The Ground Effects of Severe Space Weather

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Overview

Severe space weather is not a new phenomenon, as low-latitude aurorae have been observed and documented for hundreds of years across the globe (Kataoka and Iwahashi, 2017). However, technological impacts have only existed for the past 200 years, particularly with the great innovations of rail and telegraph. The famous geomagnetic storm in September 1859, known as the 'Carrington' event, is well documented as having rendered telegraph systems inoperable in New York but also allowed very long-distance messages to be sent in the UK (Green et al., 2006). Aurorae filled the sky for several nights and were so bright as to allow the newspaper to be read outside at midnight. The first recorded effect on the railway network was reported in Exeter in October 1848 and related to problems with signals, delaying a train by 16 minutes to much local discombobulation (Nature, 1871). Nowadays, though the risk to wired communication has reduced through the use of fibre optics, our exposure has increased in other areas such as the widespread use of GNSS (Global Navigation Satellite System) timing signals in mobile phone and financial networks.

Terms such as Space weather and Solar Terrestrial Physics are used to describe a wide range of phenomena that broadly encompass the interaction between the Sun via the solar wind and the Earth's magnetic field. The Sun emits a continuous steady stream of ionised and neutral particles and magnetic fields known as the solar wind. The 'normal' solar wind, has an average density at 1 AU of 1 particle per cm^{-3}, temperatures of ~10^5 K, a speed of around 400 km/s and a total magnetic field strength of 5 nT. Severe space weather occurs when the solar wind becomes very fast, very dense and hot and carries a large magnetic field pointing in a southward direction (Akasofu, 1981). Such events are typically triggered by the explosive release of plasma, with embedded magnetic fields, from the surface of the Sun during a Coronal Mass Ejection (CME). The CME crosses interplanetary space at high speed (> 750 km/s), with a high density (> 100 cm^{-3}) and high temperatures (> 10^6 K) compared to the steady background solar wind. The magnetic field strength embedded in such structures can reach > 40 nT for short periods of time. Additionally, associated with a CME there may be large solar flares which release X-rays and gamma rays, and solar proton events (SPE) which are bursts of high energy protons that broadly follow the open magnetic field lines emanating from the Sun. Although the Sun has a wide range of activity levels, varying over the well-known 11-year solar cycle, a severe space weather event is at the extreme end of the spectrum and can have impacts on a large number of technological systems both on and above the Earth's surface simultaneously (Fig 1.). Historical analysis suggests that large events can occur at any time during the solar cycle.

A severe space weather event

The first sign of an extreme space weather event is often an increase in X-ray emission produced by a large solar flare detected at a geostationary satellite such as GOES (Shelley et al, 1972). It can also be observed in the visible light spectrum at this point. Within a few seconds, the flare's radiation will have ionised the sun-facing side of the atmosphere and start to cause problems with high frequency (HF) radio signals as the reflective and refractive properties of the ionosphere change. At this point, a full-halo CME begins to lift off the Sun's surface. A few tens of minutes later, high energy protons travelling near the speed of light arrive, potentially causing damage to electronic devices on satellites and delivering a large dose of radiation to astronauts on the International Space Station and aircraft flying at high polar latitudes. Around 16-24 hours later, the main cloud of the CME reaches Earth. If the embedded magnetic field of the CME is south-pointing, it couples to the Earth's north-pointing field and allows efficient transfer of energy and particles into the magnetosphere. This generates a complex array of global current systems in near-earth space, which couple to the ionosphere dissipating some of the energy.

By now, on the night side of the planet, the most visible sign of the space weather event is the appearance of aurorae at low latitudes (< |55|°) where they are not usually visible. Beneath the aurora, there is a threat to ground-based technologies such as transformers in the high-voltage power network, rail and pipeline assets from geomagnetically induced currents. Navigation systems both compass-based and those using GNSS are affected by the rapidly varying magnetic fields of the ionosphere and magnetosphere, which are caused by strong fluctuations in the local density profile of the ionosphere and the flow of large electrical currents (> 1 MA) at altitudes of around 110 km. Such storms can last for up to three days, going through periods of quiescence and intensification Fig. 2 shows the variation in Declination angle over one day at three of the UK's geomagnetic observatories during the Halloween storm of 2003.

