although the farmers use modern GNSS systems such as SBAS or RTK, which compensate for many GNSS errors, they need centimetre accuracy for planting seeds and other tasks. During the storm, the ionospheric electron density gradients became very large and introduced additional errors onto GNSS correction signals. On 10 May 2024, the ionospheric storm occurred during daylight hours over the USA during the critical period for planting corn. Farmers using tractors guided by GNSS had to stop planting their crops until the worst of the storm was over [45]. The economic impact on farmers in the USA has been estimated at around $500 million [46]. Positioning errors also affected satellite manoeuvres in LEO during the storm, as described in §3.2.1.

Another new dependency on GNSS signals is drones [47] which use GNSS signals for mapping, photography, autonomous flight and safe return. There are some reports that the storm affected drones, but the extent is currently unclear and requires further research.

More generally, GNSS systems are used in a wide range of applications including navigation, banking, finance, transport and many other areas. Impacts on aviation and transport are covered elsewhere in this paper. In general, unless users have access to alternative infrastructure for backup systems, such as precision timing services (such as those provided by NPL in the UK, see https://www.npl.co.uk/ntc), or e-LORAN for navigation or accurate 'holdover' clocks for timing, the main mitigation relies on accurate forecasting of space weather events and planning alterations to operations in advance.

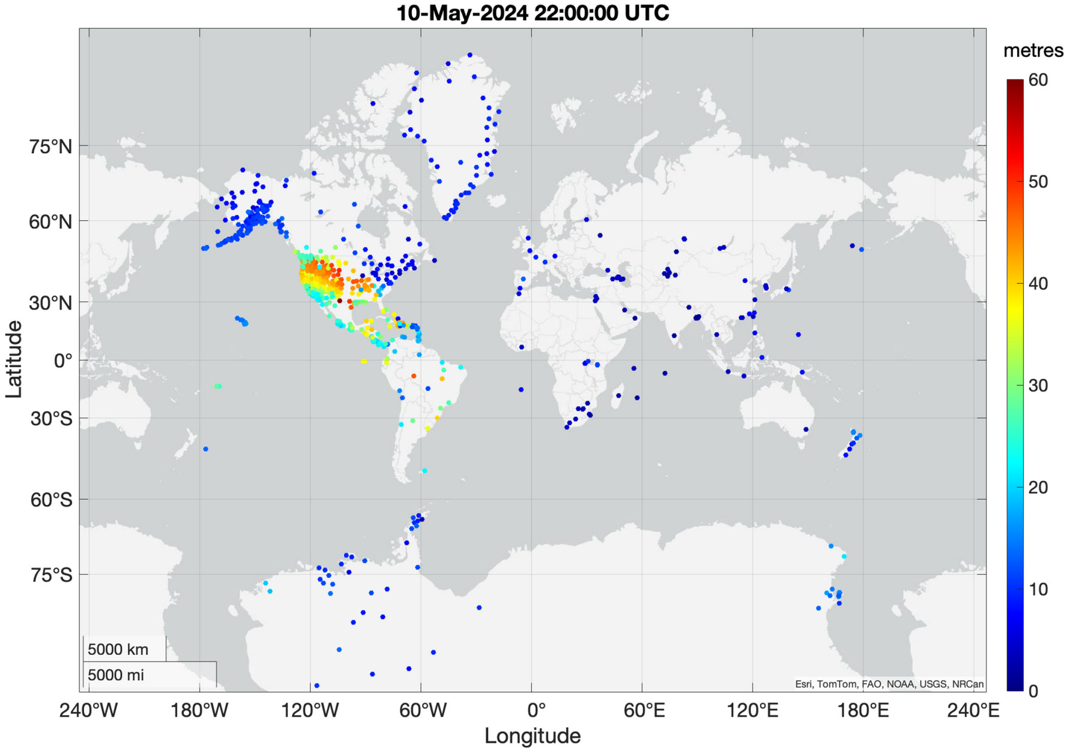

Figure 5. Positioning error (in m) at 22.00 UTC on 10 May 2024 derived from the ionospheric slant delay for an L1 GNSS receiver.

3.5. Impacts on aviation

The most frequent impacts to aviation arise from the loss of high frequency (HF) communications at high latitudes and disruption to GNSS signals owing to geomagnetic storms. SEP events also disrupt HF communications and GPS signals. Furthermore, a subset of these events causes ground level (radiation) enhancements (GLEs), additional radiation exposure to passengers and aircrew and potential disruption to on-board microelectronic components which can affect flight management systems [48].

