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Space Weather: A Hazard to Technology at the Earth's Surface

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Meeting Report

Space Weather: A Hazard to Technology at the Earth's Surface

Neil Rogers, **Juliane Hübert**, **Gemma Richardson**, and **Alan Thomson** report from a RAS meeting in March that considered the potential for extreme solar activity to damage ground infrastructure.

Figure 1. A solar coronal mass ejection may create a chain of events that leads to geomagnetically induced currents in power cables. [Credit: NASA / N. Rogers]

Our sun is a relatively stable and quiescent star that has emitted a steady stream of energy supporting life on Earth over millennia (Reinhold et al., 2020). However, a closer look at the sun's surface reveals a maelstrom of turbulent and magnetically confined plasma, which on occasions can emit a flare of intense electromagnetic and particulate radiation or eject a cloud of energetic plasma into the solar wind that flows towards the Earth (Figure 1). Perhaps the largest solar eruption of modern times was observed on 1 September 1859 by the astronomer Richard Carrington (Carrington, 1859) and was accompanied by intense disturbances in the geomagnetic field, widespread auroral displays extending to low latitudes, and multiple telegraph system failures with reported incidents of electric shocks and fires at telegraph stations (Cliver & Dietrich, 2013). It is likely that the bright flare and unusual sunspots that Carrington observed indicated a large coronal mass ejection (CME) which arrived at the Earth compressing the protective geomagnetic field and driving electrical currents that flowed within and around the magnetosphere. Bursts of electrical current flowed along magnetic field lines to the high-latitude ionosphere causing the air to glow in colourful auroral displays. Millions of Amps of current flowed in the highly conductive ionospheric layer at about 110 km altitude, contributing to the magnetic disturbances recorded at geomagnetic observatories and inducing additional electrical currents in long conductive telegraph cables on the ground. In subsequent days, as the Earth's radiation belts filled with solar plasma, a strong 'ring current' would have flowed westward around the Earth, opposing the internal geomagnetic dipole field such that the auroral regions expanded to very low latitudes (Silverman, 2006).

In the modern age, the impact of such solar activity would be far more disruptive since there is more ground infrastructure comprising long metallic cables that are vulnerable to Geomagnetically Induced Currents (GICs). These include high-voltage electricity transmission networks, oil and gas pipelines, metal communications cables, and railway signalling systems. A large geomagnetic storm in March 1989 famously caused a nine-hour electricity failure across a large region of Quebec, Canada and other power system problems in the USA, UK, and Sweden (Boteler, 2019). This event precipitated an increased drive towards a better understanding of GICs, and improvements in the design of ground infrastructure to make it resilient to extreme GICs.

On 12 March 2021, a Royal Astronomical Society specialist discussion meeting was held online to consider the findings of a four-year NERC-funded UK-wide study into GICs called "Space Weather Impacts on Ground Systems (SWIGS) (https://swigs.bgs.ac.uk) and to invite contributions and discussions from experts worldwide. A recording of the meeting is available to view online: http://swigs.bgs.ac.uk/RAS_specialist_discussion_meeting_Space-weather.mp4. The main aim of SWIGS has been to develop better physical understanding and modelling of GICs in electricity networks, pipelines, and rail networks. The SWIGS consortium consisted of space physicists and geophysicists at ten UK research institutions led by the British Geological Survey (BGS) and involved scientific project partners from the USA, Canada, Europe, South Africa, New Zealand, and China. The SWIGS project also benefitted from the expertise of industrial consultants in the UK power generation and rail industries.

The meeting covered a range of research themes, including (i) evaluating the likelihood of extreme GICs, (ii) assessing the long-term changes in the geomagnetic field which may affect systems over many decades into the future, (iii) modelling the impact of extreme solar energetic particle events and coronal mass ejections through magneto-hydrodynamic (MHD) modelling, (iv) understanding electrical current systems in the magnetosphere and ionosphere important to GIC, and (v) improving the real-time prediction and forecasting of GICs. We invited three keynote speakers to provide an overview of the latest research from Sweden and the USA and from the nuclear power industry in the UK and France.

