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Summary of space weather worst-case environments (2nd revised edition)

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Summary of space weather worst-case environments: (2nd revised edition)

Version 4.3: 19 July 2020, coordinated by Mike Hapgood (mike.hapgood@stfc.ac.uk)
on behalf of the UK Space Environment Impacts Expert Group

1 Scope of this document

1. Space weather may be described as **disturbances of the upper atmosphere and near-Earth space that disrupt a wide range of technological systems** – and, in a few cases, pose a direct threat to human health.

2. **The systems at risk are very diverse** and include power grids, GNSS, many aspects of spacecraft and aircraft operations, many types of radio communications and control systems.

3. **This note lists a number of these different systems** and outlines what we currently know of:
    - The space weather environment parameters that best summarise the threat to those systems;
    - A reasonable worst case for those parameters, together the quality of the knowledge underpinning that estimate of the worst case and the formal provenance of that knowledge, e.g. in the peer reviewed literature;
    - What can be done to improve the quality of that knowledge;
    - Other useful information.

   This information is presented in a series of tables – with each table focusing on a specific class of space weather threat to each particular system.

2 Context

1. The ultimate source of space weather is the Sun (see Appendix 1) and intervals of enhanced space weather risk are to some extent predictable, based on solar and geophysical observations. The **longest interval of severe space weather is likely to be of the order of two weeks,** based on the time it would take for a large region of activity on the Sun's surface to rotate across the Sun-Earth line [see, for example, the extreme event scenarios used in the impact studies by Eastwood et al (2018) and Oughton et al. (2018)].

2. During an interval of enhanced space weather risk, several different types of space weather can occur (see Appendix 1). The physical nature of space weather is extremely complex compared to terrestrial weather. This means that **during an interval of enhanced space weather risk, it is extremely difficult to predict the order, size, and duration of individual space weather phenomena.**

3. Therefore, different systems could experience adverse impacts (a) simultaneously, (b) sequentially, or (c) unpredictably (i.e., effectively randomly). Furthermore, **it is highly likely that these system failures will interact with each other** to cause cascading failure modes that are **fundamentally difficult to predict**.

3 Caveats

1. **This is a revision of the summary published in May 2016 (http://tinyurl.com/ydy8lu5p).** The changes reflect advances in understanding space weather impacts, e.g. the growing focus on the geoelectric field as a critical parameter in assessing space weather impacts on power grids; the growing range of studies of the GIC risk to power grids in UK and similar regions (Ireland, Scandinavia, Canada and New Zealand); the recognition that high-energy electrons can damage electronic systems on satellites, including solar arrays; the substantial progress in quantifying the likelihood of intense radiation and charging events in space, and of radiation events in the atmosphere, the solar radio burst in November 2015 that reminded us how these bursts can sometimes disrupt radar systems.
2. While this document provides separate descriptions of different space weather risks, it must be remembered that **many of these different risks will present themselves close together in time** – because they have a common origin in phenomena on the Sun. The associations between the different risks are illustrated in the figure at the end of this document.
3. This document focuses on the environmental aspects of space weather and **does not discuss measures that can be taken to provide resilience against space weather**, e.g. combined use of complementary technologies with different responses to space weather.

4 Contributors

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5 Contents

6 Description of target risk impact tables

Each table is formatted as follow:

Target risk: NAMED RISK	
Environmental risk parameters:	A description of the way in which the environmental risk is quantified by either forecasters or system users.
Rationale:	An explanation of why the risk parameters are used in terms of the physical impact on the system.
Suggested worst case:	The most severe manifestation of the risk that can reasonably be projected to occur, based on peer-reviewed literature where possible. In line with wider risk planning, we have a strong focus on 1-in-100 years manifestations of the risk, but consider manifestations at longer timescales (e.g. 1-in-1000 years) where there is good evidence of severe impacts. (Note that the UK National Risk Assessment considers risks that manifest above a likelihood of 1-in-100000 years.)
Worst case duration	The most severe duration that can reasonably be projected to occur, based on peer-reviewed literature where possible.
Worst case spatial extent	The geographic spread of the impact based on peer-reviewed literature where possible.
Anticipated effects	The likely impact on the system of the suggested worst-case risk, folding in the worst-case duration and spatial extent. It should be noted that the duration of the impact can be significantly longer than the duration of the space weather event.
Quality of case:	Evaluation of the quantity and depth of the peer reviewed literature and reports from professional/expert bodies that constitute the basis for the evaluation.
Provenance:	Key literature included in the reference list here that can be referred to for more detailed information.
How to improve case quality:	Expert group analysis describing where the impact case requires solidification or in many cases where the current state of the art lies. It should be recognised that space weather is a relatively new and evolving threat, because of scientific development, engineering development, and changes to the systems at risk that can make them both more and less exposed.
Other notes:	Other relevant information not covered elsewhere

7 Impact Tables

7.1 Power grid

Target risk: Power grid	
Environmental risk parameter:	Traditionally assessed (due to broad time-span of geomagnetic records available) via time rate of change of magnetic field (d*B*/d*t*), specified in nano-Tesla per minute). However, risk assessment can also focus on the geoelectric field, *E*, as the primary geophysical risk parameter. In the UK, E-fields are particularly spatially complex, due to the underlying geology and surrounding seas, and this contrasts with some continental-scale nations. In the UK both d*B*/d*t* and E-fields are relevant.
Rationale:	Risk at transformer level is ultimately determined by the size of geomagnetically induced currents (GIC) flowing into and out of the grid, via transformer neutral connections, GIC depends closely on *E*, which, in turn, is induced by d*B*/d*t* in the conducting Earth. d*B*/d*t* is therefore a key source of GICs and directly drives *E*. But *E* also partly depends on (local/regional) ground conductivity and GIC also partly depends on grid electrical resistances and connectivity (e.g. Watermann, 2007, Cagniard, 1953)
Suggested worst case:	For d*B*/d*t*, 5000 nT/min (one single event) is broadly consistent with the >95% upper confidence level in the Thomson et al (2011) 1-in-100 year scenario (the background level of the UK magnetic field is around 55,000 nT, for reference). Modelling work suggests a local peak geoelectric *E* field >20 V/km is typical of extreme event scenarios (e.g. 1 in 100 years or greater) in the UK (Beggan et al, 2013).
Worst case duration	Single event, or ‘spike’, of 1-2 minutes duration. Lesser spikes in geoelectric field and d*B*/d*t* (1-2 minutes each) will be observed throughout the extreme event duration (hours to days). Historical occurrences of d*B*/d*t* >500nT/min have been associated with enhanced risk to the UK grid (e.g. Erinmez et al, 2002)
Worst case spatial extent	Growing evidence that intense GIC events have spatial scales of a few hundred km at most (Ngwira et al., 2015; Pulkkinen et al., 2015). Thus a single event would cover much of the UK.

Target risk: Power grid	
Anticipated effects	• Tripping of safety systems potentially leading to regional outages or cascade failure of grid • Transmission system voltage instability and voltage sag • Possible premature ageing of transformers leading to decreased capacity in months/years following event (Gaunt, 2014). • Damage, e.g. insulation burning, to a number of transformers, through transformer magnetic flux leakage. *(NB replacement of a transformer can take 1 to 2 months if a spare is available elsewhere in the UK; and much longer if procurement of a new transformer is required. National Grid now hold an increased number of spares to account for this risk.)*
Quality of case:	Kappenman (2006) paper: Based on single measurement of earth currents on railway circuit in central Sweden during May 1921. Calibrated by linear extrapolation from similar but smaller earth currents observed in Sweden during 2500 nT/min event in 1982. Thomson et al (2011) paper: Published extreme event value statistical analysis of 1982-2010 digital magnetometer data from northern Europe. Similar results obtained in extreme event value analyses for Canada (Nikitina et al., 2016) and northern Europe (Wintoft et al., 2016), and a recent more detailed analysis for the UK (Rogers et al., 2020)
Provenance:	Peer-reviewed papers by Kappenman (2006) and Thomson et al. (2011). See also papers by Beggan et al (2013) and Kelly et al (2017) for UK hazard in terms of GIC and electric fields.

Target risk: Power grid	
How to improve case quality:	NERC has funded a consortium project, Space Weather Impacts on Ground-based Systems (SWIGS), from 2017 to 2021, to advance our understanding of this space weather impact, e.g.: • Further analysis of UK geomagnetic observatory data running from 1850s to 1982 (digitised paper records) and 1983-2012 (measured digital data) to determine spatial structure and correlations during extreme events. • Better characterisation of UK ground conductivity to enable improved modelling of geoelectric fields • Better understanding of the spatial and temporal scales of dB/dt arising from sub-storms • Assessment of industry transformer dissolved gas analysis data will improve understanding of how space weather ages transformers • Industry GIC measurements and their correlation with changes in the geomagnetic data would stimulate development and validation of models of the hazard. • Characterisation of the spectrum of dB/dt and geoelectric field E during extreme storms, e.g. to determine magnitudes and numbers of peak and any lesser spikes In addition, the NERC-funded SWIMMR Activities in Ground Effects (SAGE), running from 2020 to 2023, will develop models that can help to identify risks points in the power grid and other systems affected by GIC. Also consider the Applications Usability Levels approach (Halford et al., 2019; Cid et al., 2020).