In the UK, any loss of operational capability requires a mandatory report to the Civil Aviation Authority. Acting on the forecast of a geomagnetic storm, airlines requested a more southerly routing across the Atlantic, which was agreed with NATS (formerly the National Air Traffic Services). As a result of this mitigation, no UK airline (BA, Virgin Atlantic) reported any major disruption to aircraft operations, HF communications, GNSS navigation or system errors on aircraft during the May storm. It is important to note that given the timing of the storm, very few aircraft were in the more exposed North Atlantic Tracks, and combined with the size of the storm, it is not a surprise that no impacts were reported.

The solar flares associated with the storm caused day-side HF radio blackouts and solar protons caused polar region blackouts (these periods can overlap)—but such impacts are quite routine and it is important to note that the UK aviation community has dealt with the loss of HF comms, or poor HF comms, for years and so it is not always considered important enough to report. In the USA, at least one US carrier reported disruption to HF communications at high latitude [49].

Increased atmospheric radiation levels can potentially impact aviation either via its effect on on-board avionics via malfunctions in microelectronics or increases in radiation dose to crew and passengers (or both). Starting from approximately 21.00 UT on 10 May 2024, the extreme geomagnetic storm initially caused a *decrease* in cosmic rays hitting the upper atmosphere. This is known as a Forbush decrease and was detected by ground-based monitors around the globe, including monitors recently installed in the UK at Guildford [50]. Additional monitors have since been installed in the UK as part of the SWIMMR programme [9]. This was also reflected in the UK MAIRE+model operating at the Met Office (also delivered as part of the SWIMMR programme), which showed a sudden reduction in dose rate for aircraft flying at 40 000 feet, 70° N, from approximately 7.0 μSv h^{-1} to 5.5 μSv h^{-1} by 00.00 UT on the 11 May, after which a slow recovery started [51].

However, at 03.05 UT on the 11 May, a ground-level radiation enhancement (or GLE), numbered 74 internationally, triggered warnings from various monitoring services. It was, in fact, a very small event with no practical consequences. The magnitude of this increase (approximately 3% increase at ground level) was well below the MAIRE+GLE trigger threshold of 8% and was a factor of 1500 below the February 1956 event and a factor of 3700 below the reasonable worst-case event (1 in 100 years, [2]). MAIRE+ indicated that the dose rate on aircraft at 40 000 feet, 70° N, would have increased only slightly (approx. 0.5 μSv h^{-1}) owing to the GLE, but this was nullified by the ongoing Forbush decrease. The maximum effective dose contribution from the GLE on its own on a flight (e.g. London to Los Angeles at 40 000 feet) would have been (by scaling from the February 1956 event, which is the biggest event in modern history) approximately 7 μSv, which is very small. It is maybe worth examining these contributions further using MAIRE+, as GLEs during Forbush decreases are a challenge to the calculations.

For mitigation during an event, operators and pilots may be able to re-route aircraft or delay departures based on nowcasts and alerts, for example, owing to an extreme radiation storm. Such alerts are already provided via the International Civil Aviation Organization services, and these are due to be supplemented by the UK MAIRE+ nowcast model in 2026. These alerts are used for pre-flight and in-flight planning to support operational decision-making, in coordination with Air Traffic Control where applicable. On the other hand, space weather forecasts are not yet sufficiently reliable to enable effective operational mitigation in advance of an event. Better forecasts and measurements are required. In the future, measurements on-board aircraft could improve the ability to respond appropriately.

Some airlines in the US receive ‘advisories’ based on use of the NOAA ‘S’ scale for radiation. However, this can cause false alarms for aircraft as it uses satellite measurements of relatively low energy protons (greater than 10 MeV) that do not always penetrate the atmosphere down to aircraft altitudes. The ‘S’ scale is more aligned to satellite impact. In the short term, use of the MAIRE+ nowcast will help to avoid such unwanted false actions. However, a system of warnings based on real-time measurements of high-energy particles that can cause effects down to aviation altitudes would be much more appropriate for the aviation industry.