After a welcome introduction from SWIGS project Principal Investigator, **Alan Thomson** (British Geological Survey), our first keynote lecture was presented by **Lisa Rosenqvist** (Swedish Defence Research Agency (FOI)) who gave an overview of recent GIC research from Sweden. The southern region of Sweden is particularly vulnerable to the extreme geomagnetic activity associated with aurorae, but the magnitude of GICs also depends on the conductivity of the surface. Sweden has sharp lateral gradients in conductivity (e.g. in coastal regions) which are not well modelled from 1D conductivity profiles (varying only with depth). A new GIC modelling capability called GIC-SMAP has therefore been developed at FOI, incorporating the detailed 3D conductivity structure based on ground measurements throughout Sweden. The model shows that the geoelectric fields that drive GICs are dominated by the ocean-land boundary in southern Sweden where a simple 1D conductivity model would have underestimated GICs by about 50%. From modelling historical geomagnetic storms it was found that three storms with the largest GIC amplitudes coincided with observed impacts on the Swedish power network. The sites affected were in regions of large rapid magnetic field variations (as observed by ground-based magnetometers) and in areas of low crustal conductivity that neighboured high conductivity regions, conditions that are both conducive to large geoelectric field generation. The observed disturbances throughout Scandinavia were modelled with the Space Weather Modelling Framework (SWMF) but the model failed to reproduce the large rapid disturbances responsible for the ground impacts.

Two factors influence the intensity of space weather phenomena: the level of solar activity and the configuration of the geomagnetic field. The first is the main driver of space weather events, while the latter modulates their effect on the magnetosphere and at ground level. A presentation by **Stefano Maffei** (University of Leeds) showed how significant changes in the internal geomagnetic field occur over decadal timescales. Its evolution is an important component of space climate: the slow changes in global patterns of space weather events. The possibility to forecast space climate rests on our ability to forecast the evolution of the geomagnetic field, which is generated by convective motions in Earth's outer core. From one such forecast (Alken et al., 2021), Maffei mapped the location of geomagnetic features that are relevant to space weather and their possible evolution. This prediction showed that the northern auroral zone (the region where we expect aurorae to occur most frequently) will continue its present migration towards Siberia *(see upper panel of* Figure 2*)*. However, little will change for North-European aurora chasers. The same technique allows us to forecast the geographical location of the regions most exposed to the effect of severe space weather events. Geomagnetic field forecasts suggest that in 50 years from now, southern Canadian locations such as Quebec City and Newfoundland could be less exposed to the impact of rare, destructive events *(see lower panel of* Figure 2). At the same time, the UK and New Zealand are expected to maintain their present-day level of vulnerability.