Target risk: Power grid	
Other notes:	• The largest recorded disturbance of the last 40 years was around 2700 nT/min, measured in southern Sweden in 1982. The largest UK disturbance was 1100 nT/min at Eskdalemuir in March 1989. • Key impacts of 1989 storm on UK national grid were reported by Smith (1990) with more detail now reported by Boteler (2019). • Modelled GIC and surface electric fields suggest a per substation GIC of 10s to 100s of amps and local peak electric fields of ~25 V/km for Carrington scale events (c. 1 in 200 years) is possible (e.g. Pulkkinen et al, 2015; Ngwira et al, 2013; Beggan et al, 2013; Kelly et al., 2017) • Initial studies of GIC in the Irish power grid (which serves both Northern Ireland and the Irish Republic) have been published by Blake et al. (2017 and 2018). • The recent and extensive studies on the New Zealand grid (Rodger et al., 2017 and 2020; Divett et al., 2017; Mac Manus et al., 2017; Clilverd et al., 2018) may provide valuable insights for the UK grid, as it is an island nation with similar magnetic latitude. • For context, the Dst index (an equatorial measure of the magnetospheric ring current) reached -589 nT in March 1989. The Dst of the Carrington event was estimated as -1760 nT (Tsurutani et al, 2003), but more recent work (Siscoe et al., 2006; Cliver and Dietrich, 2013) suggests a value between -850 and -1050 nT, with a recurrence likelihood of 3-12% per decade (e.g. Riley, 2012; Love, 2012; Riley and Love, 2017).

7.2 Satellite operations – electronic component ageing and solar array degradation (cumulative radiation effects)

Target risk: Satellite operations –cumulative radiation effects	
Environmental risk parameter:	Cumulative damage (ageing) is due to the deposition of energy or 'dose' into materials due to both the electron and proton environments. While this dose accumulates over the whole satellite lifetime, an extreme event would cause a more sudden ageing effect which could be significant. Thus solar proton fluence and energy spectrum, as well as radiation belt energetic electron and proton fluences and energy spectra are the key parameters. Lower energy protons (1 to 10 MeV) and medium energy electrons (0.1 to 1MeV) are the most relevant for solar array damage, while higher energies of both species penetrate to internal electronic components. For electrons, the relevant population is essentially the same as that which causes internal charging (see section 4). The ionising element of dose is usually measured in rads (1rad = 0.01Gy). The non-ionising dose element (also called displacement damage) is measured by the equivalent damage fluence of 10 MeV protons or 1 MeV electrons, or by the Non-Ionising Energy Loss (NIEL) in MeV/g or J/kg. Electrons and protons contribute to both elements of the dose.
Rationale:	Modern digital metal-oxide semiconductor (MOS) electronic technology is mainly damaged by ionising dose. Bipolar (primarily analog) electronic devices can be strongly affected by non-ionising dose (displacement damage): included in this category is loss of solar cell efficiency. However many bipolar devices can also be damaged by ionising dose. Depending on the orbit, energetic electrons can be more important than protons for solar array damage (Hands et al., 2018).

Target risk: Satellite operations –cumulative radiation effects	
Suggested worst case:	Protons, >1 MeV (for solar array damage): 1.3 x10^{11} cm$^{-2;}$ Protons, >30 MeV (for ageing of internal components): 1.3 x 10^{10} cm^{-2} both from Xapsos et al., 1999 & Xapsos et al., 2000 Electrons: as for internal charging with fluence integrated over 1 week; i.e. 4.4x10^{11} cm^{-2}sr^{-1}for 1-in-100, 1x10^{12} cm^{-2}sr^{-1} for 1-in-150 year event based on GOES-West. Would be factor 1.11 worse at worst GEO longitude of 160°W according to the AE8 model (Vette, 1991) and 1.04 according to the AE9 model (Ginet et al., 2013). See the extensive discussion below showing how the worst case varies with type of orbit (GEO, MEO and LEO) and location around that orbit in the case of GEO. (N.B. see the glossary for an explanation of orbit acronyms.)
Worst case duration	Protons: Single event lasting 2 days or series of events lasting 1 week. Electrons: one week enhancement (see discussion under internal charging) For worst case a severe electron enhancement would probably follow after the severe proton event so both events need consideration together: the electron enhancement maybe the more damaging (Ryden et al., 2008; Hands et al., 2018).
Worst case spatial extent	Most satellite orbits are exposed; the magnetosphere will provide shielding from solar energetic particles for some orbits, especially equatorial LEO. Electrons dominate this impact for MEO satellites, and have an impact comparable with solar protons for GEO satellites.
Anticipated effects	Premature ageing (potentially by some years) of spacecraft electronic components, including solar arrays, leading to decreased capacity following the event and/or reduced lifetime. See Hands et al (2018) for examples.

Target risk: Satellite operations –cumulative radiation effects	
Quality of case:	We refer to ECSS-E-ST-10-04C for our current worst case event which is based on extrapolating existing models. Note that recent work by Cliver and Dietrich (2013) estimates that the Carrington event was most likely a factor 2 more intense than any event of the space age but with considerable uncertainty around this value. The 1-sigma uncertainty range spans been a factor 20 higher than any space age event, and a factor 5 lower than any such event. Hence it is still very reasonable to consider a worst case event 2.4 times higher than any space age event as an estimate for 1 in 100 year event and 4 times worse for 1 in 150 years.
Provenance:	ECSS-E-ST-10-04C standard. Also papers by Xapsos et al. (1999), Xapsos et al. (2000) and Cliver and Dietrich (2013).
How to improve case quality:	• Continue to monitor work on proxy data such as ^{14}C and ^{10}Be studies (Miyake et al, 2012; Mekhaldi et al., 2015), especially efforts to derive energy spectra and to improve time resolution of historical events, such as 774AD. The subject has recently been reviewed in Miyake, Usoskin, Poluianov et al. (2020). • In addition, the NERC-funded Satellite Radiation Risk Forecasts (Sat-Risk), part of the SWIMMR programme running from 2020 to 2023, will develop a real-time system to forecast radiation exposure to satellites for a range of different orbits, and help quantify the risk of damage or degradation.
Other notes:	Damage depends on energy spectrum. Internal components suffer more from hard spectra. For solar cells, damage is more severe for soft spectra. Further investigation of models is needed, e.g. SAPPHIRE (Jiggens et al, 2018).

7.3 Satellite operations – Single Event Effects/control

Target risk: Satellite operations – SEE/control	
Environmental risk parameter:	Solar energetic proton flux and fluence (> 30 MeV). Heavy ions also contribute to SEEs and can double the rates calculated from protons alone (Dyer et al., 2005). In addition, heavier ions can give hard failures not produced by protons.
Rationale:	The rate at which SEEs occur is related to this flux but depends on the hardness of the spectrum and the amount of shielding. Thus the frequency of service interruptions, and the size of operator workload, in any period, will also rise and fall with this flux. The fluence over a day is useful guide to total number of problems to be expected.
Suggested worst case:	Peak proton flux, >30 MeV: 3.8 x 10^5 $cm^{-2}s^{-1}$, 1-day proton fluence, >30 MeV: 6.8 x 10^9 cm^{-2} , 1-week proton fluence, > 30 MeV: $1.6x10^{10}$ cm^{-2} all with energy spectrum as in October 1989 or August 1972. Based on values from Creme96 (Dyer et al., 2004) and multiplied by four to estimate the 1-in-150 year event. For 1-in-100 year event the estimate is 2.4 times the Creme96 values giving Peak proton flux, >30 MeV: $2.3x10^5$ $cm^{-2}s^{-1}$, 1-day proton fluence, >30 MeV: $4.1x10^9$ cm^{-2} , 1-week proton fluence, > 30 MeV: $1.0x10^{10}$ cm^{-2} Cliver and Dietrich (2013) estimate a fluence between 10^9 and 10^{11} cm^{-2} >30 MeV for the 1-in-150 year Carrington event, with a best estimate of $1.1x10^{10}$ cm^{-2}. For now rates can be doubled to allow for ions.
Worst case duration	1-2 days for each event, but there could be several lasting a week as in October 1989 and October 2003.
Worst case spatial extent	Most satellite orbits are exposed: the magnetosphere will provide shielding for some orbits, especially equatorial LEO. We do not consider the South Atlantic Anomaly here as that is a slowly varying feature that will cause SEEs when satellites cross that region, irrespective of solar events.
Anticipated effects	High anomaly rates on spacecraft: • High workload by spacecraft operators to restore nominal spacecraft behaviour • Temporary reduction in capacity of spacecraft services • Some potential for permanent loss of sub-systems and of whole spacecraft.

Target risk: Satellite operations – SEE/control	
Quality of case:	Based on extrapolation from space age measurements. This may be supplemented in future by use of cosmogenic isotopes to estimate historical SEP events; this is an area of ongoing research.
Provenance:	Dyer et al., 2005; Cliver and Dietrich (2013).
How to improve case quality:	Improved understanding SEP events as discussed above and inclusion of worst case fluences from ions and their Linear Energy Transfer (LET) spectra. Dyer et al (2005) shows that Creme96 is a reasonable worst-case LET spectrum for the space age, but 1-in-150 year event might well be factor 4 worse as with the proton estimates.
Other notes:	Depends on energy spectrum of the particles. Probably most severe for intermediate hardness. Suggest use October 1989 or August 1972 to enable scaling from existing space standards- maybe by factor 4 for 1 in 150 years. Also need to assume worst case composition for heavy ions.

