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UK Space Safety Engagement Meetings: 24-26 March 2021

Development of Space Weather Reasonable Worst-Case Scenarios for the UK National Risk Assessment

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Background

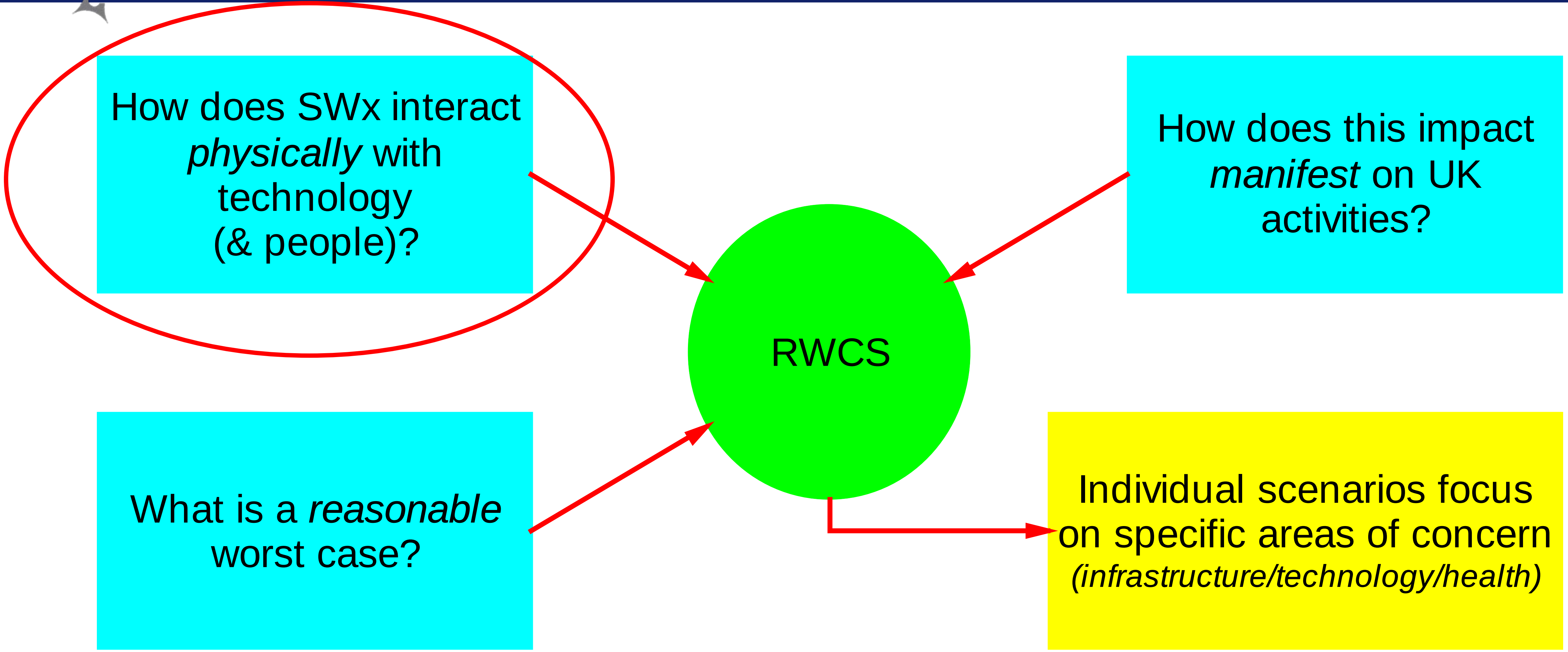
- Severe space weather identified as candidate risk for UK National Risk Assessment in 2010
  - Scenarios developed to advise Civil Contingencies Secretariat (CCS)
  - Formalised via establishing Space Environment Impacts Expert Group (SEIEG) as *independent* expert group providing advice to CCS
- Scenarios first published 2012 (as RAL Tech Report) to support Royal Academy report on engineering impacts of severe SWx
  - Updates published as Tech Reports in 2016 and 2020
  - Scientific background published 2021 in *Space Weather* journal
  - All open access (CC BY licence), links on meeting web-site
- This talk is my summary of the scenario development
  - Encourage you to read and share definitive version (reports above)

Outline of presentation

- How we built the scenarios
  - Key drivers – *physics* of impacts, consider *application to UK* (global events with local impacts), what is a *reasonable worst case*
  - Structure of the scenarios – focus on worst case <u>environments</u>
  - Important to follow the physics, but make good use of statistics
- Range of reasonable worst case scenarios (RWCS)
  - Diversity of space weather (SWx) impacts
  - And a few examples (not all cases)
- Bringing the scenarios together
  - SWx as an *ensemble*, timeline dictated by solar activity
- Outcomes and future work
  - Technological innovation requires continuing assessments