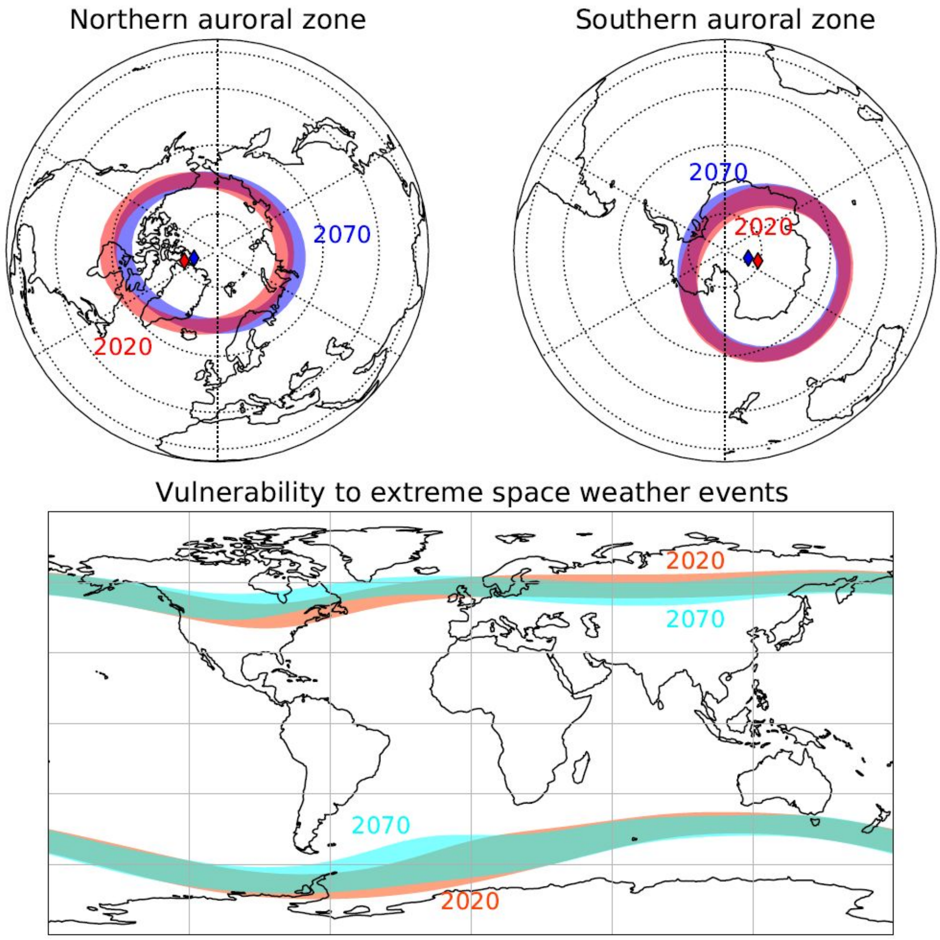

Figure 2. Upper panel: Orthographic projections of the northern and southern auroral zones, defined as the region between 65 and 70 degrees of corrected geomagnetic (CGM) latitude, as they were in 2020 and as they are predicted to be in 2070 according to the International Geomagnetic Reference Field (IGRF13) (Alken et al., 2021). Lower panel: Location of the 50° to 60° CGM latitudinal bands, associated with high exposure to severe space weather events, in 2020 and 2070. [Credit: ***Stefano Maffei, University of Leeds****]*

A useful indicator for the magnitude of GICs is the rate of change of the magnetic field, *dB/dt*, as observed at magnetometer stations around the world. GICs are driven by geoelectric fields that depend on both *dB/dt* and the electromagnetic wave impedance of the ground. **Andy Smith** (Mullard Space Science Laboratory, University College London) discussed the magnetospheric phenomena that are responsible for the largest rates of change of the ground magnetic field in the UK. Approximately half of the extreme *dB/dt* events are associated with substorm expansion and recovery phases associated with auroral current systems (Freeman et al., 2019). However, when a large coronal mass ejection or other shock fronts in the solar wind arrive at the Earth, they can initiate a strong electrical current in the magnetopause boundary that is detected in ground-based magnetometers as a “Sudden Commencement” (SC), often presaging a geomagnetic storm. Smith discussed how SCs could also cause large *dB/dt* in the UK, but found that only a maximum of 8% of the extreme *dB/dt* events were linked to SCs (Smith et al., 2019) and that this percentage decreased with increasing latitude in the UK. Nonetheless, SCs were followed by a three-day interval that accounted for over 90% of extreme rates of change of the field, meaning they are a useful phenomenon for forecasting intervals at which infrastructure may be at risk of large GICs.

On a similar theme, **Neil Rogers** (Lancaster University) presented a model of the global climatology of extreme *dB/dt* over timescales (*dt*) from 1 second to 60 minutes. The model characterised how extreme *dB/dt* events are more likely to occur at certain geomagnetic latitudes and local times, and how their occurrence rate and magnitude depend on the timescale of the fluctuation. Using magneto-telluric transfer functions (measurements of ground impedance) recorded at the three UK magnetic observatories, he showed that for events occurring several times a year (at the 99.97th percentile) the induced geoelectric fields were greatest for fluctuations of 20-min period, whilst 1-in-100-year return levels would be greatest for 0.5–2 min period fluctuations.

Global MHD models, which are used to model the impact of large CMEs on the Earth's magnetosphere, tend to underestimate high-frequency variations in the ground-level magnetic field that are important for GIC modelling. To address this, **Carl Haines** (University of Reading) presented a proof-of-concept scheme in which he introduced realistic high-resolution noise with which to drive an "impacts" model. He showed that the scheme outperformed a reference "do nothing" approach under the Fractions Skill Score for events where the measured *dB/dt* magnitude exceeded the 99.9th percentile.

Xiangcheng Dong (RAL Space, STFC) presented work showing how strong *dB/dt* variations were related to magnetic field-aligned currents (FACs) due to near-Earth bursty bulk flows (BBFs) of plasma from the magnetosphere. These FACs were observed by sensors on the Cluster and SWARM spacecraft constellations, revealing both small-scale (10's of km) flows and more stationary large-scale (> 100 km) structures. A comparison with measurements of *dB/dt* on ground-based magnetometers during a geomagnetic storm in January 2015 showed FAC fluctuations mapping simultaneously (with suitable time lags) to *dB/dt* variations in both hemispheres. The most intense *dB/dt* variations were associated with FACs corresponding to a large-scale substorm current system driven by multiple BBFs.