7.4 Satellite operations – internal charging

Target risk: Satellite operations – internal charging	
Environmental risk parameter:	Energetic electron flux (~0.5 to 10 MeV) It is important to consider the electron spectrum. The electron flux >2 MeV is often used as the measure of risk. The minimum energy depends on the level of shielding around sensitive components. Significant flux >6 MeV has been observed by Van Allen Probes.
Rationale:	These very energetic electrons penetrate deep inside spacecraft. Thus electrical charge can accumulate in dielectric (electrically insulating) materials. If this accumulation becomes too large, the dielectric will breakdown resulting in an electrical discharge. This can (a) damage nearby spacecraft systems, and (b) generate false signals that cause the spacecraft to misbehave. The latter will drive up operator workload.
Suggested worst case:	This depends on electron energies and orbit location as follows (see the spatial extent section for how to adjust to other longitudes). **Geosynchronous orbit**: • 1 in 100 year daily average flux of E > 2 MeV electrons at GOES West is 7.7x10^5 cm^{-2}s^{-1}sr^{-1} [*Meredith et al*., 2015]. • 1 in 100 year flux of electrons in the energy range 0.69-2.05 MeV at L* = 6.0 in the near equatorial region (-15^o < magnetic latitude < 15^o), representative of geosynchronous orbit ranges from 4.7x10^6 cm^{-2}s^{-1}sr^{-1}MeV^{-1} at 0.69 MeV to 1.6x10^5 cm^{-2}s^{-1}sr^{-1}MeV^{-1} at 2.05 MeV. A spectrum of worst cases is available at 10 energies in the range 0.69-2.05 MeV. [*Meredith et al*., 2017]. **Medium Earth orbit (e.g. for GPS and Galileo)**: • 1 in 100 year flux of electrons in the energy range 0.69-2.05 MeV at L* = 4.5 in the near equatorial region (-15^o < magnetic latitude < 15^o), representative of the peak fluxes encountered in GNSS type orbits, ranges from 1.5x10^{7}cm^{-2}s^{-1}sr^{-1}MeV^{-1} at 0.69 MeV to 5.8x10^5 cm^{-2}s^{-1}sr^{-1}MeV^{-1} at 2.05 MeV [*Meredith et al*., 2017]. • 1 in 100 year daily average internal charging current, averaged along the orbit path, behind 1.5 mm of aluminium is 1.3 x 10^{-13} A cm^{-2} [*Meredith et al*., 2016a] which exceeds the NASA guidelines of 1 x 10^{-13}A cm^{-2} over a 10 hour period [*NASA*, 2011] **Low Earth orbit: 800 km altitude.**

Target risk: Satellite operations – internal charging	
	• 1 in 100 year flux of E >300 keV electrons shows a general decreasing trend with L*, ranging from ~10^7 $cm^{-2}s^{-1}sr^{-1}$ at L* = $3x10^5$ $cm^{-2}s^{-1}sr^{-1}$ at L* = 8.0 [*Meredith et al.,* 2016b]. *NB. L* is the invariant coordinate developed by Roederer for radiation belt studies (Roederer, 1970; Roederer and Lejosne, 2018).*
Worst case duration	2-5 days
Worst case spatial extent	Peak fluxes vary with longitude around the geostationary ring, because magnetic latitude also varies around the ring. Worst case GOES *E* > 2 MeV flux above is for the GOES West location (135°W). The 1 in 100 year *E* > 2 MeV flux at the GOES East location (75° W) is a factor of 2.4 less than that at GOES West (Meredith et al., 2015). Using the AE8 average model, the UK longitude at 0°E has only slightly lower flux (by about 10%) than that at 20°E which is the local maximum in the European region. Note however that fluxes higher than those at 20°E occur at longitudes from approximately 170°E to 230°E (130°W). Using AE9 gives different factors.
Anticipated effects	High anomaly rates on spacecraft: • High workload by spacecraft operators to restore nominal spacecraft behaviour • Temporary reduction in capacity of spacecraft services Some permanent damage from electrostatic discharges is also possible
Quality of case:	Recent peer reviewed papers by Meredith et al, 2015, 2016a, 2016b and 2017 gives robust extremes. These fluxes are consistent with earlier theoretical estimates [Shprits, 2011; O'Brien et al, 2007].
Provenance:	Peer reviewed papers by Meredith et al (2015, 2016a, 2016b, 2017), O'Brien et al., (2007) and Shprits et al., 2011)

Target risk: Satellite operations – internal charging	
How to improve case quality:	NERC has funded a consortium project, Rad-Sat, from 2017 to 2021, to advance our understanding of this space weather impact, e.g. • To investigate the role of magnetosonic waves, hiss, transmitters and lightning generated whistlers on the global dynamics of the radiation belts and develop state-of-the-art modelling and forecasting for space weather events • To determine how wave-particle interactions depend on the time history of the solar wind driver so as to significantly improve forecasting models • To investigate radiation belt dynamics during shock-driven severe space weather events and provide a new forecasting capability In addition, the NERC-funded Satellite Radiation Risk Forecasts (Sat-Risk), part of the SWIMMR programme running from 2020 to 2023, will develop a real-time system to forecast radiation exposure to satellites for a range of different orbits, and help quantify the risk of damage or degradation.
Other notes:	Radiation-induced conductivity can help to mitigate internal charging by increasing the rate at which charge leaks out of dielectric materials in satellites (Ryden and Hands, 2017)

7.5 Satellite operations – surface charging

Target risk: Satellite operations – surface charging	
Environmental risk parameter:	Electron flux (1 to 100 keV) It is important to consider the electron spectrum. The worst-case spectrum from SCATHA was mostly enhanced above the average between 20 - 100 keV.
Rationale:	The surfaces of objects in space always acquire some electrical charge. In strong sunlight, this is usually dominated by photoemission from the object, which stabilises the electrical potential at a few volts positive. But in regions of space containing hot plasmas, especially outside sunlight, the surface can go to a negative potential of several thousand volts. If this potential becomes too large it may trigger an electrical discharge. This can (a) damage systems on the spacecraft surface (e.g. solar arrays), and (b) generate false signals that cause the spacecraft to misbehave. The latter will drive up operator workload. Surface charging often occurs: • As a satellite passes out of eclipse into sunlight, due to change in currents to & from the spacecraft • During substorms which inject typically 1 – 100 keV electrons across geosynchronous and medium Earth orbit, usually between midnight and dawn (O'Brien, 2009). • During intense aurora caused by 1-10 keV electrons which affect satellites in polar low Earth orbits crossing the auroral regions Surface charging is determined by the flux of electrons in the hot plasma in these regions.
Suggested worst case:	Typically a peak electron flux of 10^7 cm^{-2} sr^{-1} s^{-1} keV^{-1} at 30 keV and 3 x 10^6 cm^{-2} sr^{-1} s^{-1} keV^{-1} at 100 keV where the SCATHA worst case flux exceeds the average most (Fennel et al., 2001) and also Mateo-Velez et al. (2018).
Worst case duration	Substorms causing plasma injections may last several mins after which the peak flux will decay. However, during active periods multiple substorms occur with an interval of one to a few hours between each substorm. Prolonged periods of multiple substorms can last for 10 days or more during high speed solar wind streams.
Worst case spatial extent	Needs further study
Anticipated effects	Permanent damage to spacecraft systems, particularly solar arrays. High anomaly rates on spacecraft: • High workload by spacecraft operators to restore nominal spacecraft behaviour • Temporary reduction in capacity of spacecraft services

Target risk: Satellite operations – surface charging	
Quality of case:	Surveys of publicly available measurements.
Provenance:	Analysis of GEO data (Fennel et al., 2001; Mateo-Velez et al., 2018)
How to improve case quality:	Further survey of available datasets & the published literature, especially new papers that address the issue.
Other notes:	

7.6 Satellites – Thermospheric Drag

Target risk: Satellites – Thermospheric Drag	
Environmental risk parameter:	Change in thermospheric neutral density at LEO satellite orbit altitude
Rationale:	Density changes affect satellite orbital determination, since they lead to changes in the drag on the satellite
Suggested worst case:	Observed relative density enhancements of up to 750%. Model simulation suggests density enhancements of over 1400% for a 1 in 100 year extreme event, but this result has a high uncertainty (estimated to be 100%).Absolute density changes of up to at least 4 x 10^{-12} kg m^{-3} (at 490 km altitude), as observed during the October 2003 storms.
Worst case duration	Large changes described above take place within 1 day.
Worst case spatial extent	Effects likely all over the world. Further study needed to assess regional responses. Oliveira et al. (2017) show how thermospheric response to geomagnetic activity can take several hours to spread from high to low latitudes.
Anticipated effects	• Satellite loses altitude, or satellite raising manoeuvres need to be carried out to counteract this. Examples: ▪ NOAA SWPC estimated the ISS would drop by 200 m in a day during the October 2003 Halloween storm, but by 45 m in a day on a non-stormy day during the same month. ▪ CHAMP (GRACE) drops in satellite altitude by 90-120 m (40-50 m) (Krauss et al, 2018) during extreme CMEs • Such altitude changes impact satellite orbital tracking. For example, during the very large geomagnetic storm of 13-14 March 1989, tracking of thousands of space objects was lost and it took North American Defense Command many days to reacquire them in their new, lower, faster orbits. • The drops in orbital altitude can also lead to premature re-entry for satellites already close to end of life (e.g. the Student Nitric Oxide Explorer during the 2003 Halloween Storm). • Issues with orbital determination – in extremis satellites have crashed into each other • Tracking of space debris is made significantly more problematic
Quality of case:	Observed worst case based on 2003 to 2015 period. Model simulation on 1 in 100 year event contains uncertainties but is usable as a guide. Extending model simulations to theoretical worst case is not yet possible without further research.