Overall, the May 2024 event was a useful test for the new MAIRE+ which performed very well, but we currently lack any aircraft-based measurements over the period with which to validate the model, though flights of the UK SAIRA radiation monitors [52] developed under the SWIMMR programme are planned. The occurrence of a GLE (albeit small) in the middle of the geomagnetic storms and the other complications emphasizes that it is vital that airborne radiation measurements are commenced with the UK SAIRA monitors as soon as possible, certainly before the next GLE occurs, and they should be maintained in continuous operation on as many high dose routes as possible. This would also improve our ability to offer accurate advice (e.g. on dose received) in the immediate aftermath of an event based on *in situ* observations.

We recommend the following.

Aviation (DfT):

(8) Airborne radiation measurements should be commenced with the UK SAIRA monitors (developed under the SWIMMR programme) as soon as possible in preparation for the next GLE so that robust mitigation measures can be put in place to protect aircraft, passengers and crew. These measurements should be maintained in continuous and ideally expanded operation.

(9) To protect aviation from harmful levels of particle radiation, the Met Office should develop a system of warnings based on real-time measurements of high-energy particles that can cause radiation increases down to aviation altitudes (and to the ground). Real-time measurements will provide the reliability that operators need to take mitigating action.

3.6. Railways and other transport

There is an ongoing conversation between the Rail Safety and Standards Board and Lancaster University to explore potential anomalies in control systems during the storm. So far, none has been attributed to the storm.

3.7. Drilling for oil and gas

There were reports that drilling for oil and gas had to be suspended as the storm caused deviations in the Earth's magnetic field which makes directional drilling unreliable.

4. Future R&D priorities for the UK

4.1. Forecasting

Government planning and the ability for operators to take mitigating action to protect critical national infrastructure is highly dependent on the timely and accurate forewarning of an event. However, reliable forecasts of the severity of the geomagnetic storm are limited to approximately 30 min, which does not meet user demands. There is virtually no warning currently available for a SEP event. The highest priority must therefore be given to increasing the accuracy and forecasting lead time of geomagnetic storms and SEP events since their impacts are so wide-reaching. We need to forecast

- the time of arrival at Earth;
- the severity of the event;
- the duration of the event.

To forecast a geomagnetic storm several hours ahead, the Met Office forecasters use a mix of information. They use the estimated speed of the CME, as faster CMEs are more likely to have a higher impact [6], and the ENLIL model to estimate the time of arrival. However, the uncertainty in the time of arrival is approximately plus or minus 13 h [43]. In the May 2024 storm, the STEREO spacecraft was temporarily located in a fortuitous location, just off the Sun–Earth line, and helped to reduce this uncertainty (§2.3). Even so, the storm commenced 2.5 h earlier than expected. Forecasters also use their experience to make a judgement on the severity of the storm, but without knowing the polarity of the embedded magnetic field. They correctly predicted a low-level G5 storm, but this may not work every time as the polarity of the magnetic field is a key factor that cannot be measured until the CME has reached the L1 position, and then there is only approximately 30 min warning until impact.

Most users want 24 h warning. However, at the US Space Weather Workshop in March 2025, power grid operators in New Zealand stated that they could take mitigating action on a reliable forecast of the severity of a geomagnetic storm with 2–3 h warning. Similar mitigation measures could be put in place by UK operators. We therefore recommend setting a scientific goal of achieving a reliable forecast of the severity of a geomagnetic storm with 2–3 h warning. Such a goal may be achievable with innovative satellite mission proposals.

A predictive capability also needs to be developed for the onset and duration of a SEP event. While high-energy ions in a SEP event may only take 10 min or more to reach the Earth, there is evidence that solar eruptions and shock waves could be useful warning indicators.

Access to real-time data from ground and space is essential for forecasting. So too are the models developed during the SWIMMR programme and delivered to the Met Office for operational use as part of research to operations. To provide earlier reliable forecasts, it is important that the UK continues to take a leading role in spacecraft missions such as the ESA Vigil mission, due for launch in 2031, which will provide earlier warnings of dangerous activity on the Sun and be much better able to track CMEs from Sun to Earth. It also requires close collaboration between the UK Met Office, which provides the forecasts, academia where there is considerable expertise in the UK and system operators. Continued collaboration will enable feedback from operations to research and will focus the academic community on where research is needed for operational requirements.

We recommend the following.