Robert Shore (British Antarctic Survey) provided a summary of a technique, developed during the SWIGS project, which resolves and separates the large-scale ionospheric equivalent current systems in space and time, allowing their relationships to the solar wind drivers to be subsequently determined. This tells us where and why we can expect space weather impacts, and how big their effect will be. Shore also summarised a new technique which is the opposite approach to their previous work; starting with the solar wind driver, the new technique determines its response function within the ground-based data. The technique is called 'Spatial Information from Distributed Exogenous Regression' (SPIDER) (Shore et al., 2019). The discovered relationship between the ensemble ground geomagnetic variation and the solar wind driving highlights the localised reconfiguration timescale of the ionosphere to disturbances in the solar wind. This tells us about the strength and location of the space weather effects, in addition to when they will occur and how long they will last. Lastly, Shore et al. described the conversion of this localised SPIDER response model into a forecast of the magnetic variation at UK latitudes. This is laying the groundwork for the next generation of Met Office space weather forecast models.

John Coxon (University of Southampton) presented spatiotemporal distributions of FACs (Birkeland currents) measured with the "AMPERE" dataset – measurements from 66 satellites in low Earth orbit – with particular regard to latitude and local time variations and the dependence on the interplanetary (heliospheric) magnetic field orientation. Coxon outlined the results of applying the SPIDER technique to AMPERE data, yielding maps of the timescales on which currents react to changes in the solar wind (Coxon et al., 2019). He also presented functional fits to the spatial distribution of current densities, yielding probabilities of current densities exceeding certain thresholds.

Juliane Hübert (British Geological Survey) presented a new data set collected under the SWIGS program, 2017-2020, across the UK power grid using the Differential Magnetometer Method (DMM, Matandirotya et al., 2016). This technique provides a proxy measurement of GIC in high-voltage power lines to supplement scarce Hall probe GIC data in the UK (see Hübert et al., 2020). Field locations were chosen that are highlighted as hotspots in the BGS GIC model (Kelly et al., 2017). Albeit collected at the minimum of the solar activity cycle, with few periods of larger geomagnetic activity, the dataset captured many smaller geomagnetic storms that allowed an in-detail analysis and validation of the GIC model. The DMM GIC data set provides a solid base to refine and validate models of GICs in the UK power network. It is now available from the National Geoscience Data Centre.

The second keynote address was given by **Matt Allcock** (EDF Energy). EDF is Britain's biggest generator of zero carbon energy and manages 27 nuclear power stations that all need protection from natural hazards, including extreme rainfall, coastal flooding, and space weather. The regulatory requirement is that nuclear power stations must be able to operate safely under a 1 in 10,000-year natural hazard event but resilience of the power station must not be significantly diminished for more severe events. Build standards are dependent on the expected lifetime of the power stations as a longer lifetime will expose the power station to evolving risks such as changes in climate and space climate over the next century. GICs pose a risk to the off-site power supply to nuclear power stations, which is important for safe reactor shutdown. Working with the BGS, EDF R&D have estimated GICs in the UK and France electricity networks under historically extreme storms (such as that in 1989 which caused the Quebec blackout), benchmark geoelectric field scenarios, and scaled historical geoelectric fields to model 1 in 10,000-year geomagnetic storms. Results indicate that the simulated GICs are highly sensitive to the ground conductivity model applied.

EDF have also researched ground-level enhancements (GLEs) of cosmic rays that occur during solar energetic particle events. GLEs pose a risk of single event effects (SEEs) in electronic devices important for reactor operation and shutdown procedures. Allcock presented extreme values analysis of data from the Dourbes neutron monitor in Belgium, estimating the ground-level neutron count rates expected with arbitrarily small annual occurrence probability. These values were compared against the historic extreme GLEs estimated from proxy data such as radioisotope counts in ice cores and tree rings. Finally, Allcock discussed the use of mitigating strategies that reduce the impact of extreme space weather events. These include transformer add-ons and forecasting for GICs, and concrete shielding and logical redundancy for GLEs.