Target risk: Satellites – Thermospheric Drag	
Provenance:	Krauss et al. (2015, 2018) – density fluctuations observed by CHAMP and GRACE during geomagnetic storms from 2003-2015; Sutton et al (2005) - density fluctuations observed by CHAMP in October 2003 geomagnetic storms. Reeves et al. (2019),- thermospheric response to increase in EUV over a period of at least 1 day Le et al. (2016) – thermospheric response to theoretical strongest solar flares. Oliveira et al. (2017) – shows how thermospheric response spreads from high to low latitudes following geomagnetic activity
How to improve case quality:	▪ Further exploitation of satellite accelerometer data, including assimilation of such data into models. ▪ A general improved understanding of the interactions between extreme forcing and the thermosphere, so that key parts of models are based on physical understanding rather than being based on observations (which cannot represent the most extreme events). A particular focus on improving knowledge of saturation of magnetospheric forcing on the thermosphere and ionosphere is needed. The NERC-funded Space Weather Instrumentation, Measurement, Modelling and Risk: Thermosphere (SWIMMR-T) project running from 2020 to 2023, will use novel mathematical techniques to assimilate a broad range of measurement data into a fully coupled (neutral and ionized) model of the lower and upper atmosphere.
Other notes:	Enhancement of EUV on timescales of greater than 1 day and associated with strong solar active regions can lead to neutral density increases, for a theoretical worst case, of 105% at 250 km and 165% at 400 km (Reeves et al., 2019). Transient density increases above quiet conditions due to an assumed theoretical maximum solar flare can be as high as 20% at 200 km, 100% at 400 km and 200% at 600km (Le et al., 2016). Integrated effect of many such small storms, or flares, on satellite orbit may also need to be examined. Impact of anticipated effects is likely to increase in future due to increasing space debris and proposed constellations of hundreds of nanosatellites. We need to better understand implications for satellite survey and tracking.

7.7 Terrestrial Electronics

Target risk: Terrestrial Electronics	
Environmental risk parameter:	Cosmic ray neutron flux (>10 MeV) at Earth's surface
Rationale:	Secondary neutrons are dominant source of single event effects below 60000 feet and are produced when energetic protons and ions from space interact with nitrogen and oxygen nuclei in the atmosphere. The flux > 10 MeV is used in the standards but allowance must be made for lower energy neutrons, especially thermal. Note that energetic protons can contribute significantly while for new technologies stopping protons and muons are increasingly significant.
Suggested worst case:	For a 1-in-150 year event, 200-fold increase in surface radiation environment for latitudes such as London, UK. For a 1-in-100 year event the estimated increase is a factor 120. This is based on a recent assessment of extreme events by Dyer et al. (2017). Using both the ground level radiation monitor records and proxies such as ^{14}C and ^{10}Be, this assessment suggests to use a 1-in-150 year worst case that is 4 times more intense than the largest event observed with instruments (a 50-fold increase measured at Leeds on 23 Feb 1956). For 1-in-150 year event, sea level neutron fluxes > 10 MeV are: • 2.1×10^3 cm^{-2}hr^{-1} at London • 1.1×10^4 cm^{-2}hr^{-1} for North of Scotland For 1-in-100 year event these fluxes become: • 1.3×10^3 cm^{-2}hr^{-1} at London • 6.6×10^3 cm^{-2}hr^{-1} for North of Scotland For higher latitudes there is essentially no geomagnetic shielding. This assessment also suggests the 1-in-1000 year worst case would be a 1000-fold increase in the surface radiation environment at London and 5000-fold for the North of Scotland. For more detail see the tables in Dyer et al. (2017)
Worst case duration	Timescales of events range from 1 to 12 hours but note that for impulsive events such as Feb56, nearly all the fluence (77%) arrives in the first hour and fluxes during the first few minutes are a factor 3 higher.,

Target risk: Terrestrial Electronics	
Worst case spatial extent	Considerable variations across the world due to radiation from the Sun being directed by the interplanetary magnetic field, and the shielding effects of Earth's magnetosphere. The former can lead to variations with longitude, whilst the latter can lead to greater fluxes at high latitudes – but with marked differences between the northern and southern poles. If a ground level enhancement occurs during an extreme geomagnetic disturbance, such as that during the Carrington event, low latitudes could be severely exposed.
Anticipated effects	Greatly enhanced error rates in unprotected digital electronic systems, also potential for damage to such devices and burnout in high voltage devices (see Box 2 in Cannon et al. (2013),also discussion in Dyer et al. (2017) and Dyer et al. (2020)).
Quality of case:	This is based on observations of the ground level enhancement (GLE) radiation event of 23 Feb 1956 and comparison with other GLEs in the instrumental and proxy records, as consolidated by Dyer et al., 2017.
Provenance:	Marsden et al (1956), Quenby and Webber (1959), Rishbeth, Shea and Smart(2009), Tylka and Dietrich (2009), Mekhaldi et al. (2015), Dyer et al. (2017).
How to improve case quality:	Further work on cosmogenic nuclides and co-ordinated observations of future GLEs across a wide range of locations and altitudes.
Other notes:	Feb 56 is hardest event observed (since observations commenced in 1942). The Carrington event itself does not appear to have been a hard event as it is not seen in the cosmogenic nuclide records. However, the analysis by Dyer et al. shows that events of 4xFeb56 occur approximately every 150 years on average. Evidence from AD774 event suggests that this event was very hard. Effects are probably worst for short events that give high rates. Event durations are typically 1-12 hrs. Dyer et al. (2017) propose adoption of a new space weather scale for atmospheric radiation with February 1956 fluxes as the baseline for the scale and with scaling measurements obtained from ground-based neutron monitors. The low energy neutron spectra at ground level are greatly influenced by local conditions such as soil moisture and precipitation. This can be important if components are sensitive to low energy neutrons (< 10 MeV) and/or to thermal neutrons.

7.8 Radio technologies

Target Risk: Radio technologies	
Environmental risk parameter:	Solar radio flux
Rationale:	The Sun can produce strong bursts of radio noise over a wide range of frequencies from 10 MHz to 10 GHz. These bursts may interfere with radio systems operating at these frequencies if the solar signal is stronger than the operational signal. This will arise, in particular, where it is necessary to detect relatively weak radio signals, e.g. GNSS receivers; radars; base station reception of signals from mobile phones; VHF, UHF and L-band satellite communications. For avoidance of doubt, we note that the Sun can produce strong radio bursts at frequencies below 10 MHz, but these are blocked by the ionosphere. Thus, they do not interfere with ground- and aircraft-based radio systems working at lower frequencies.
Suggested worst case:	2 x 10^{-16} W m^{-2} Hz^{-1} (2 million SFU) over a broad range of frequencies.
Worst case duration	1 hour
Worst case spatial extent	Whole dayside of the Earth.
Anticipated effects	Interference can disrupt operation of vulnerable radio systems, with the form of the disruption dependent on the system design and configuration. This is a natural jamming process.
Quality of case:	Statistical studies show that radio bursts up to 10^{-17} W m^{-2} Hz^{-1} are fairly common. A burst of 10^{-16} W m^{-2} Hz^{-1} was recorded in Dec 2006 and disrupted GNSS systems across the sunward side of the Earth (Cerruti et al., 2007). In November 2015, a burst in excess of 10^{-17} W m^{-2} Hz^{-1} disrupted aircraft control radars in Belgium, Estonia and Sweden (Marqué et al., 2018).
Provenance:	Statistics in peer-reviewed paper by Nita et al. (2004). Impact analyses by Cerruti et al. (2007) and Marqué et al. (2018).
How to improve case quality:	Conduct extreme value analysis to determine reasonable worse case and assess in light of wireless system operating parameters.

Target Risk: Radio technologies	
Other notes:	The potential for radar disruption by solar radio bursts has been known since 1942 (Hey, 1946). So, this disruption is generally well-mitigated by good design and operational procedures. However, the November 2015 event cited above shows a need to maintain awareness. For mobile cellular systems, SRBs with energy flux 10^{-17} W m^{-2} Hz^{-1} should just be detectable by mobiles, but the event of 10^{-16} W m^{-2} Hz^{-1} should have been widely detected. For base stations, the effect will be greatest at sunrise/sunset when the Sun lies in the base station antenna beams. There are no reports of impacts on mobiles from the large radio burst in Dec 2006. However, the terminator (sunset/sunrise line) on the Earth's surface did not cross any significant inhabited areas, so the potential for interference with base stations was not tested. The impact on satellite communications will be most significant for geostationary satellites around equinox, when the satellites lie close to the direction of the Sun (at certain times of day), and for mobile satellite systems with large beamwidths and low signal-to-noise ratios [Franke, 1996].

7.9 GNSS – Total Electron Content (TEC) correction

Target risk: GNSS – Total Electron Content (TEC) correction	
Environmental risk parameter:	TEC and related gradients
Rationale:	The ionospheric range correction on GNSS position and time estimates is directly proportional to TEC, e.g. an uncorrected TEC value of 6 ×10^{16} m^{-2} gives a range correction of 1m. Most contemporary accurate GNSS systems use augmentation systems (e.g. EGNOS), that measure TEC and send corrections to receivers. This assumes that TEC does not change significantly between the measurement and delivery of the correction. If the spatial or temporal rate of change of TEC is too large, the corrections will be inaccurate (as happened over the US during the October 2003 event).
Suggested worst case:	Defining a TEC of 1 ×10^{16} m^{-2} = 1TECu Midlatitude vertical TEC: 500 TECu based on double the measured value of 250 TECu on 30 Oct 2003 (Mannucci, 2010). Midlatitude TEC spatial range gradient: 800 mm km^{-1}, based on double the spatial gradient from Datta-Barua et al. (2010) for the same event. Midlatitude TEC temporal range gradient: 38 m min^{-1}, based on double the spatial gradient from Datta-Barua et al. (2010) and double the typical major storm time frontal velocities.
Worst case duration	Several days
Worst case spatial extent	Effects likely all over the world. Further study needed to assess regional responses.
Anticipated effects	Inaccurate TEC corrections, leading to errors in GNSS position and timing.
Quality of case:	Measurements are good. Extrapolation unsubstantiated.
Provenance:	Vertical TEC: (Mannucci, 2010) TEC spatial range gradient: (Datta-Barua et al., 2010). TEC temporal range gradient (Datta-Barua et al., 2010). Duration: Expert assessment.