Forecasting (DSIT, MOD):

(10) As mitigation measures depend critically on accurate forecasts, research should be undertaken to improve our capability to predict the emission of CMEs from the Sun, the time of CME arrival at Earth, the direction of the interplanetary magnetic field and the severity of the resulting geomagnetic storms. We recommend a scientific goal of achieving a reliable forecast of the severity of a geomagnetic storm with 2–3 h warning. A predictive capability also needs to

be developed for solar energetic particle events. A variety of different approaches should be employed, including AI and machine learning, where appropriate, and the forecasts should be tested and verified in line with good practice using separate, independent and unbiased datasets for training, testing and validation.

(11) The Met Office should continue to make operational the models delivered to it during the SWIMMR programme. This requires close collaboration with the academic community since this is where the expertise resides. Closer collaboration will focus the research community on operational requirements, enable updates and refinements to the models, and efficiently close the loop on research-to-operations-to-research.

(12) Data from GEO, MEO and LEO satellites should be used to test and verify radiation belt models to help ensure the safe operation of satellites in all orbits, particularly equatorial orbits between 1300 km and 20 200 km where there are no *in situ* data.

(13) The UK should work to ensure the future availability of observational space weather data needed for forecasting. A key example here is the UK-led ESA Vigil mission which will provide earlier observations of potentially dangerous activity as it develops on the Sun and improved observations of CMEs in transit from the Sun to the Earth. Thus, continued support for the development of Vigil, and of the data systems needed to exploit Vigil data, is a critical step towards improved space weather forecasts, especially improved estimates of the time of arrival of CMEs at the Earth.

4.2. Impacts of a reasonable worst case

In 2013, the Royal Academy of Engineering published a report describing the impacts of space weather on critical national infrastructure [1] and the Space Environment Impacts Expert Group has published and updated a realistic assessment of the worst-case space environment [2,3, and references therein]. However, there is still a lot of uncertainty around impacts and new technological developments (e.g. digital data centres) still need to be assessed for their resilience against severe space weather.

To better understand the impact of space weather on the critical national infrastructure industry and government, there is a need to share information about their systems and to work more closely with scientists and engineers from the academic sector. Many smaller impacts, which may not be reported publicly, are often essential information when scaling up what happens in a small event to assess the impact of a reasonable worst case. This is likely to require sharing of confidential information. A mechanism for enabling this, perhaps requiring non-disclosure agreements, should be established.

We recommend the following.

Working together (DSIT, MOD, DESNZ, DfT):

(14) The UK should encourage operators of infrastructures affected by space weather to reach out to technical experts, engineers and scientists in academia and beyond when they need advice. Our ability to mitigate the adverse impacts of space weather depends fundamentally on our understanding of how space weather environments interact with each of those infrastructures and how those interactions can disrupt infrastructure operations. Thus, we need processes that enable ideas to flow between science, engineering and operations, while protecting any confidential information associated with particular infrastructure.

5. What went well and what needs to be improved

The May 2024 event provided a test of the UK investment in space weather forecasting. There is substantial evidence (see appendix A) that first-level warnings were issued in a timely fashion, there were effective communications ‘out of hours’ between the Met Office, the US Space Weather Prediction Centre (SWPC), the Space Environment Impacts Expert Group (SEIEG) core team, Government and business, that the forecast of a ‘low-level’ G5 storm was accurate, and that organizations such as the NESO and SATCOM operators took appropriate mitigating action based on those forecasts. This was the first test of some of the SWIMMR models which performed well, but in general, there is a need for more observational evidence with which to validate the models. All of this effective communication relied on the underpinning availability of electrical power. This may be compromised during a severe or extreme event.

The May storm attracted huge media and public interest, mainly in the aurora which was visible across the UK. It is impossible to control the media in such events, but members of the Met Office and of SEIEG who gave interviews to the press and media helped to convey the excitement while giving a realistic assessment of the impact. The Met Office forecasts and advisories also played an important role.

The May storm was classified as G5 on the NOAA scale, but it underlined that this scale is inadequate. G5 covers everything from a 1 in 20 year to a 1 in 100 year event, and everything above. The impact of a storm is not necessarily linear, i.e. a storm of twice the size does not mean twice the impact; it could mean 5 or 10 times the impact. We need a scale that can differentiate different levels above G5 to give a more accurate picture to enable more appropriate levels of mitigation to be implemented. The US SWPC is already leading international discussions to replace the existing NOAA scale, and the UK must continue to play an important part so that any revisions also meet UK needs.