How we built the scenarios

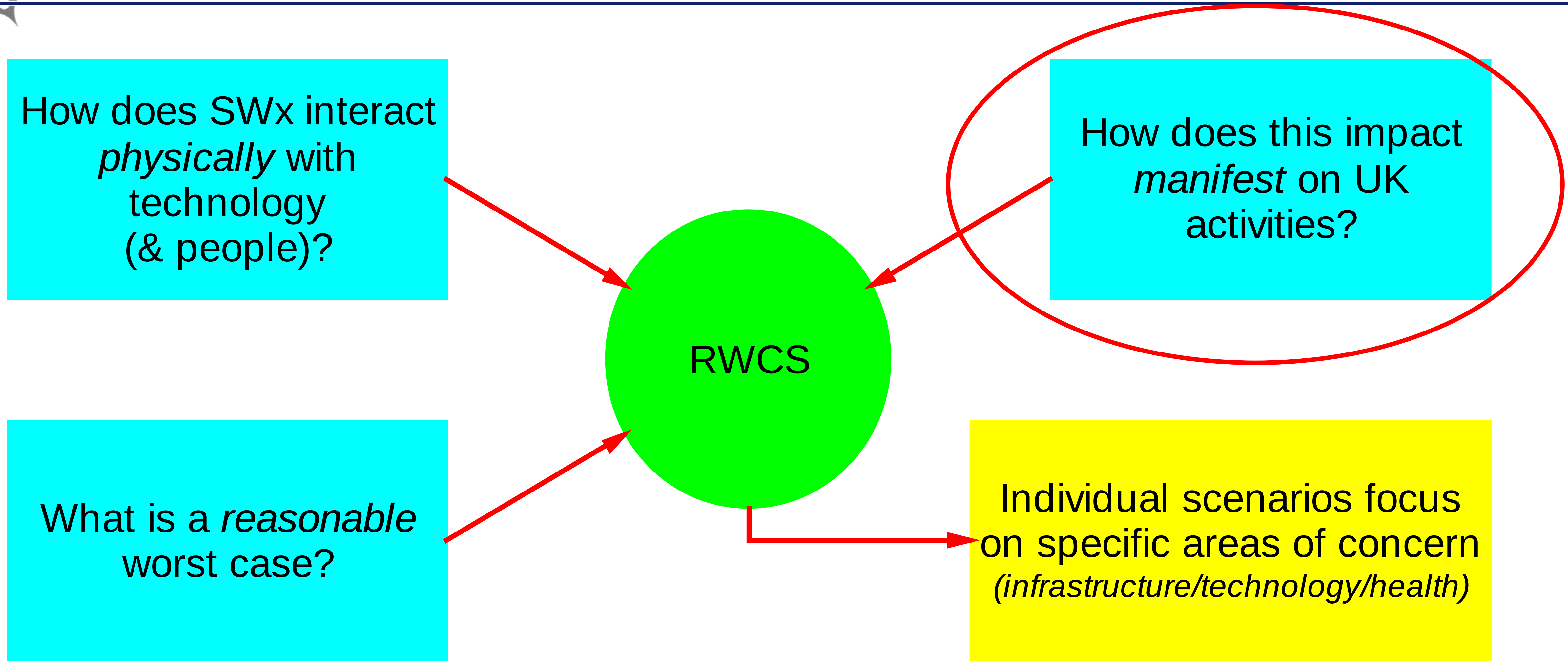
Key drivers and outputs



How does SWx interact with technology?

- Key to developing scenarios of adverse SWx environments
  - How does the SWx environment physically interact to cause problems?
  - Does it inject something “bad” (induced electric field, particle radiation, …) into the technology, or a human body?
  - Does it disrupt how a technology exploits an environment (changes in neutral or plasma density) during normal operations?
- So we identify
  - environment parameters that characterise adverse interaction(s)
  - extreme values of that parameter (size, duration, spatial extent)
- Always start with the technology
  - Trace to the immediate environment – then back to the Sun
  - Timeline on Sun drives dangerous ensemble of different SWx threats

Key drivers and outputs



Impact on UK activities

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- Immediate focus is on impacts that disrupt UK:
  - manifest over national territory
  - affect links with other countries, e.g. transport, economic
- Geography influences SWx impacts on UK, e.g.
  - Substorms central to risk to power grid
  - No air routes over high Arctic (>82° N)
  - GB grid has only HVDC interconnects with other power grids
  - NI grid now part of Eirgrid
  - Atmospheric radiation effects higher in Scotland
- But international collaboration is vital in dealing with what is a global problem

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Key drivers and outputs

How does SWx interact *physically* with technology (& people)?