Target risk: GNSS – Total Electron Content (TEC) correction	
How to improve case quality:	Real-time monitoring and modelling. NERC Knowledge Exchange Fellowship held by C Mitchell at Bath will create simulated TEC during extreme storm conditions, in a collaboration with G Attrill, DSTL. The NERC-funded Space Weather Instrumentation, Measurement, Modelling and Risk: Ionosphere (SWIMMR-I) project running from 2020 to 2023, will deliver an advanced assimilative model that will enhance the UK's ability to model and forecast ionospheric enhancements and depletions.
Other notes:	• Dual-frequency GNSS receivers allow TEC corrections without the need for augmentation or differential systems. These are common in geodesy, surveying, etc. • Vertical TEC values given – multiply by 2-3 to adjust for oblique paths and avoid using low-elevation satellites • Emerging evidence that position errors in consumer-level GNSS receivers can lead to dangerous situations (Scoles, 2017)

7.10 GNSS – Effects of Ionospheric Scintillation

Target risk: GNSS – effects of Ionospheric Scintillation	
Environmental risk parameters:	Scintillation is caused by small scale irregularities which can be quantified by the strength of turbulence parameter, CkL. Amplitude scintillation is often quantified by the S4 index. Phase scintillation is often quantified by the σ_ϕ (sigma-phi) index
Rationale:	Small-scale spatial irregularities in the ionosphere can diffract and refract radio signals. This causes rapid fluctuations in signal intensity and phase, known as amplitude and phase scintillation respectively. • Amplitude scintillation can reduce radio signal intensity below a receiver's lock threshold, thereby causing loss of signal on GNSS and other satellite links). • Phase scintillation may lead to cycle slips and loss of lock for receivers as they track the signal. Very intense scintillation is characterised by a Rayleigh amplitude distribution (and associated random phase) due to scattering of signals by multiple spatial irregularities.
Suggested worst case:	Rapid fluctuations in the amplitude and phase of radio signal, leading to errors in positioning of more than 100 m, and repeated losses of service, each lasting from seconds to tens of minutes.
Worst case duration	These effects will occur intermittently over a period lasting several days.
Worst case spatial extent	Global. Storm induced ionospheric scintillation covering all high and mid geomagnetic latitudes, and low latitude scintillation effects also possible.
Anticipated effects	Widespread loss of GNSS signals for location and timing – with economic impacts on UK as studied by London Economics (2017).
Quality of case:	Studies by international Satellite-based Augmentation Systems (SBAS) Ionospheric Working Group with representatives from the European, Japanese and US systems (EGNOS, MSAS and WAAS).
Provenance:	Peer-reviewed papers by Doherty (2000) and Skone (2000)

Target risk: GNSS – effects of Ionospheric Scintillation	
How to improve case quality:	• Better understand how intermittent reception of signals impacts GNSS applications • GNSS navigation and timing receivers have specific vulnerabilities that relate to the internal receiver configuration. Simulation testing of the effects of ionospheric scintillation on specific receiver configurations is necessary to understand the true impacts of space weather events (Pinto Jayawardena et al., 2017). The NERC-funded Space Weather Instrumentation, Measurement, Modelling and Risk: Ionosphere (SWIMMR-I) project running from 2020 to 2023, will develop a range of tools for forecasting scintillations in a variety of ionospheric environments, including those with limited monitoring.
Other notes:	Test equipment for GNSS scintillation has been developed through NERC Knowledge Transfer Partnership at Spirent Communications/University of Bath.

7.11 Satcom - Effects of Ionospheric Scintillation

Target risk: Satcom - effects of Ionospheric Scintillation	
Environmental risk parameters:	Scintillation is caused by small scale irregularities which can be quantified by the strength of turbulence parameter, CkL. Amplitude scintillation is often quantified by the S4 index. Phase scintillation often quantified by the σ_ϕ (sigma-phi) index
Rationale:	Small-scale spatial irregularities in the ionosphere can diffract and refract radio signals. This causes rapid fluctuations in signal intensity and phase, known as amplitude and phase scintillation respectively. • Amplitude scintillation can reduce radio signal intensity below a receiver's lock threshold, thereby causing loss of signal on satellite links. • Phase scintillation may lead to loss of lock for receivers as they track the signal. Both effects are significant at frequencies below 3 GHz. Very intense scintillation will be characterised by a Rayleigh amplitude distribution (and associated random phase) due to scattering of signals by multiple spatial irregularities.
Suggested worst case:	Rapid fluctuations in the amplitude and phase of radio signal, leading to repeated disruption of communications links.
Worst case duration	These effects will occur intermittently over a period lasting several days.
Worst case spatial extent	Global. Storm induced ionospheric scintillation covering all high and mid geomagnetic latitudes, and low latitude scintillation effects also possible.
Anticipated effects	Potential loss of communications links for L-band, UHF and VHF systems that route signals via satellites.
Quality of case:	Tbd
Provenance:	Cannon et al (2013)
How to improve case quality:	• Calculation / simulation of simulation impacts on link budgets • Understand when and how intermittent reception of signals impacts satcom applications

Target risk: Satcom - effects of Ionospheric Scintillation	
Other notes:	• L band and UHF satcom systems are potentially vulnerable but detailed impact will depend on a detailed engineering assessment against the reasonable worst-case conditions specified here. Such assessment is outside the scope of this document. • AIS maritime reporting via VHF satcom (i.e. out of sight of land) is potentially vulnerable, but requires detailed engineering assessment, as above (and taking account of what may be low data rates). • Satcom systems at frequencies above 3 GHz, such as C, X, Ku and Ka bands, do not suffer significant impacts from ionospheric scintillation.

7.12 Blackout of high frequency radio communications

Target risk: Blackout of high frequency radio communications	
Environmental risk parameters:	Absorption of high-frequency (3-30 MHz) radio waves in the upper atmosphere
Rationale:	Ionisation in the upper atmosphere at altitudes of 60 to 90 km ("D region") will absorb HF radio waves, so they cannot reach the higher ionospheric layers that can reflect these waves. In such "blackout" conditions, HF radio cannot be used for over-the-horizon radio communications.
Suggested worst case:	Total blackout of HF radio frequencies
Worst case duration	• Two or three hours during daytime at low- and mid-latitudes (when the absorption is caused by a large solar flare) • Several days at high latitudes (when the absorption is caused by a strong solar energetic particle event – sometimes termed a polar cap absorption event)
Worst case spatial extent	• All low- and mid-latitude regions on the dayside of the Earth (when the absorption is caused by a large solar flare) • High latitude regions (when the absorption is caused by a strong solar energetic particle event)
Anticipated effects	Loss of operation of HF radio systems
Quality of case:	Long-recognised issue with heritage back to 1930s (flare-induced effects) and the 1950s (SEP-induced effects).
Provenance:	Halcrow and Nisbet (1977), Jones and Stephenson (1975), Lockwood (1993), Rogers and Honary (2015), Rogers et al (2015), Schumer (2009), Sauer and Wilkinson (2008), Warrington et al (2012). Also, for commercial aviation operations: ICAO (2015).
How to improve case quality:	Increase international collaboration for collection of riometer measurements. Additional collaboration with airlines and ATC to identify operational and safety impacts that will validate improved ionospheric models for forecasting loss of HF.

Target risk: Blackout of high frequency radio communications	
Other notes:	In November 2019 a range of new 24/7 space weather services for aviation were launched by ICAO, These advisories focus on solar events that can potentially impact on air transport, including HF communications. These are delivered by three global consortia, with the Met Office a partner in the PECASUS consortium.. It has been suggested that the need for HF comms will disappear because of the use of line-of-sight datalink systems and satcom transmissions. Datalink does overcome some of the ATC difficulties for airspace management caused by disruption or loss of HF in the relevant regions, but in many emergency situations a voice call on HF is the quickest and safest option. The use of Satcom is not a viable tool for use by ATC to manage and control safe separations between multiple aircraft in normal or emergency situations (regardless of space weather activity). Therefore, it is considered that the use of HF will remain for at least the next 10-15 years.

7.13 Anomalous high frequency radio communications

NB This scenario will be expanded in future work by SEIEG, as indicated by several TBD entries. It is included here to indicate that work is planned.