Similarly, the May storm also showed that the NOAA scale for Solar Radiation Storms (the S scale) may be appropriate for satellites but is not appropriate for aviation. During the May storm, the raised proton flux was mainly restricted to lower energies, whereas to assess the impact on aviation, we need to look at the higher energies measured by the GOES spacecraft. The SAIRA detectors that were developed in the SWIMMR programme can only report doses at the end of the flight, and therefore real-time data must continue to rely on proton measurements from the GOES protons and ground-level monitors. Again, the UK must continue to play an important part in the discussions to revise the NOAA scales so that they meet UK needs.

The May storm brought to light some but not all aspects of a significant space weather event. For example, the SEP events that took place in 1956 and 1972 were two to three orders of magnitude higher than those during the May 2024 storm at aircraft and satellite altitudes. If a severe geomagnetic storm and a severe SEP event occurred at the same time in the near future, then it could have a much higher impact on aviation, satellites and electronic systems on the ground than in 1972 as electronic components have become much smaller and more vulnerable to high-energy charged particles.

6. Conclusion

The following are some ‘key takeaways’ from the May 2024 event:

1. Despite being the largest space weather storm for over 20 years, with a large and complex source active region and spectacular auroras, the individual solar flares and CMEs that combined into this sustained event mean that the May 2024 event was benign compared to a reasonable worst-case space weather event.
2. [Recommendations 10, 11, 12, 13] Space weather forecasting needs improving. The Met Office forecasting models predicted the time of CME arrival, but the actual time of arrival was still 2.5 h earlier than predicted. The fortuitous and temporary location of the STEREO A spacecraft (off the Sun–Earth line) contributed to this higher than usual level of accuracy, which is otherwise more like ±13 h.
3. Communications worked, and so did all the enabling infrastructure. This may be compromised for a reasonable worst-case space weather event. Contingency planning for this is required.
4. [Recommendations 1, 2, 3, 4, 8, 9, 10] Data are needed to verify and validate the models and to provide input for future warnings. Funding needs to be identified to support this in the post-SWIMMR era (after 1 April 2025). This includes enabling GIC monitors, flying the UK SAIRA radiation monitors and effective operations to research (O2R) information sharing (which may require non-disclosure agreements).
5. [Recommendations 5, 6] Understanding the impact of space weather on satellite collisions needs assessment, given the anticipated increase to over 60 000 satellites by 2030. We recommend that the impact of space weather on satellite collisions is considered as a risk for the national risk register to help focus mitigation planning. Reaching a tipping point for runaway collisions culminating in unusable orbits in LEO is not an ‘if’, but a ‘when’.

Ethics. This work did not require ethical approval from a human subject or animal welfare committee.

Data accessibility. Data and imagery from the Atmospheric Imaging Assembly (AIA) instrument on the Solar Dynamics Observatory (SDO) spacecraft and the LASCO coronagraph instrument on the Solar and Heliospheric Observatory (SOHO) spacecraft used for figure 1 are available via jHelioviewer https://www.jhelioviewer.org. Data from the Hartland magnetometer are available via https://intermagnet.org. Data from the University of Surrey neutron monitor and the MAIRE-S model are available via https://spaceweather.surrey.ac.uk/surreyneutronmonitor.php. Data from the Oulu neutron monitor are available via https://cosmicrays.oulu.fi. GNSS observations used for figure 5 are available through the International GNSS Service (IGS) at https://igs.org/. Data from Space-Track (https://www.space-track.org) were used to assess changes to the ICESat-2 orbit following the storm.

Declaration of AI use. We have not used AI-assisted technologies in creating this article.

Authors' contributions. R.B.H.: conceptualization, writing—original draft, writing—review and editing; M.J.A.: writing—review and editing; G.D.R.A.: writing—original draft, writing—review and editing; C.D.B.: formal analysis, writing—original draft, writing—review and editing; M.M.B.: writing—review and editing; P.C.: writing—review and editing; E.C.: writing—review and editing; C.D.: formal analysis, writing—original draft, writing—review and editing; J.P.E.: writing—review and editing; S.E.: writing—review and editing; D.G.: writing—review and editing; M.G.: writing—original draft, writing—review and editing; L.M.G.: writing—review and editing; M.A.H.: writing—original draft, writing—review and editing; M.H.: writing—review and editing; D.R.J.: writing—review and editing; B.J.: writing—original draft, writing—review and editing; S.M.: writing—original draft, writing— review and editing; C.N.M.: formal analysis, writing—original draft, writing—review and editing; H.M.: writing— review and editing; M.O.: writing—review and editing; J.P.: writing—review and editing; J.R.: writing—review and editing; G.R.: writing—review and editing; K.A.R.: writing—original draft, writing—review and editing; H.K.S.: formal analysis, writing—review and editing; R.J.T.: writing—review and editing; J.W.: writing—original draft, writing—review and editing; M.W.: writing—review and editing.