The impacts of space weather on the UK railways were presented by **Cameron Patterson** (Lancaster University), in a poster focusing on the historically most vulnerable aspect – track circuits. Track circuits are an integral part of the signalling system and crucial to smooth railway operation, being electronic components, they are susceptible to the effects of GICs. Using (i) track circuit modelling based on transmission line theory, (ii) the Spherical Element Current System method (Amm & Viljanen, 1999) to interpolate track-side magnetic field variations, and (iii) a ground conductivity model, Patterson determined the geoelectric field around railway lines, which can be used to investigate the impact of GICs in the railway network.

The meeting received reports from GIC research institutes not only in the UK but around the world. **Anna Martí** (University of Barcelona) presented a poster entitled "The role of the Lithospheric

Electrical Conductivity of Iberia in the Characterisation and Prediction of the GIC in Critical Infrastructures". The main outcomes from project 'IBERGIC' are a geoelectric lithosphere model of Iberia and the characterization of the Spanish electrical network to model GICs. Martí and her colleagues have applied for a new project which will include Machine Learning techniques to predict the magnetic variations that trigger GICs.

Peter Gallagher (Dublin Institute for Advanced Studies) gave an overview presentation on solar and geomagnetic monitoring and modelling in Ireland, describing instruments and tools to monitor and forecast phenomena associated with space weather, from their origins on Sun to the Earth. He described a solar monitoring and forecasting service, www.SolarMonitor.org, the Magnetometer Network of Ireland (MagIE; www.MagIE.ie), VLF radio monitoring of the ionosphere, and described new tools to model electric and magnetic field variations across Ireland in near real time.

Our last keynote speaker was **Chigomezyo Ngwira** (ASTRA LLC) who described GIC-related studies in the USA, which have received increased government funding over recent years to protect the US power grid. Ngwira reported several new programmes of research into data analysis of historical storms, numerical MHD simulations, Machine Learning techniques, instrument deployments, and new forecasting capabilities. A NASA-funded collaboration entitled "Enhancing GIC understanding and prediction over continental United States" is helping NOAA to improve space weather forecasting capabilities by (i) extending magnetometer coverage to support geoelectric field mapping; (ii) developing an auroral boundary identification tool based on equivalent ionospheric currents (derived from magnetometer measurements); and (iii) carrying out an extensive analysis of the impact of extreme GICs on the US power grid. The project will further enhance the ability of end-users to synthesize space weather information and provide an improved operational geoelectric field mapping tool.

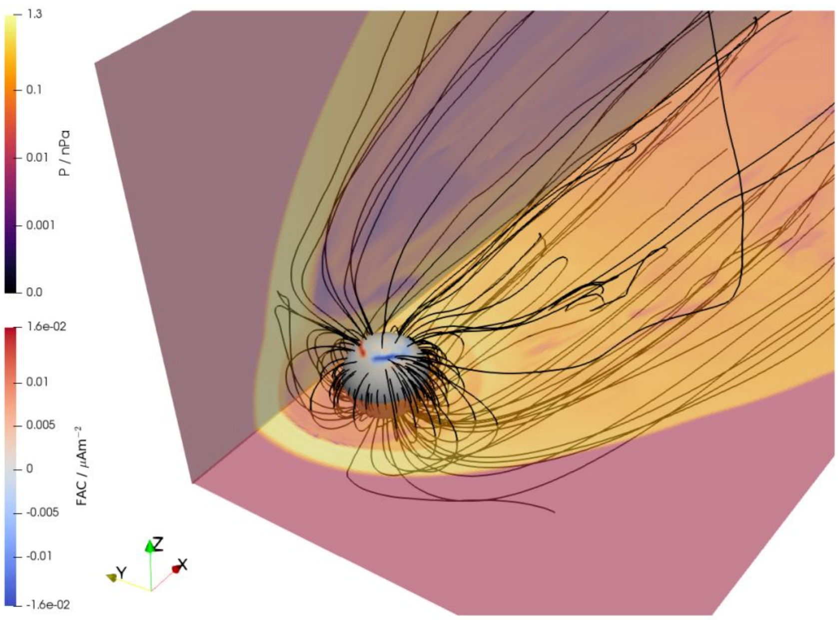

Figure 3. This Gorgon MHD model simulation from Imperial College London represents the Earth's magnetic field (black lines), thermal pressure in the magnetosphere (colour shading in the X and Z planes), and field-aligned currents (FAC) near the Earth's surface (blue-red shading). The sun is toward the bottom left of the picture (in the –X direction). FACs were mapped from a spherical shell (shown at 4 Earth radii) down to an ionospheric grid where the electric potential is solved and mapped back out to the magnetosphere to set the inner boundary flow. The model was driven using a synthetic steady solar wind (density 5 cm^{-3}, speed 400 km s^{-1} , and ion and electron temperatures of 5 eV) and an Interplanetary