How does this impact *manifest* on UK activities?

RWCS

What is a *reasonable* worst case?

Individual scenarios focus on specific areas of concern *(infrastructure/technology/health)*

What is a *reasonable* worst case?

- Adverse event with significant likelihood in a human lifetime
  - but not so common that society naturally develops resilience
  - 1-in-100 and 1-in-200 years often used by governments and insurers
  - 1-in-100 years used to assess flood risks in UK
- Lower probability events with catastrophic consequences
  - Important to understand 1-in-1000 year events
  - 1-in-10000 years used to assess safety of UK nuclear facilities
- UK considered risks with likelihood > 1-in-10^5 years
  - Longer-term risks noted but not taken further, e.g. significant meteor impacts over UK

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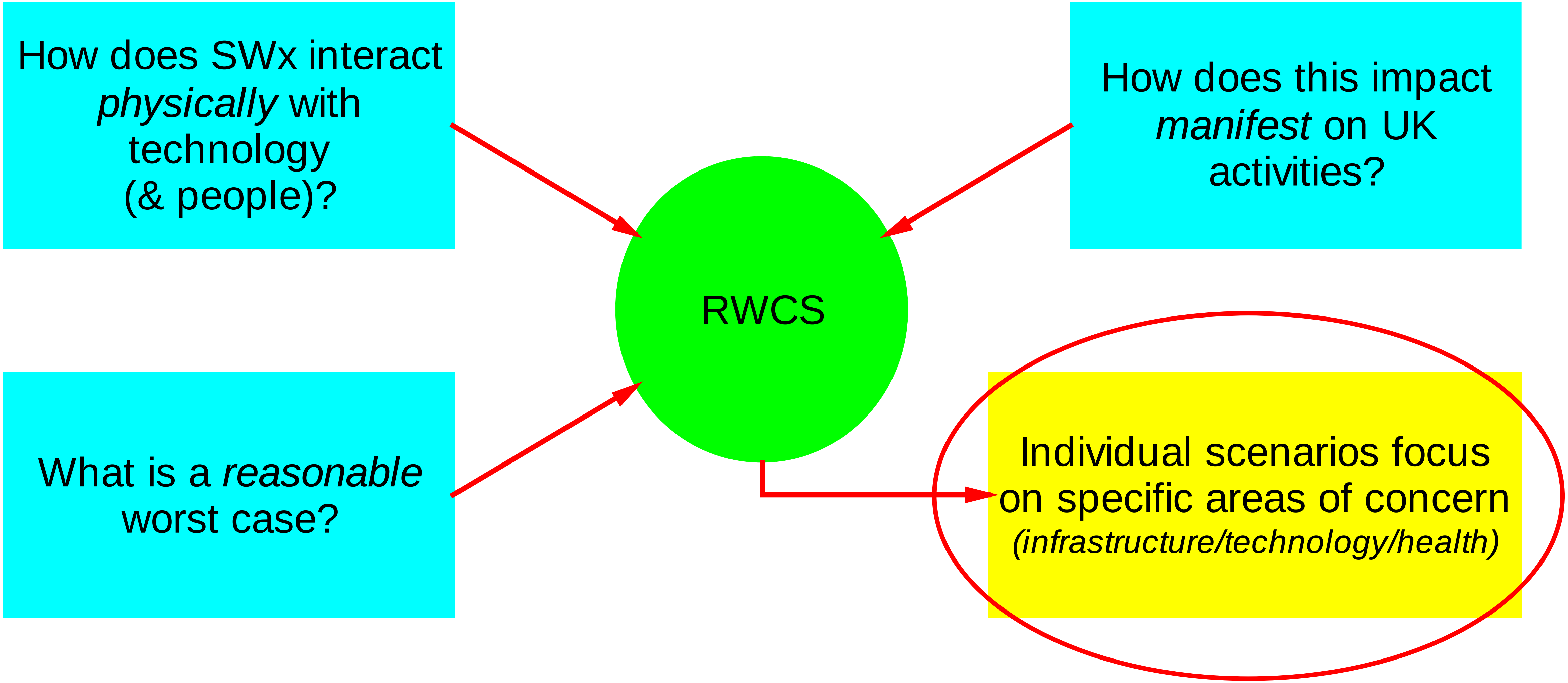
Key drivers and outputs