Target risk: Anomalous high frequency radio communications	
Environmental risk parameters:	Anomalous propagation of high-frequency (3-30 MHz) radio waves in the upper atmosphere
Rationale:	At mid-latitudes severe storms cause a significant reduction in the critical frequency of the F2-region, foF2, for periods of up to 3-days. At high and low latitudes additional reflecting structures, ionospheric gradients and irregularities occur. These manifest on HF paths as multipath causing frequency selective fading and Doppler distortion of HF signals.
Suggested worst case:	Mid-latitudes: Availability of frequencies reduces, especially during local night-time hours, and as a result of this the likelihood of interference increases. This extended reduction in foF2 may be preceded by a few hours of increased foF2 values in the early hours of the storm. Low and High-latitudes: 60 Hz Doppler spread, multipath spreads ranged 15 ms.
Worst case duration	• Mid-latitudes. TBD • Low and High-latitudes: TBD
Worst case spatial extent	• Mid-latitudes. TBD • Low and High-latitudes: TBD
Anticipated effects	Loss of operation of HF radio systems
Quality of case:	Long-recognised issue dating back to the early days of HF communications
Provenance:	Angling et al (1998) Cannon et al (2000)
How to improve case quality:	TBD
Other notes:	TBD

7.14 Railway signal systems

Target risk: Railway signal systems	
Environmental risk parameter:	Rate of change of magnetic field (d*B*/d*t*, specified in nano-Tesla per minute) – as for power grids.
Rationale:	Track circuits are widely used to detect the presence of trains on specific sections of railway track. The presence of the train changes the flow of electricity in the circuit, compared to an unoccupied track. If GIC from space weather also enters a track circuit, it may confuse the operation of that circuit.
Suggested worst case:	Unknown
Worst case duration	Single event, or 'spike', of 1-2 minutes duration. Lesser spikes in d*B*/d*t* (1-2 minutes each) will be observed throughout the extreme event duration (hours to days).
Worst case spatial extent	Growing evidence that intense GIC events have spatial scales of a few hundred km (Ngwira et al., 2015; Pulkkinen et al., 2015).
Anticipated effects	Additional currents flowing in track circuits
Quality of case:	
Provenance:	
How to improve case quality:	Needs better understanding of GIC impact on rail systems including different types of track circuits. Also analysis of databases of rail system anomalies. As noted under power system impacts, NERC has funded a consortium project, Space Weather Impacts on Ground-based Systems (SWIGS), from 2017 to 2021, to advance our understanding of space weather impacts from GIC. This includes some studies of impacts on rail systems.
Other notes:	Space weather interference with track circuits has been reported in Sweden and Russia, e.g. see Eroshenko et al., 2010. Recent work in China has provided direct measurements of GIC in track circuits of modern high-speed lines (Liu et al., 2016) Space weather risks to rail systems are gaining more attention, e.g. an international workshop was held in London in September 2015 (Kraussmann et al., 2015).

7.15 Aviation – avionics

Target risk: Aviation – avionics	
Environmental risk parameter:	Neutron fluence > 10 MeV
Rationale:	Secondary neutrons are dominant source of single event effects below 60,000 feet. At altitudes above 60,000 feet ions make a significant contribution to SEEs and dose-equivalent for humans. The flux > 10 MeV is used in the standards but allowance must be made for lower energy neutrons, especially thermal, which can increase rates in certain components by a factor 10. Note that energetic protons can contribute significantly while for new technologies stopping protons and muons are increasingly significant.
Suggested worst case:	For a 1-in-150 year event, 4000-fold increase in radiation environment (2400-fold increase for 1-in-100 years), compared to solar minimum conditions, at 40,000 feet (12 km) and high latitude. This is based on a recent assessment of extreme events by Dyer et al. (2017). Using both the instrumental record and proxies such as ^{14}C and ^{10}Be, this assessment suggests to use a 1-in-150 year worst case 4 times more intense than the 23 Feb 1956 event, which is calculated to have produced a 1000-fold increase for high geomagnetic latitudes (Dyer et al., 2017). For the 1-in-150 year event at 40,000 feet neutron fluxes > 10 MeV are: • 1.2×10^6 cm^{-2}hr^{-1} above London • 2.3×10^7 cm^{-2}hr^{-1} above North of Scotland For the 1-in-100 year event at 40,000 feet neutron fluxes > 10 MeV are: • 7.2×10^5 cm^{-2}hr^{-1} above London • 1.4×10^7 cm^{-2}hr^{-1} above North of Scotland For higher latitudes there is essentially no geomagnetic shielding. For a 1 in 1000 year event, the distribution given in Dyer et al. (2017) suggests high latitude fluxes of 5 times worse than the above values for 1-in-150 years. For 1 in 10,000 years the factor increase is 12.5. For more detailed insights please see Tables 1 and 4 of Dyer et al. (2017). Fluxes are 3.6 times higher again at 60,000 feet and high latitude. Above this altitude ions must also be considered.

Target risk: Aviation – avionics	
Worst case duration	Timescales of events range from 1 to 12 hours but note that for impulsive events such as Feb56, nearly all the fluence (77%) arrives in the first hour and fluxes during the first few minutes are a factor 3 higher.
Worst case spatial extent	Considerable variations across the world due to radiation from the Sun being directed by the interplanetary magnetic field, and the shielding effects of Earth's magnetosphere. The former can lead to variations with longitude, whilst the latter can lead to greater fluxes at high latitudes – but with marked differences between the northern and southern poles. If a ground level enhancement occurs during an extreme geomagnetic disturbance, such as that during the Carrington event, low latitudes could be severely exposed.
Anticipated effects	High upset rates and possible high failure rates in inadequately protected digital avionic systems
Quality of case:	This is based on observations of the ground level enhancement (GLE) radiation event of 23 Feb 1956 and comparison with other GLEs in the instrumental and proxy records, as consolidated by Dyer et al. (2017).
Provenance:	Peer-reviewed papers by Dyer et al (2003), Dyer et al (2007), Dyer et al. (2017), Lantos and Fuller (2003), Tylka and Dietrich (2009), Mekhaldi et al.(2015). 1956 observations in research note by Marsden et al (1956), Quenby and Webber (1959), Rishbeth, Shea and Smart (2009).

Target risk: Aviation – avionics	
How to improve case quality:	The NOAA Solar Radiation Storm S-scale, derived from the GOES >10 MeV solar proton energy channel, was designed for warning of harmful increases in solar radiation during NASA astronaut EVA's. It is now recognised that the vast majority of these protons are not sufficiently energetic to reach commercial airline cruising altitudes and will not give harmful radiation increases to flight crews and passengers. Therefore the current S-scale is considered wholly inappropriate for use by airlines as an operational or duty of care decision-tool. Space weather events that produce significant solar proton fluxes with energies >400 MeV are required to yield increased flight doses and SEEs in avionics. More measurements on board aircraft, balloons, and by ground-based neutron monitors, to stimulate development and validation of improved models of radiation exposure. Further modelling of radiation in the upper atmosphere for UAVs, buoyant stratospheric balloons and space tourism. Determination of susceptibility of avionics equipment and systems. Consider susceptibility of new electronics to stopping protons and muons. The NERC-funded SWIMMR Aviation Risk Modelling (SWARM) project running from 2020 to 2023, will develop a new data-driven atmospheric radiation model to nowcast secondary particle fluxes, biological dose rates and electronic upset/failure rates throughout the atmosphere, including those from GLEs.
Other notes:	Assumes near worst case altitude (40,000 feet/12 km) and route (e.g. high latitude such as LHR-LAX or polar). Fluxes would be factor 3.6 worse at 60,000 feet and ions must be considered above this altitude. Any existing geomagnetic storm could expose lower latitude routes to similar fluxes. Duration is probably worst for short events that give high rates. Event durations are typically 1-12 hrs. Dyer et al. (2017) propose adoption of a new space weather scale for atmospheric radiation with February 1956 fluxes as the baseline for the scale. This would complement the NOAA S-scale for space radiation and would be far more appropriate for atmospheric radiation impacts.

7.16 Aviation – human radiation exposure

Target risk: Aviation – human radiation exposure	
Environmental risk parameter:	High radiation dose rates at aviation altitudes. Secondary neutrons are the main contribution below 60,000 feet but above this altitude ions make a significant contribution to SEEs and dose-equivalent for humans.
Rationale:	**Air crew**: are occupationally exposed. Airlines operate to a limit of 20 mSv per year and seek to keep doses below a constraint of 6 mSv per year. **Pregnant air crew:** airlines are expected to limit the dose received to 1 mSv, once they have been informed that their employee is pregnant. (In the US, the FAA guideline is 0.5 mSv in one month.) **Passengers including frequent business fliers**: not covered by legislation so no formal dose limits or constraints apply.
Suggested worst case:	**1 in 150 year event**: 28 mSv (17 mSv for 1 in 100 years), based on a recent assessment of extreme events by Dyer et al., 2017. Using both the instrumental record and proxies such as ^{14}C and ^{10}Be, this assessment suggests that the 1-in-150 year worst case would be 4 times more intense than the 23 Feb 1956 event, which is estimated to have produced a route ambient dose of 7 mSv at 40,000 ft on high latitude routes such as London to Los Angeles (Dyer et al., 2017). **1 in 1000 year event**: 150 mSv, based again on the assessment by Dyer et al., 2017, which takes account of extreme events in the proxy record, such as the 774 AD event (Miyake et al., 2012; Mekhaldi et al., 2015) For more details see Table 4 of Dyer et al. (2017)
Worst case duration	1-12 hours for a single event, but perhaps longer in a sustained series of events with several large X-class flares and fast CMEs. Note that for impulsive events such as Feb56, nearly all the dose (77%) arrives in the first hour and dose rates during the first few minutes are a factor 3 higher.
Worst case spatial extent	Considerable variations across the world due to radiation from the Sun being directed by the interplanetary magnetic field, and the shielding effects of Earth's magnetosphere. The former can lead to variations with longitude, whilst the latter can lead to greater fluxes at high latitudes – but with marked differences between the northern and southern poles. Any existing geomagnetic storm could expose lower latitude routes to similar fluxes. Doses received by individuals are probably worst for short events that give high rates.

Target risk: Aviation – human radiation exposure	
Anticipated effects	**Aircrew:** could exceed 6 mSv and airlines would seek to limit further doses by changes to flight duties. This may be logistically problematic. **Pregnant crew:** may exceed 1 mSv limit if they are still undertaking flight duties. However, airlines routinely change the flight duties of pregnant crew once they are notified of the pregnancy. **Passengers**: will need information on exposures received.
Quality of case:	This is based on observations of the ground level enhancement (GLE) radiation event of 23 Feb 1956 and comparison with other GLEs in the instrumental and proxy records, as consolidated by Dyer et al., 2017.
Provenance:	Papers by Dyer et al. (2007), Dyer et al. (2017), Lantos and Fuller (2003), and Tylka and Dietrich (2009). 1956 ground level observations in research note by Marsden et al (1956), Quenby and Webber (1959), Rishbeth, Shea and Smart (2009). 774 AD event: Miyake et al., (2012); Mekhaldi et al (2015).