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

Conflict of interest declaration. We declare we have no competing interests.

Funding. R.B.H. was supported by Natural Environment Research Council (NERC) grant NE/Y006178/1 PRESCIENT (2024-2028).

Acknowledgements. We thank staff at the Met Office Space Weather Operations Centre for valuable information, Craig Rodger and the Solar Tsunami team for their information on the New Zealand power grid, and Hugh Evans and Ingmar Sandberg for helpful discussions on satellite data from LEO. We also thank two anonymous referees for their helpful comments.

Dedication. We note with sadness that Captain Bryn Jones who made a huge contribution to space weather passed away just before this paper was published. We would like to dedicate this work to his memory.

Appendix A. Timeline of events

A.1. Wednesday 8 May 2024

On Wednesday 8 May 2024, the Met Office forecasters were monitoring two active regions on the Sun, referred to as AR3663 and AR3664. These active regions correspond to large sunspot groups with complex magnetic field structures and from which minor X-class solar flares and CMEs were being emitted. AR3663 had been considered the main threat but was now on the western limb of the Sun and decreasing in size (by convention, the western side is the right-hand side when looking at the Sun). A 'be aware' alert was already in force for geostationary SATCOM operators. Active region AR3663 remained a threat as its location on the western limb of the Sun could produce a solar energetic particle event, also known as a radiation storm. In the event, there was a radiation storm later, but its impact was small.

The other active region, AR3664, was developing just south of the solar equator and just west of the central meridian. The sunspot group was already comparable in size to that of the famous Carrington event of 1859 and therefore of considerable concern. Both AR 3663 and AR 3664 were classified as beta–gamma–delta, reflecting their significant magnetic configuration complexity. On 8th May a refreshed 'be aware' alert was issued for geostationary SATCOM operators for AR3664. Three halo CMEs were observed at 05:30 UTC, 12:48 UTC and 22:36 UTC on the 8 May, associated with X1.0, M8.7 and X1.1 flares, respectively.

A.2. Thursday 9 May 2024

On Thursday 9 May at 09:20 UT, an X2.2 solar flare was emitted from AR3664 together with a very wide and fast halo CME (observed at 09:24 UT in LASCO C2) travelling at approximately 1000 km s^{-1}. The fact that it was a halo CME meant that it could not miss the Earth, and the combination of this CME with the sequence of CMEs on 8 May indicated that it could trigger a large geomagnetic storm [6].

One more halo CME was emitted from the active region, associated with an X1.1 solar flare which peaked at 17:44 UTC on 9 May. Analysis suggested that the faster CME ejected at 09.20 UT would overtake the preceding CMEs ejected earlier, before they reached the Earth. The coalescence of two or more CMEs in interplanetary space (a CME is known as an interplanetary CME or ICME once it has left the Sun) is a complex problem in plasma physics; in general, ICMEs do not mix. Instead, one tends to 'push' against another, compressing, twisting and distorting the magnetic field, compressing the plasma density and changing the velocity. Existing forecast models cannot cope with the complexity of this process. Thus, there was a large uncertainty in forecasting the magnitude and geo-effectiveness of the storm that would take place; a storm triggered by fast-flowing compressed magnetic fields could be much larger and more sustained than that triggered by a single CME. However, owing to the high velocities involved, there was a much greater confidence in the time of arrival—although this was still within a 15 h window.

At 21.54 UT on Thursday 9 May, a G4 Geomagnetic Storm Watch was issued for an expected time of arrival at Earth, somewhere between 21.00 on the 10 May and 12.00 on the 11 May. Note that the window in the time of arrival was approximately 15 h, which was very large and undesirable, but is a result of the limited available imagery for this event and the scientific tools available.

At 21.56 UT on 9 May, the Met Office Space Weather Operations Centre (MOSWOC) called the NESO control room informing them of a G4 Storm Watch. MOSWOC also initiated online discussions with the US SWPC and the Australian Bureau of Meteorology.