Delivering the scenarios to Government

- Target audience is contingency teams in government
  - Dialogue showed they needed concise scenarios for specific sectors
  - So they can explore resilience of sectors
- Agreed format is a set of tables
  - Each specifies SWx environment that impacts an area of concern
- Tables also published as RAL Technical Report (right)
  - open access on STFC Epubs
  - CC BY licence (use freely with attribution)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Technical Report
RAL-TR-2020-005

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

M Hapgood, M Angling, G Attrill, M Bisi, C Burnett, P Cannon, C Dyer, J Eastwood, S Elvidge, M Gibbs, R Harrison, C Hord, R Horne, D Jackson, B Jones S Machin, C Mitchell, J Preston, J Rees, N Rogers, A Richards, G Routledge, K Ryden, R Tanner, A Thomson, J Wild, M Willis

July 2020

Content of each scenario (table)

- Environmental risk parameter(s) for the area of concern
  - Short description of the parameter(s)
  - Rationale for this parameter
  - Worst case size, duration, spatial extent
- Summary of anticipated effects arising from worst case
- Quality and provenance of the scenario
  - Encouraged to anchor provenance in peer-reviewed literature
  - Summarise ways to improve quality of the scenario
- Other notes

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Content of each scenario (table)

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 ($\mathrm{d}B/\mathrm{d}t$), 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 $\mathrm{d}B/\mathrm{d}t$ 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 $\mathrm{d}B/\mathrm{d}t$ in the conducting Earth. $\mathrm{d}B/\mathrm{d}t$ 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 $\mathrm{d}B/\mathrm{d}t$, 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

Any questions so far?