Target risk: Aviation – human radiation exposure	
How to improve case quality:	The NOAA Solar Radiation Storm S scale, derived from the GOES >10MeV solar proton energy channel, was designed for warning of harmful increases in solar radiation during NASA astronaut EVAs. It is now recognised that the vast majority of protons in this channel are not sufficiently energetic to reach commercial airline cruising altitudes, and thus cannot give harmful radiation increases to flight crews and passengers. Therefore the current S scale is considered wholly inappropriate for use by airlines as an operational or duty of care decision-tool. SW events that produce solar proton energies >400MeV are likely to yield increased flight doses, but a new alerting scale based on this energy must also be correlated with ground-based neutron monitor data, and/or ideally with on board aircraft measurements. More measurements on board aircraft and balloons, and by ground-based neutron monitors, to stimulate development and validation of improved models of radiation exposure. Better space-based solar proton data for energies > 400 MeV, such as on the new GOES satellites. International agreement is needed to determine the thresholds for advising restrictions on take-off, and advice on rerouting or changing altitude. This should also be related to the susceptibility of avionics. The NERC-funded SWIMMR Aviation Risk Modelling (SWARM) project running from 2020 to 2023, will develop a new data-driven atmospheric radiation model to nowcast secondary particle fluxes, biological dose rates and electronic upset/failure rates throughout the atmosphere, including those from GLEs.

Target risk: Aviation – human radiation exposure	
Other notes:	Assumes near worst case altitude (12 km) and route (e.g. high latitude such as London-Los Angeles or polar). However, a simultaneous geomagnetic storm could produce similar doses for lower latitude routes. Doses are probably worst for short events that give high dose rates and little time for avoidance. Longer duration events could affect more flights and/or expose more passengers. Dyer et al. (2017) propose adoption of a new space weather scale for atmospheric radiation with February 1956 fluxes as the basepoint for the scale. This would complement the NOAA S-scale for space radiation and be more appropriate for atmospheric radiation impacts.

7.17 Public behaviour impacts

Target risk: Public behaviour impacts	
Risk parameter:	No consensus on quantitative parameters at this time, but keep under review.
Rationale:	Infrastructure failure following an extreme space weather event may result in behaviours such as public disorder or stockpiling that might be expected in a major crisis.
Suggested worst case:	Lack of public awareness/confidence combined with very severe event (widespread power blackouts, major interruptions to GNSS-based services).
Worst case duration	Several days?
Worst case spatial extent	All of UK. Similar problems in other affected countries.
Anticipated effects	• Rejection of scientific understanding in favour of conspiracy / rumour • Reframing of the event with negative consequences for social cohesion • Stockpiling (sometimes called ‘panic buying’) • Millenarianism See Appendix 2 to this report for a detailed discussion
Quality of case:	This is based on evidence discussed in Appendix 2
Provenance:	McBeath (1999), House of Lords Science and Technology Committee (2005), Kerr (2011), Sciencewise (2014), Preston et al. (2015),
How to improve case quality:	Monitor developments in the research community
Other notes:	

8 Glossary

AE8	Model of electron fluxes in the radiation belts
AIS	Automatic Identification System, an automatic tracking system used by shipping.
ATC	Air traffic control
BAS	British Antarctic Survey
BGS	British Geological Survey
CHAMP	Challenging Minisatellite Payload (DLR satellite)
CME	Coronal mass ejection
DSTL	Defence Science and Technology Laboratory
EGNOS	European Geostationary Navigation Overlay Service (European SBAS)
EUV	Extreme ultra-violet
EVA	Extra vehicular activity
FAA	Federal Aviation Administration
GEO	Geosynchronous orbit
GIC	Geomagnetically induced currents
GLE	Ground Level Enhancement
GNSS	Global Navigation Satellite System
GOES	Geostationary Operational Environmental Satellite
GRACE	Gravity Recovery and Climate Experiment. Joint NASA/DLR satellite.
HF	High Frequency (3 to 30 MHz) radio
ICAO	International Civil Aviation Organisation
keV	Kilo-electron-volt
L-band	Radio frequencies between 1 and 2 GHz
LAX	Los Angeles international airport
LEO	Low Earth Orbit
LHR	London Heathrow airport
MEO	Medium Earth Orbit
MeV	mega electron-volt
MSAS	Multi-functional Satellite Augmentation System (Japanese SBAS)
mSv	milliSievert – unit of radiation dose for human exposure (effective dose or dose equivalent).
NERC	Natural Environment Research Council
NOAA	National Oceanic and Atmospheric Administration
PECASUS	Pan-European Consortium for Aviation Space weather User Services
SAPPHIRE	Solar Accumulated and Peak Proton and Heavy Ion Radiation Environment model
SBAS	Satellite-based Augumentation System (for GNSS)
SCATHA	US Air Force satellite mission to study charging effects, flown in late 1970s and early 1980s.
SEE	Single event effect
SEP	Solar energetic particle
SFU	Solar flux unit (measure of solar radio signal strength); 1 SFU = 10^{-22} $Wm^{-2}Hz^{-1}$)
SRB	Solar radio burst
SWIMMR	Space Weather Instrumentation, Measurement, Modelling and Risk (research programme)

TBD	To be done
UAV	Unmanned Aerial Vehicle
UHF	Ultra High Frequency (300 MHz to 3 GHz) radio
VHR	Very High Frequency (30 to 300 MHz) radio
WAAS	Wide Area Augmentation System (US SBAS)
UKSA	UK Space Agency

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10 Appendix 1: Interrelationships between effects

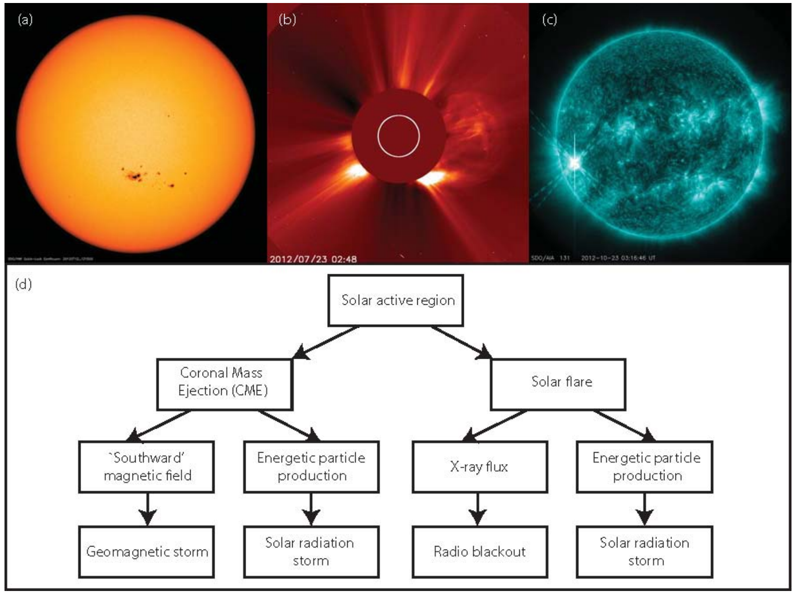

Figure 1 Sources of space weather (Reproduced from Eastwood et al., Risk Analysis, 2017 https://dx.doi.org/10.1111/risa.12765, Figure 1)

The Sun is essentially the ultimate source of space weather at Earth as illustrated in Figure 1 (Eastwood et al., 2017). Large sunspot groups on the solar disk (panel a) indicate the presence of active regions in the solar atmosphere which are the typical site of *coronal mass ejections* (panel b) and *solar flares* (panel c). These two solar phenomena can interact with the Earth's magnetic field in space (magnetosphere), ionosphere, and atmosphere to generate geomagnetic storms, solar radiation storms, and radio blackouts.

The duration of an interval of severe space weather is expected to depend on its likelihood, with rare severe events lasting longer in time. Studies by Eastwood et al. (2018) and Oughton et al. (2018) examining power grid economic impact in Europe and the UK respectively have made use of 1-in-10 year, 1-in-30 year, and 1-in-100 year scenarios based on the October 2003, March 1989, and 1859 Carrington periods respectively. Figure 2 shows the expected duration of each scenario and illustrates the potential complexity of an interval of extended space weather risk, which could for several weeks.

Figure 3 outlines many of the most important associations between space weather effects and system impacts such as those described in this document. Many space weather effects will occur close together in time as they have a common origin in solar phenomena such as coronal mass ejections. Given the expected complexity as illustrated in Figure 2, it is reasonable to expect that different systems will experience interacting adverse impacts causing unpredictable and cascading failures.