A.3. Friday 10 May 2024

During the early hours of Friday 10 May, MOSWOC performed several runs of the ENLIL model to get a better assessment of when one or more ICMEs would arrive at Earth. The model indicated that up to five ICMEs would merge into one and reach the Earth at about the same time. The risk and uncertainty associated with the May 2024 events had increased substantially.

In the early hours of Friday 10th May MOSWOC issued the highest level of alert for geostationary SATCOM operators.

At 09:30 UT on the 10th May MOSWOC initiated a call with SATCOM operators.

At 11.17 UT on the 10 May, an assessment of forecasting models led MOSWOC to issue an 'informal briefing'. An informal briefing is the first low-level official warning of a space weather event and informs emergency responders, local authorities, health services, utilities, transport operators and government departments. The warning indicated that there were multiple ICMEs on their way to Earth, that the time of first arrival was approximately 20.00 UT on the 10 May and that there was a 10% chance of a G4 storm early on the 11 May. A Space Weather Technical Forecast was issued to the public at 13.30 UT providing this information. It also outlined the possible range of impacts.

At 17.07 UT on the 10 May, a sudden increase in the Earth's magnetic field was detected by the magnetometer at Hartland, Devon, operated by the British Geological Survey. The increase was a jump of 103 nT and indicated that the first ICME had reached the outer boundary of the Earth's magnetic field and had started to compress the Earth's field. By 19.40 UT, the field had increased by another 257 nT.

At 20.01 on the 10 May, MOSWOC issued a Geomagnetic Storm Watch stating there was a 30% chance of a G5 storm, the highest level on the NOAA scale. However, the data suggested that this would only just exceed the G5 threshold, and so a 'low-level' G5 was referred to.

Between 20.20 UT and 21.10 UT, MOSWOC conducted a series of calls with Met Office Management, NESO and DESNZ appraising them of the situation.

At 21.37 UT, the chair of the SEIEG contacted the Met Office Management by email and arranged a call to discuss the event. The chair was on holiday in Peru but had received the MOSWOC alerts. They reviewed the evidence and agreed with the updated assessment that the storm would just reach the G5 level. The chair of SEIEG also informed the SEIEG core team.

Between 22.30 and 22.37 UT, the magnetic field detected at Hartland dropped by 471 nT and by 00.13 UT a G5 storm was in progress. Note that the Hartland observatory was on the evening or nightside of the Earth and not in an ideal location to detect magnetic field compressions on the dayside.

A.4. Saturday 11 May 2024

At 00.15 UT on Saturday 11 May the SEIEG core team discussed the event with the Met Office Management. MOSWOC issued a G5 storm warning at 00.17 UT for the 12 h period 00.00–12.00 UT of the 11 May based upon evidence from a number of geomagnetic indices available from a range of UK and international partners. The fact that more ICMEs were on their way to Earth was a concern as this could increase the severity of the storm or reduce it, depending on the polarity of the magnetic field in the next ICME, but either way, would further sustain the disrupted period. However, since the estimated time of arrival was another 6 h away, there was time to make another assessment closer to the time of arrival. The current storm might also have started to subside by then. Furthermore, a G5 storm was already in progress; there is no higher level of warning on the NOAA scale. The Chair of SEIEG informed the whole SEIEG committee, many of whom were already aware of the MOSWOC forecasts.

A.5. Sunday 12 May 2024

At 00.53 onwards, a series of calls took place between MOSWOC and NESO to confirm that a G5 storm was in progress.

At 01.40 UT, Met Office Management informed the Duty Officer at DESNZ.

At 02.05, a small ground-level enhancement was reported.

At 02.25 UT, DESNZ confirmed their contact with NESO.

At 04.00 UT, NESO control room call with MOSWOC.

At 07.07 UT, Met Office Management provided an update to DESNZ by email.

The timeline of events illustrates the considerable amount of successful communications between MOSWOC, Government departments, agencies (both national and international) and scientists before and after warnings to the general public. Note that these information transfers were enabled by internet, mobile phone and landlines, underpinning that power availability is a concern for all of these during an event.

The most obvious impact of the storm was the aurora which was visible across the UK and received considerable media coverage. There were reports of the aurora as far south as El Peyote in Mexico at 35.5° N invariant latitude and Tivoli Astrofarm in Namibia at −29.8° S in the Southern Hemisphere [53].

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