The range of scenarios, and a few examples

Scenarios for critical infrastructure

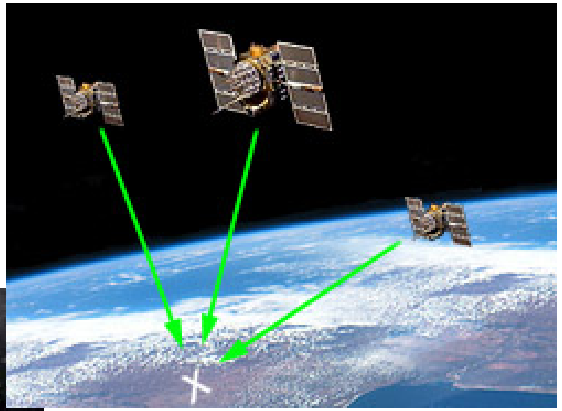
Electricity transmission

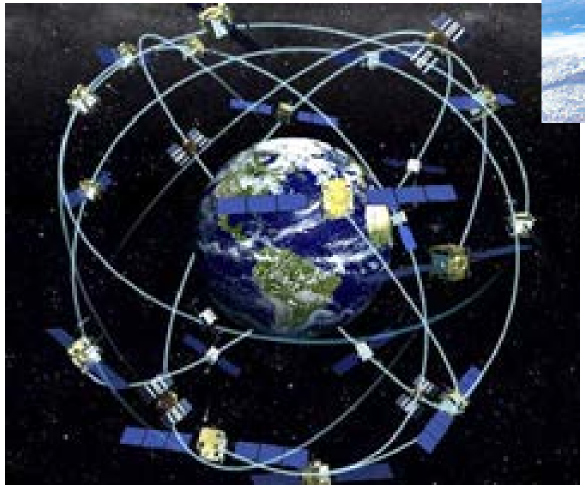
Civil aviation

Satellites

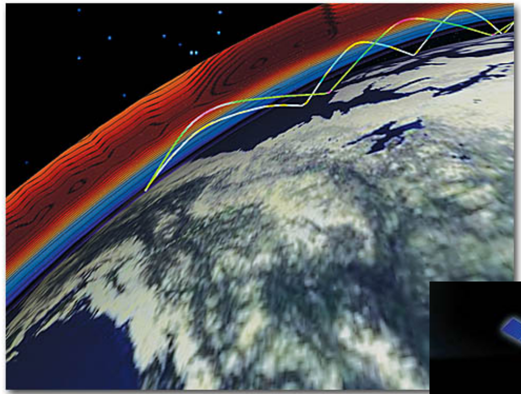
Rail

More scenarios: infrastructure & embedded tech





GNSS

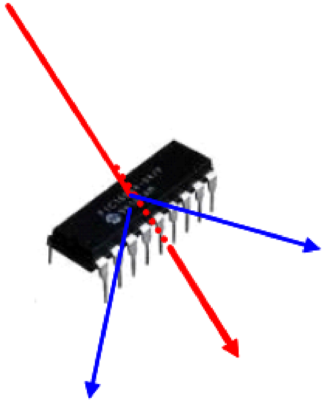


HF

Satcom

Radio comms

Digital systems

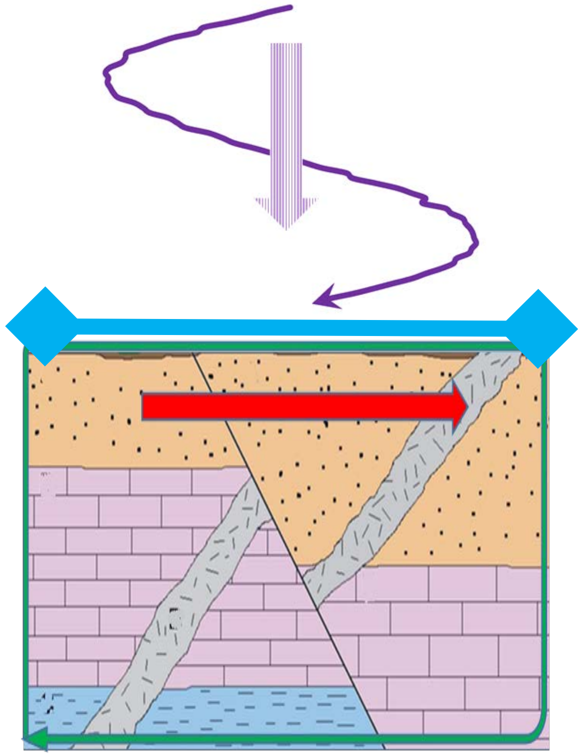


Infrastructure vs tech exemplifies diversity of SWx impacts. Accept diversity!

Power grid 1: geoelectric field

environment		technology		
Geoelectric field	+	Conducting network: Ohm/Kirchoff's law	=> GIC	=> AC harmonics, voltage sag, …

Geoelectric fields are induced inside the Earth by magnetic fluctuations, particularly 1-100 mHz frequencies which penetrate 100s of km => large induction loop. Size of Efield strongly determined by subsurface conductivity.



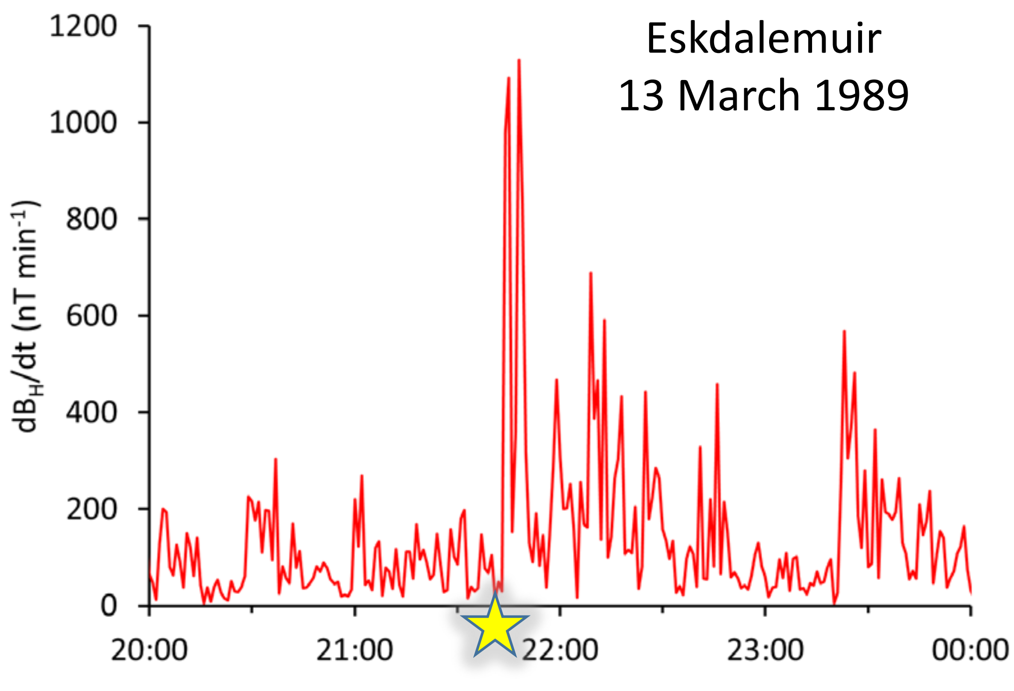
Modelling suggests Efields > 20 V km^{-1} possible in 1-in-100 year storms

Also use dB/dt to characterise this environment – see next slide.