*Magnetic Field of 2 nT in the southward (–Z) direction. The ionosphere was modelled with a uniform Pedersen conductance of 10 mho and zero Hall conductance. [Credit: **Joseph Eggington, Imperial College London**]*

Space weather and GIC forecasting is also currently attracting significant research interest and government funding in the UK, with many institutions now contributing to a new four-year £20 million UKRI programme called Space Weather Instrumentation, Measurement, Modelling and Risk (SWIMMR: https://nerc.ukri.org/research/funded/programmes/sfp-swimmr/). **Jonathan Eastwood** (Imperial College London) discussed ongoing work developing the Gorgon global MHD simulation of the Earth's magnetosphere (Figure 3), and in particular outlined how this work is being translated from basic research (such as in the SWIGS project) towards operational use at the UK Met Office in the context of the new 'SWIMMR Activities in Ground Effects' (SAGE) project, part of the SWIMMR programme.

SAGE is one of five NERC-funded consortia, and the objectives of SAGE are (i) to provide accurate nowcasts and forecasts of the ground geomagnetic field and ground electric field across the UK, as the space weather source of power grid GIC, pipeline Pipe-to-Soil Potential (PSP), and rail network faults and (ii) to make operational, at the Met Office, new UK capabilities in space weather nowcasting and forecasting of GIC, PSP and rail hazards. SAGE's forecast capability will, in part, be based on first-principles physics models using MHD simulation codes, as these are an increasingly valuable tool for space weather forecasters to quantify GIC hazard.

Eastwood described how Imperial College has implemented an ongoing programme of work developing the Gorgon global model of the magnetosphere using its heritage in laboratory plasma modelling (e.g. Mejnertsen et al., 2018; Eggington et al. 2018; 2020). As part of the SWIMMR/SAGE consortium, Imperial will realise an operational version of the Gorgon global magnetospheric model at the Met Office as part of an integrated GIC modelling suite. Eastwood reviewed Imperial's work on Gorgon to date and described the proposed implementation of a resilient methodology for forecasting ground geomagnetic perturbations. This will use two different approaches to find the ground magnetic field perturbations (Rastaetter et al. 2014, Pirjola and Viljanen 1998), providing forecast diversity, and is being built to also work with other Met Office models. In future developments, a further long-term goal is to bring the Gorgon model to the wider world and make it more accessible to potential users.

The SWIGS project, which ends in 2021, has already created a body of scientific research that has moved the study of space weather impacts on ground-based technology to a position where operational nowcasts and forecasts have more accuracy and therefore have more utility for industry and government. Several of the SWIGS partners are therefore implementing operational services to monitor, model and forecast impacts though the new SAGE project, noted above, to be delivered through the Met Office Space Weather Operations Centre. Within the SWIMMR programme, **Alan Thomson** (BGS) is lead-PI on the SAGE project, which will enhance UK real-time magnetic monitoring and, for the first time in the UK, forecast GIC impacts, based on magnetospheric modelling driven by real-time, or forecast solar wind measurements near Earth.

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Authors

Dr Neil Rogers is a Senior Research Associate in the Lancaster University Space and Planetary Physics group. He is interested in the statistics of extreme space weather and its impacts on ground-based infrastructure. Neil is currently implementing models for the UK Met Office that will predict shortwave radio outages during solar flares, solar proton events, and geomagnetic storms. He is also ionospheric consultant to Airbus Defence & Space ltd. on the European Space Agency's 'Biomass' satellite radar mission.

Dr Juliane Hübert is a Researcher within the Geomagnetism Capability of the British Geological Survey, specializing in the magnetotelluric method. Her main research area is the Solid Earth's response to the influence of Space Weather, especially how monitoring and modelling of the ground electric field can be improved. Juliane likes rocks and astronomical bodies equally.