Our Current Knowledge

Little of the above described scenario is disputed – indeed it occurs in some form several times per decade. However, what is presently unknown is how large an extreme event can be, how often such events may happen and what the consequences on modern technology might arise. Linked to these unknowns are factors such as how civil authorities should act to prevent and/or prepare for space weather, how infrastructure operators and insurance companies might be made aware of the potential impacts in order to mitigate against them and how end-users and the general public may react to such a scenario. On March 9th 2018, a one-day Specialist Meeting, organized by the authors, was held in Burlington House, London, to discuss these topics. The meeting entitled the 'Ground Effects of Severe Space Weather', attracted a varied audience including industrial and academic researchers, students and interested members from the Society.

Prof Mike Hapgood (Rutherford Appleton Laboratory) gave the introductory talk at the meeting, weaving together the vexed issues of policy response to High Impact Low Probability (HILP) events. Although there have been a handful of large storms since the Carrington event, the lack of long term global measurements of the magnetic field has made it difficult to place this storm in context. Was it just a larger version of storms recorded in the digital age or a rare class of 'superstorm' in which different processes operate? Though there are measurements from a few locations during the Carrington storm, such as at Greenwich magnetic observatory and Alibag (near Mumbai) in India, there remain large uncertainties as to the absolute size of the storm and its dynamic structure. Presently, severe space weather is considered a 1-in-100 year risk on the UK government's Risk Register, with its impact estimated to be below or on par with heavy snowstorms (Fig 3.). Mike also pointed out that although some risks are diminishing as new technology supersedes the old, new and potentially creating greater ones may be created; he cited the navigation of self-driving cars and lorries as potentially a risk, though this will depend on how connected they need to be (e.g. via mobile networks) and how heavily they rely on GNSS for navigation. In some instances, known vulnerabilities can be engineered out but in complex systems it is difficult to detect weak points until they become exposed by extreme environmental factors.

Ground effects on power grids

This was the case in Quebec (Canada) in 1989. After several decades of relative quiescence (or lucky escapes perhaps) from severe geomagnetic storms, the risk of a severe space event to high-voltage power grids was realised with a major blackout event in March of that year (Bolduc, 2002). The guest speaker, *Dr David Boteler* from Natural Resources Canada, gave a detailed analysis of the events leading to the collapse of the Quebec-Hydro grid for nine hours on 14th March. The cause was the flow of large Geomagnetically Induced Currents (GIC) through the grounding points of several of the Quebec-Hydro system's high voltage transformers. A series of circuit-breakers tripped as they overloaded, closing off the link between the hydro-electric dams producing power in the north of the province with the consumers in cities to the south. The collapse took less than 90 seconds from the start of the instabilities in the grid to blackout and it took over 9 hours to restore the system.

The 1989 event forced utility companies to examine their exposure to space weather events. In the UK, two transformers were damaged in the 1989 storm. The Halloween storm in 2003 caused a blackout in Malmo, Sweden and substantial damage to many transformers in South Africa. *Dr Sean Blake* (Trinity College Dublin) described his recent work to understand the potential impacts of large GIC on the Irish national grid. With access to very detailed engineering properties of the network, he was able to reproduce GIC measurements made at one site near Dublin by modelling the response of the conductive Earth to the time-varying magnetic field and estimating the current flow through individual HV transformers. Using this methodology, he analysed the entire network to find the most vulnerable transformers, with both hypothetical and historical geomagnetic storms to test his grid model.

In the UK, there has been an ongoing research programme into the risk to the high voltage grid for the past two decades, particularly at the British Geological Survey, University of Edinburgh and Lancaster University. In 2011, the introduction of space weather as a hazard onto the UK National Risk Register prompted the creation of the Met Office Space Weather Operations Centre (MOSWOC) who have responsibility for monitoring and forecasting severe events. One issue with severe space weather is actually how to classify its magnitude. Presently a magnetic activity indicator, known as the Kp index, is used as a proxy. This quasi-logarithmic scale (0 – 9) is based on the variation of the magnetic observatories around the world over the past three hours, so may not fully reflect local conditions in the UK. Although a local version, known as K, can be computed from regional magnetic observatories, the index stops at 9 which is inadequate to describe very large variations that are important to grid operators. *Dr Gemma Richardson* (British Geological Survey) investigated other proxies for describing magnetic activity and relating them to GIC in the UK power grid. Using 30 years of magnetic field data she found that the range of the magnetic field (ΔB) over a fifteen-minute period was a better predictor than the rate of change of the magnetic field (dB/dt) as is often cited in the research literature. This work should lead to a more useful index for severe space weather and the resultant GIC, which can be employed by MOSWOC in the future.