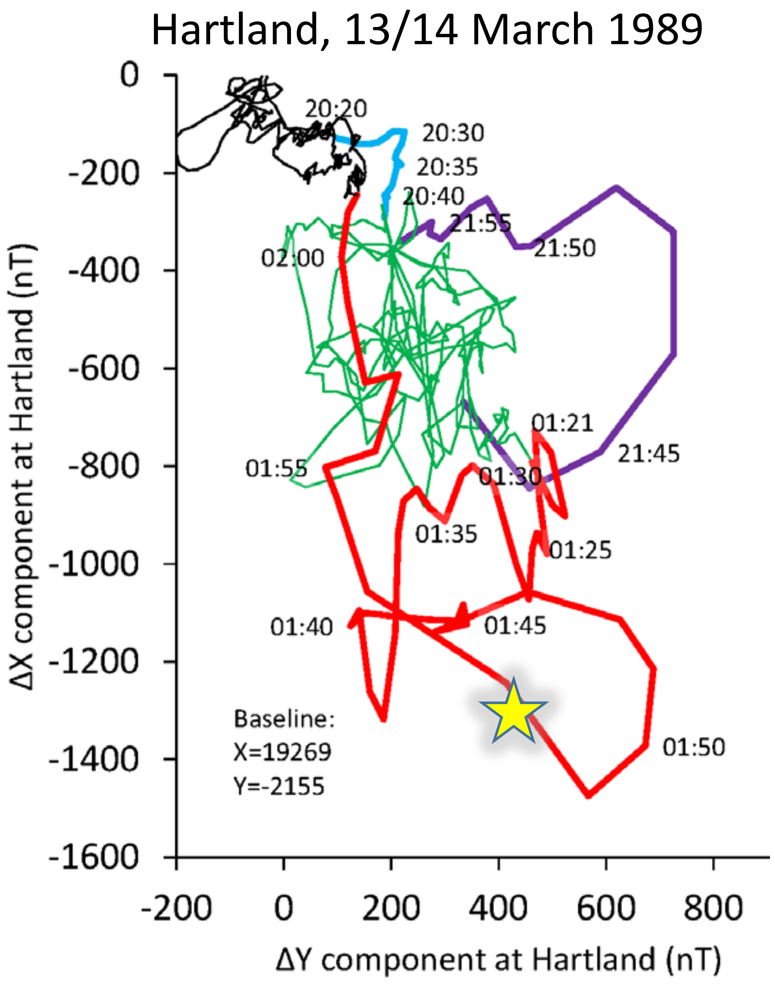
Power grid 2: geomagnetic field

dB_H/dt, the rate of change of H, the *horizontal* component of the geomagnetic field, is a convenient proxy for Efield

- But must treat H as a vector, see example right
- Take $dB_H/dt \sim 5000$ nT min^{-1} as UK reasonable worst case
- As a spike lasting 1 or 2 minutes, covering 100s of km



Left: largest UK observed dB_H/dt, 1100 nT min^{-1}, during 1989 storm



Satellites: single event effects during SEP events

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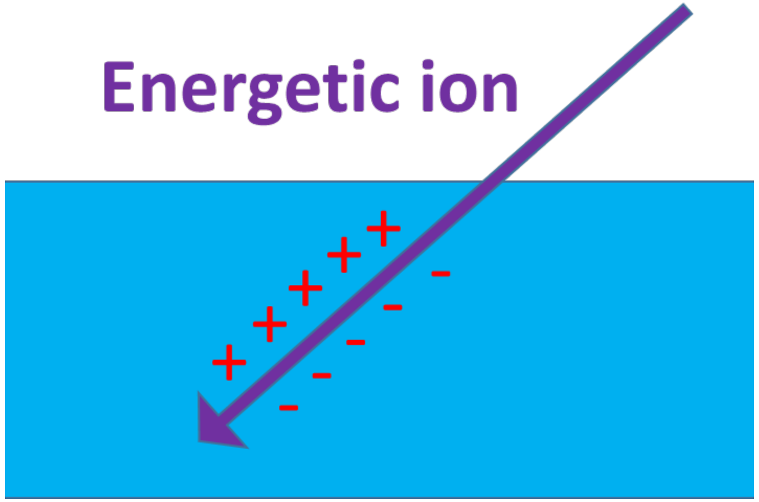
environment ***technology***