Dr Gemma Richardson is also a Researcher within the Geomagnetism Capability of the British Geological Survey. Her main research interests are in the impacts of space weather on ground-based infrastructure, such as power networks and pipelines. She is also one of a team of space weather forecasters delivering the BGS daily global geomagnetic activity forecast. Gemma is currently developing a new model of pipe-to-soil potentials in the UK high pressure gas transmission network, and updating BGS GIC modelling code to improve nowcasting and forecasting capabilities as part of the 'SWIMMR Activities in Ground Effects' (SAGE) project.

Dr Alan Thomson is a Principal Researcher within the Geomagnetism Capability of the British Geological Survey. He is Principal Investigator for the recent SWIGS and SAGE space weather research and services projects, funded by NERC and UKRI respectively, and as described in the meeting report. Alan's interests are in the ground-level impacts of space weather and the relation of these impacts to solid Earth geophysics. Alan has led space weather projects benefitting ESA, National Grid, EDF Energy and Scottish Power and has been grant-funded in space weather research and services both in the UK, Europe and elsewhere over 25 years. Alan is a member of the UK government's Space Environment Impact Expert Group, advising Cabinet Office. He is a Vice President of the International Association for Geomagnetism and Aeronomy and is a member of the International Union of Geodesy and Geophysics' Geophysical Risk Commission.

Figure 1. A solar coronal mass ejection may create a chain of events that leads to geomagnetically induced currents in power cables. [Credit: NASA / N. Rogers]