There are relatively few direct measurements of GIC in the UK (obtained by clamping a Hall probe to the grounding wire of a transformer), which is one of the main reasons for the uncertainty around the actual risk. *Dr Alexis Ruffanach* (EDF Energy R&D UK) described the work within his company to examine the risk in respect to their assets and to help external research partners expand their understanding of the geophysical effects. As a responsible operator of nuclear power stations, EDF have a longer term perspective than most of us, seeking to understand 1-in-1,000 or even 1-in-10,000 year events to ensure safe performance of their infrastructure.

As the UK is an island, there is a significant coastal effect which causes channelling of electric current along the boundary between electrically resistive land and conductive sea water. The UK also has very complex geology – from conductive chalk in the south of England to resistive granites and metamorphic rock in the Highlands. This complexity means that simple one-dimensional treatment of the way in which the variation of a magnetic field during a geomagnetic storm induces an electric field in the ground is inaccurate. At the bare minimum, the coastal effect needs to be included and to perform a more accurate calculation of geoelectric field requires a geological model to be included (Beamish et al, 2002). The magnetotelluic (MT) method uses simultaneous magnetic and electric field measurements at a single site to deduce the local conductivity of the ground and its capacity to generate anomalous geoelectric fields. *Dr Fiona Simpson* (University of Southampton) initiated a measurement campaign in the summer of 2017 to better quantify the regional conductivity across the UK, beginning in the Scottish Highlands. Ten sites were set up and, by good fortune, happened to capture the geomagnetic storm of 7/8th September 2017. Although not a particularly large storm in the UK, the geoelectric field at some sites exceeded 1 V/km, which was an unexpected finding. Further MT data will be gathered in southern Scotland and northern England over the next two field seasons.

The ability to remotely estimate the geoelectric field over a wide area or infer GIC at low cost without requiring a Hall probe would greatly benefit both researchers and operational forecasters. *Dr Joan Campanya* (Trinity College Dublin) has developed a new way of estimating the geoelectric field by remote referencing. Using MT transfer functions of the relationship between the magnetic and electric field at one site, it is possible to estimate the electric field at another site using the magnetic field at the first location. This has applications to real-time estimation of the geoelectric field using just a handful of permanent observatories. However, the initial site must be occupied by an MT station for a few weeks in order to compute the transfer function. In a similar vein of using remote-sensing methods to estimate GIC, *Dr Mark Clilverd* (British Antarctic Survey) gave a summary of the use of a very low frequency (VLF) radio detector to measure electrical harmonics generated in high voltage transformers during severe space weather. An experiment carried out in Dunedin in New Zealand saw a loop antenna placed close to a transformer in the Halfway Bush substation, which also has a Hall probe installed to measure GIC. During the 7/8th September 2017 storm, the transformer experienced GIC, which caused magnetic flux to leak out of the iron core and windings. When this happens, the transformer saturates on one side of the hysteresis loop causing odd and even harmonics around 50 or 60 Hz to develop. These electromagnetic harmonics were detected from 50 Hz all the way to 15 kHz by the VLF receiver.

Rail and air travel

The effects of GIC on power networks is a major focus of the research community due to the direct applicability of geophysical knowledge, but there are other space weather effects that can cause indirect damage or disruption to ground-based infrastructure. *Les McCormack* from Atkins Global discussed the potential effects on the rail sector from interference with signalling through to loss of communications with drivers via the rail mobile phone network. Some other notable consequences of GNSS loss could be the failure of automatic train doors at stations to open (as the train does not realise it is in a station), or the disruption to points causing trains to be halted. Clearly, in emergency situations, reliable channels of communication between the driver and train controllers are imperative to avoid unwanted scenarios such as passengers escaping onto rail lines after several hours delay.