High energy ions + **Silicon devices: Electron-hole pairs** => Ionisation => disruption, damage

High energy protons & ions (>30 MeV) flood near-Earth space **during SEP events**: they can penetrate into satellite electronics and create ionisation inside silicon devices



We do not consider background SEE rates from high-energy ions in radiation belts (and South Atlantic Anomaly)

Satellites: single event effects during SEP events

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environment ***technology***

High energy ions **+** **Silicon devices: Electron-hole pairs** **=> Ionisation** **=> disruption, damage**

Note that SEEs have different physics to other particle impacts on satellites:

- Radiation damage – coulomb force
- Internal charging – charge deposition
- Surface charging – current exchange

Assess worst case conditions for range of timescales – see next slide.

SEEs also arise in devices on aircraft and on the ground during SEP events. But this has extra physics: SEPs -> atmospheric neutrons -> silicon nuclei -> high energy ions

Satellites: single event effects during SEP events

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- Consider worst case as fluxes (rate) & fluences (time integral)
  - Fluxes drive instantaneous SEE occurrence rates & hence likelihood of service interruptions (e.g. if SEE rates exceed error correction rates)
  - Fluences are guide to total number of problems to be expected and hence size of operator workload
- 1-in-100 year worst cases (energy integrals, >30 MeV) include
  - Peak proton flux: 2.3×10^{5} $cm^{-2}s^{-1}$,
  - 1-day proton fluence: 4.1×10^{9} cm^{-2} ,
  - These take account of recent (2012-present) discoveries of proxy data about historical radiation events, e.g. 774/775 AD.
- These are for SEPs outside magnetosphere/GEO:
  - Application to specific satellite must consider the amount of shielding (both shielding provided by satellite, geomagnetic shielding for lower orbits)

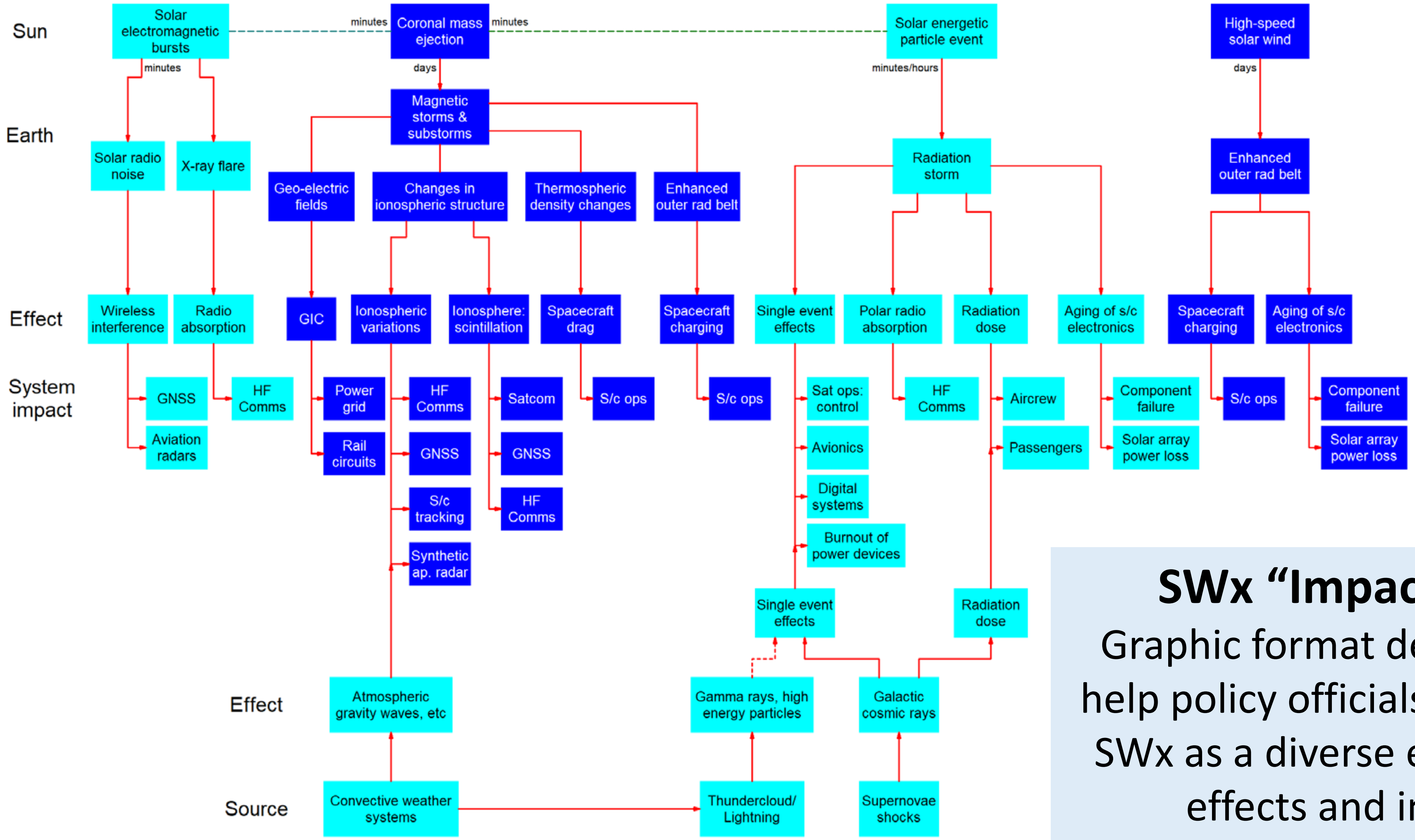
An non-physical impact: Public behaviour