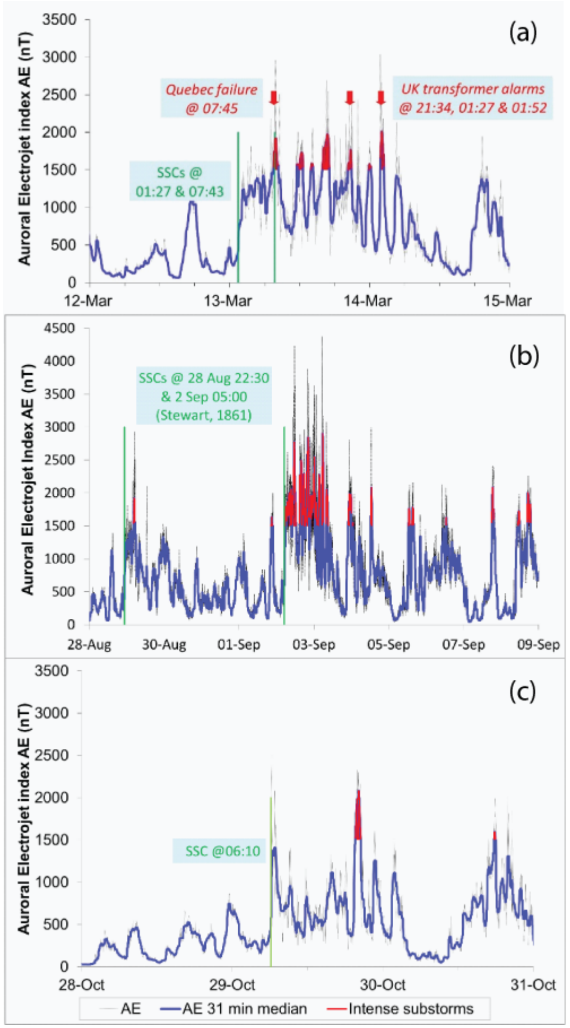

Figure 2 Candidate scenarios for the duration and complexity of 1-in-30 (panel a), 1-in-100 (panel b), and 1-in-10 year events (panel c). Figures show the time series of the AE index (used to characterize auroral activity associated with risk to power grids) with a 31-min running median trace overlaid (blue). Intervals of intense activity representing risk to power grids are shown in red. SSC refers to sudden storm commencement. (Reproduced from Eastwood et al., Space Weather, 2018 https://doi.org/10.1029/2018SW002003, Figure 1; see also Oughton et al. 2018).

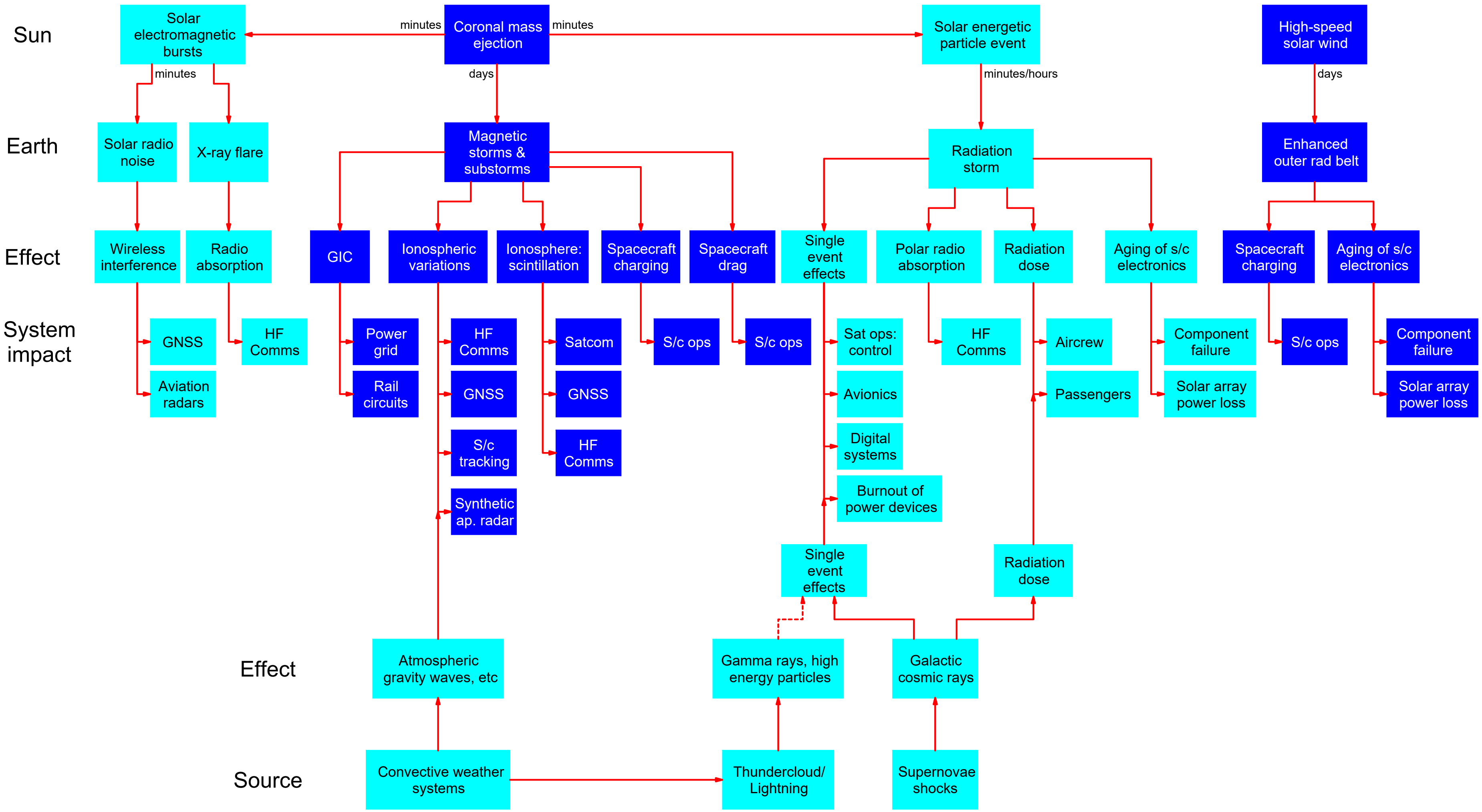

Figure 3 The association between the physical drivers of space weather and downstream system impacts.

11 Appendix 2. Space Weather: potential ‘worst case’ public behaviour impacts: note by John Preston.

Introduction

Public behaviour after a severe space weather event is difficult to predict as the infrequency of such events does not give us a baseline. Infrastructure failure following an extreme event may result in behaviours such as public disorder or stockpiling that might be expected in a major crisis. This depends on the scale of the event. The 1989 solar storm which caused a blackout in Toronto, closing schools and businesses, did not result in notable public behaviour anomalies but the impact on the electricity grid was short lived.

Because of the source of space weather events they might be subject to conspiracy theories and rumours that reject scientific explanations. Very rarely, cult groups have used solar events as a ‘sign’ to take action in terms of mass suicides or violent actions. The four potential impacts provided below would only be seen in a worst case scenario.

Rejection of scientific understanding in favour of conspiracy / rumour

Severe space weather is a low probability, high impact event where there is little public understanding. A telephone survey of 1,010 adults in England and Wales conducted in 2014 found that 46% had never heard of space weather and an additional 29% had heard of it but know almost nothing about it. 35% of respondents would be more concerned about a power cut in their area caused by space weather when compared to other causes (Sciencewise, 2014). Scientific understanding of space phenomena can be undermined by conspiracy theories which may propagate online through the echo chamber effects of social media. For example, online rumours concerning the existence of a so called ‘Planet X’ or ‘Nibiru’ which will collide with earth have circulated online since 1995 despite the absence of scientific evidence (Kerr, 2011). *A worst case scenario would be that lack of existing knowledge of space weather and the propagation of rumour and conspiracy on line would increase public anxiety around the event.*

Reframing of the event with negative consequences for social cohesion

A recent comparative survey of public behaviour in disasters and emergencies which impact at regional or national level showed that in most cases communities will usually react in ways with neutral or positive impacts on social cohesion (Preston et al, 2015). However, in some cases communities will react negatively to official help and advice and politicise the event. This community behaviour in disasters, known as *reframing*, may occur in a severe space weather event particularly if communities consider that the official response is not equitable. For example, if power is restored to communities in a way that is perceived to be unfair then it is likely that there will be negative political consequences that may result in demonstrations or public disorder.

Mitigating against this, unpredictable or novel emergencies will not usually lead to political outrage as long as the public are made aware of the reasons for the event (but see point 1 above). *A worst case scenario would be that there is public disorder in communities where the government response is seen to be inadequate.*

Stockpiling (sometimes called ‘panic buying’)

Stockpiling is a rational behaviour in disasters and emergencies and is not a problem as long as retail stocks and supply chains are not compromised. Goods that are usually stockpiled are petrol, bottled water and canned goods. If people consider that stocks and supply chains may be compromised in the future, or that they need excess supplies at home for an anticipated event, they may increase demand to the extent that current supply cannot meet demand. This can become a self-fulfilling prophecy as in the Coronavirus pandemic when in March 2020 many supermarkets were experiencing shortages. Fear of shortages leads to stockpiling which in turn leads to shortages that exacerbate demand through ‘panic buying’ resulting in shortages. Prices may rise rapidly, queuing may occur, stocks can be depleted and (rarely) some individuals may resort to theft to obtain supplies. Supply chains in the UK are lean (little stock is held) and are particularly vulnerable to panic buying in a crisis (House of Lords Scientific Committee, 2005). *A worst case scenario would be widespread panic buying which would compromise supply chains and lead to inefficiencies such as queuing for petrol.*

Millenarianism

Millenarianism refers a view of certain religious sects, or individuals, who consider that certain events are a sign that the world is coming to an end. These events are often linked to space events such as comets (McBeath, 2011) and pseudo-scientific concepts such as changes in ‘galactic alignment’ or cataclysmic ‘pole shifts’. Sometimes religious cults use space events as a justification for mass suicides or violent events. For example, the 1999 suicide of 31 members of the ‘Heaven’s Gate’ cult in San Diego, California was planned after their observations of the Hale-Bop comet in 1997 (they believed a spacecraft trailing the comet would take them from earth). 53 members of The Order of the Solar Temple, who worship the Sun, died in Switzerland in 1994. Many of these deaths were as a result of shooting and stabbing of their own members as well as from suicide. The Order of the Solar Temple is still in existence. Such events are difficult to predict but may coincide with a solar event such as severe space weather. *A worst case scenario would be a mass suicide, or other violent event, initiated by a cult group.*