Other transport systems such as air travel may be heavily impacted as well. *Dr Neil Rogers* (University of Lancaster) spoke about his work on a European-funded project to create an early warning system to alert airlines and air-traffic controllers of the fade-out of high frequency (HF) radio links to transoceanic aircraft. *Prof Clive Hands* (University of Surrey) outlined some of the risks to travellers over the polar regions where the magnetic field lines are more open to the magnetosphere. This allows a greater number of higher energetic particles to enter into the atmosphere. Depending on the height of the aircraft, crew and passengers become very susceptible to receiving larger doses of radiation. Clive described a famous solar proton event (SPE) in February 1956, where the background particle level rose 14-fold over a few minutes (Shea and Smart, 1990). A typical person receives around 6 mSv per year. Anyone travelling on a polar-routed aircraft at that time would have received their entire annual dose in a few hours. Presently, such SPEs are not forecastable and by the time the crew could react to take the aircraft to a lower altitude, much of the dose would already have been received. *Dr Alex Hands* (University of Surrey) has been investigating the direct effects of SPEs on electronics. High energy protons can cause single event upsets as they pass through computer memory, disrupting registers by flipping 1's to 0's or vice versa. At the extreme end, the transistor gates could be destroyed. During a large SPE, for an aircraft flying by auto-pilot this could result in an unwanted disengagement every few minutes. As communication with the ground would also be affected, an aircraft crew could potentially have a very high workload during such an event, coupled with confusion as to what was occurring.

Returning to the issue of policy and risk, the question of economic impact is often discussed. This is a difficult question to answer, given the huge uncertainties of how severe space weather might impact the systems discussed above. *Dr Edward Oughton* (University of Cambridge) has been working on this topic for the past few years. By creating several 'what-if' scenarios for the US economy where large regions were without power for months to years, he estimated the monetary cost of lost production and consumption (Oughton et al., 2017). He has applied similar ideas to the UK, improving them by employing a more realistic estimate of where specific damage or outages to the HV power network might occur. Edward examined three different scenarios for a 1-in-100 year event depending on the preparedness level: a no-forecast scenario, present-day capability and an enhanced forecasting capability (i.e. using yet-to-be developed monitoring platforms). He applied the Oxford Economic Model to predict the effects on a large number of economic sectors and geographic regions of the UK to estimate the cost of a severe space weather event. The outcome of his ongoing work is that it is well worth paying for space weather forecasting infrastructure such as satellites and early warning systems, as the overall economic savings are much larger than the cost of investment. The meeting ended with a short discussion on future progress in this research area.

Wider impacts

The recognition of the potential impacts within the UK Risk Register has prompted new interest in this area of research. The Natural Environment Research Council has recently awarded a grant to the Space Weather Impacts of Grounded Structures (SWIGS) consortium consisting of 9 UK research centres and universities as well as over a dozen research partners around the world. This ambitious project aims to produce a detailed understanding of the risks in the UK, starting with the observation of a CME from the Sun and modelling its effects all the way to the ground in order to determine GIC flow in any transformer in the UK. Several aspects of this research programme were discussed at the RAS meeting, although the link between the solar wind, magnetosphere and ionosphere were specifically excluded from the specialist meeting to narrow the focus for the day. Nevertheless, they are a vital part of any system which aims to produce a useful forecast of activity. Other projects recently funded by NERC include the British Antarctic Survey led 'RadSat' project, for example.

With regards to current forecasting capability, there are several monitoring platforms and satellites in space (such as DSCOVR, ACE, SOHO and SDO) which sample the solar wind properties, observe the electromagnetic spectrum and monitor the Sun's surface. However, a key ingredient is missing in our ability to accurately forecast the arrival times of Earth-directed CMEs. Presently, the majority of solar wind spacecraft sit at the L1 Lagrange point around 1 million km upstream from the Earth toward the Sun (Fig 4.). A new mission has been proposed to sit at the L5 point, at a 60° angle from the Sun-Earth line, which can give a side-view of CMEs and help determine their velocity more accurately. Currently the best estimates of travel time have errors of at least 6 hours and refining this to 3 hours, or less, along with increased user confidence in the forecasts would be a large step forwards in mitigation. The NASA STEREO satellites science mission has already demonstrated the benefit in CME arrival forecasting from a side-on view of the Sun-earth line. As noted by Oughton, the costs versus benefits of such forecasting infrastructure are strongly positive.