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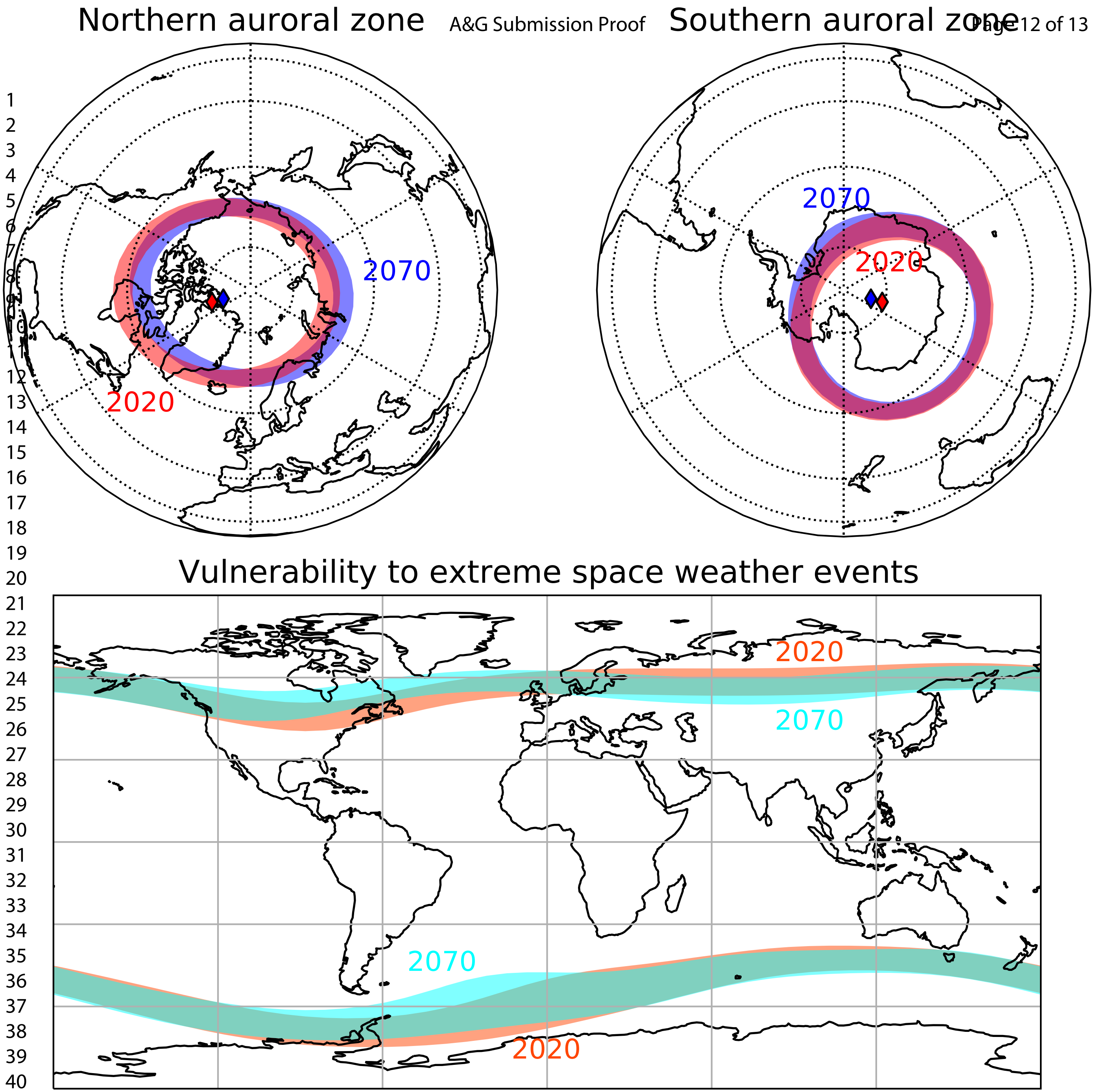
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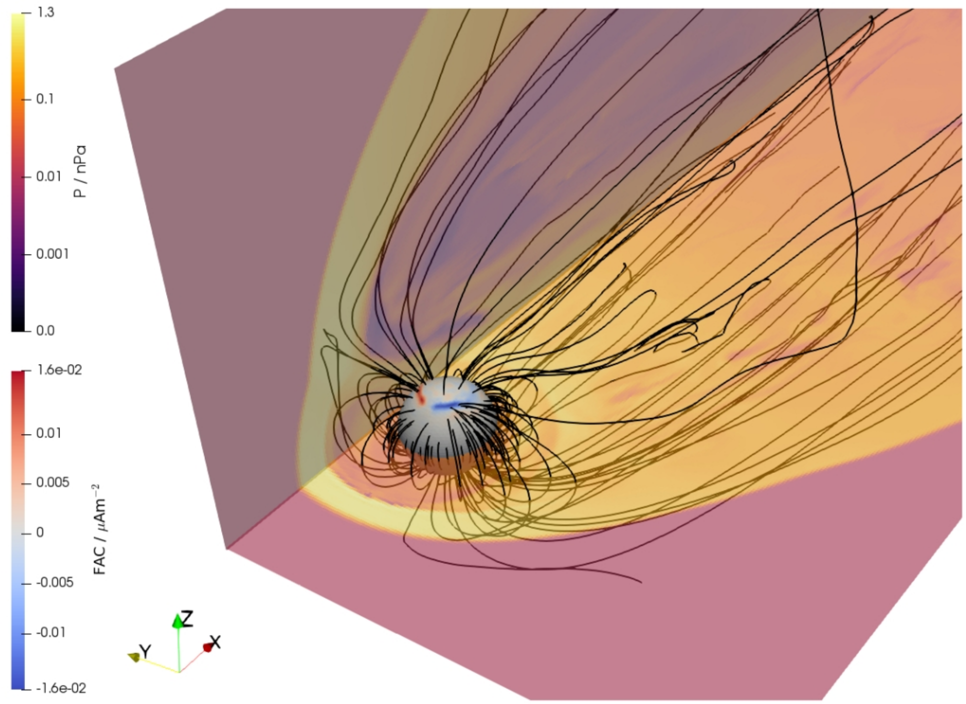

Figure 3. This Gorgon MHD model simulation from Imperial College London represents the Earth's magnetic field (black lines), thermal pressure in the magnetosphere (colour shading in the X and Z planes), and field-aligned currents (FAC) near the Earth's surface (blue-red shading). The sun is toward the bottom left of the picture (in the -X direction). FACs were mapped from a spherical shell (shown at 4 Earth radii) down to an ionospheric grid where the electric potential is solved and mapped back out to the magnetosphere to set the inner boundary flow. The model was driven using a synthetic steady solar wind (density 5 cm^{-3}, speed 400 km s^{-1} , and ion and electron temperatures of 5 eV) and an Interplanetary Magnetic Field of 2 nT in the southward (-Z) direction. The ionosphere was modelled with a uniform Pedersen conductance of 10 mho and zero Hall conductance. [Credit: Joseph Eggington, Imperial College London]