A final point to make about this type of research is that is cross-disciplinary by nature. As such, it is often difficult to bridge the gap in knowledge, understanding and application between geophysicists and engineers. As engineers often point out, certain types of infrastructure may already have their exposure to space weather risk reduced or removed. However, a concerted effort is being made by academic researchers to engage with engineers who design and build vulnerable technologies. Around the world, the risk is being considered as genuine and appropriate measures are being considered. There remain however major uncertainties, as noted above, about the size, duration and effects a Carrington-sized event might have on advanced technology. Given our present knowledge, the impact of a large event may vary between mild inconveniences in some regions to severe economic or social impacts in others.

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Figure 1: European Space Agency (ESA) visualisation of the effects of severe space weather on technological systems. Impacts such as geomagnetically induced currents, radiation hazards to aircraft and loss of GPS signals are illustrated © ESA.

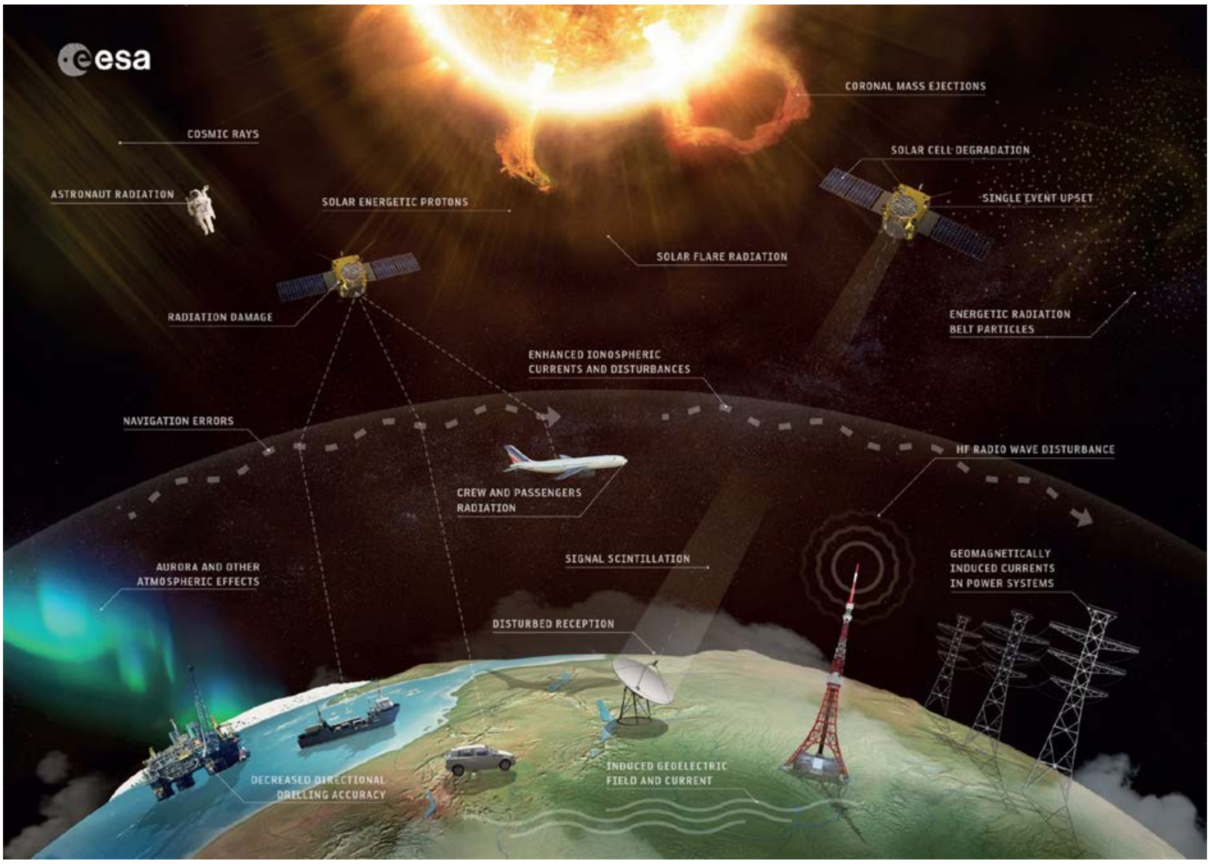


Figure 2: Declination angle at the three UK observatories during the 29-30th October 2003

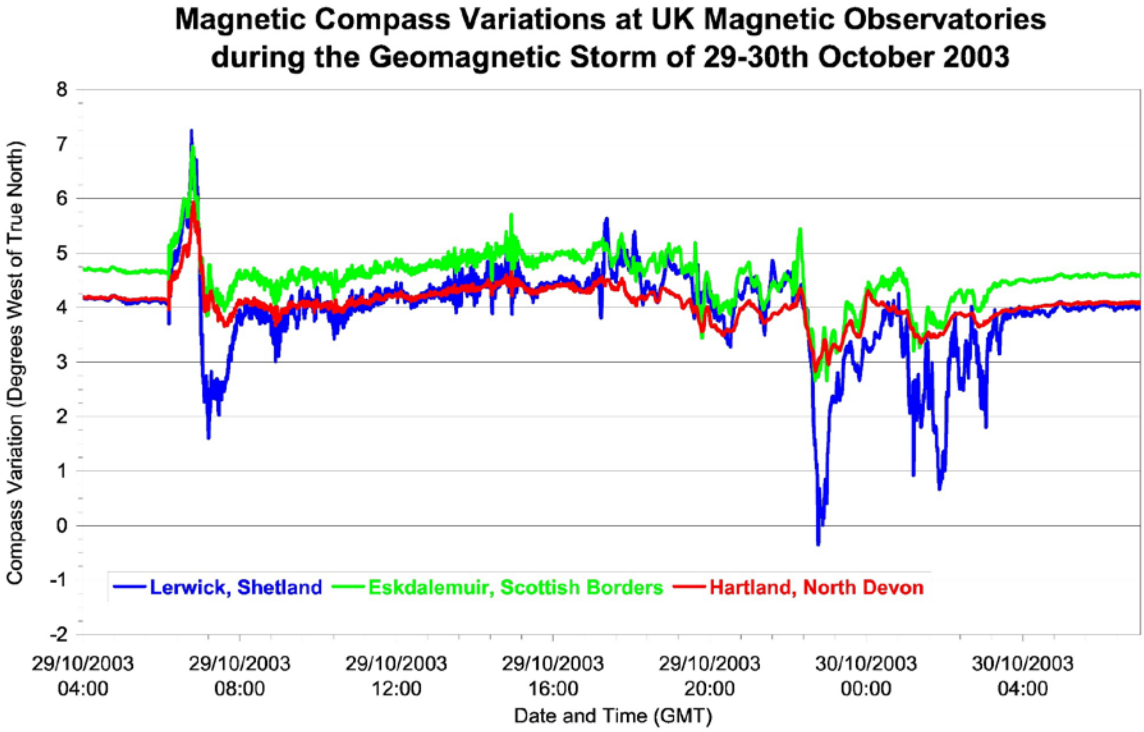
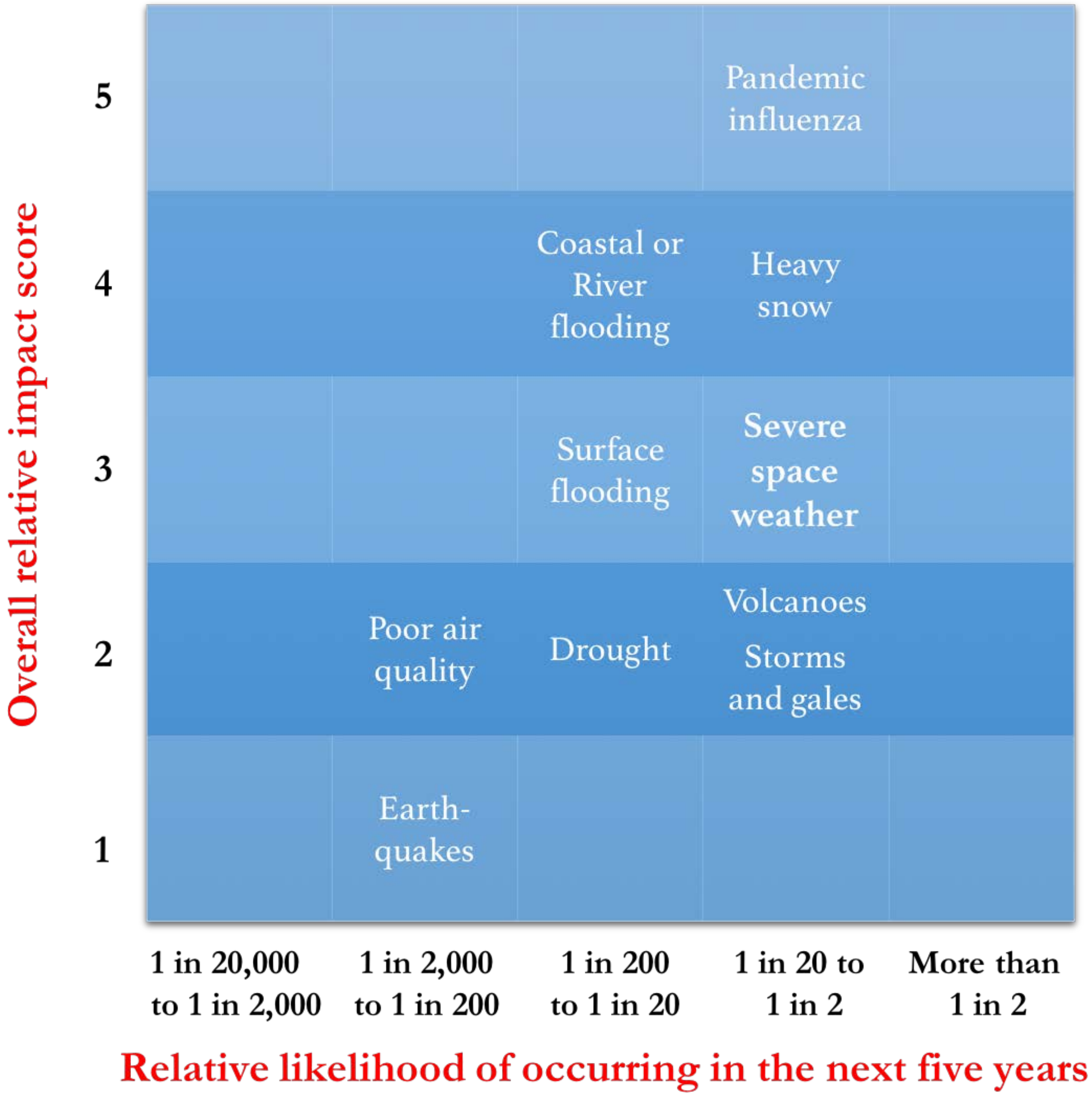


Figure 3: Relative likelihood versus impact of selected natural hazards for the UK, as adapted from the National Risk Register of Civil Emergencies, 2017 edition. Severe space weather is rated as between a 1-in-100 and 1-in-10 year occurrence probability.



Overall relative impact score	1 in 20,000 to 1 in 2,000	1 in 2,000 to 1 in 200	1 in 200 to 1 in 20	1 in 20 to 1 in 2	More than 1 in 2
5				Pandemic influenza	
4			Coastal or River flooding	Heavy snow	
3			Surface flooding	**Severe space weather**	
2		Poor air quality	Drought	Volcanoes Storms and gales	
1		Earth-quakes			

Figure 4: Location of the Lagrange points around Earth's orbit in the ecliptic plane (not to scale). Most of the present-day satellite monitoring assets orbit at the L1 point. Ideally, L4/L5 would also be occupied to provide additional three-dimensional view of the Sun-Earth line.