- Important to assess public response to severe SWx event, e.g.
  - Loss of electricity (nuisance within minutes, serious inconvenience within hours, total disruption within days, …)
  - Intermittent GNSS (disrupting logistics, emergency services, …)
- Without good public communication, this could include generic responses to poorly understood natural hazards:
  - Rejection of scientific understanding in favour of conspiracy / rumour
  - Breakdown of social cohesion if impacts perceived to be unfair
  - Stockpiling (sometimes called ‘panic buying’)
  - Millenarianism (especially because of link to “space”)
  - Increased anxiety => health risk
- These are all reinforced by experience with covid

Any questions so far?

Bringing the scenarios together: space weather as an ensemble of risks

Space weather as an ensemble

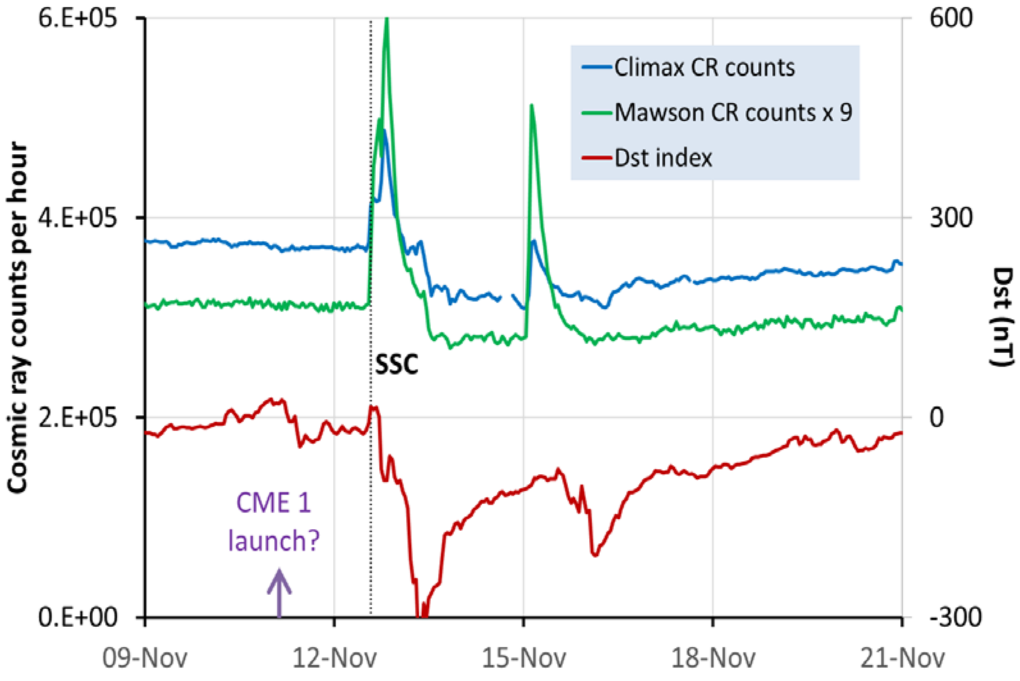


SWx "Impact Tree"

Graphic format developed to help policy officials understand SWx as a diverse ensemble of effects and impacts

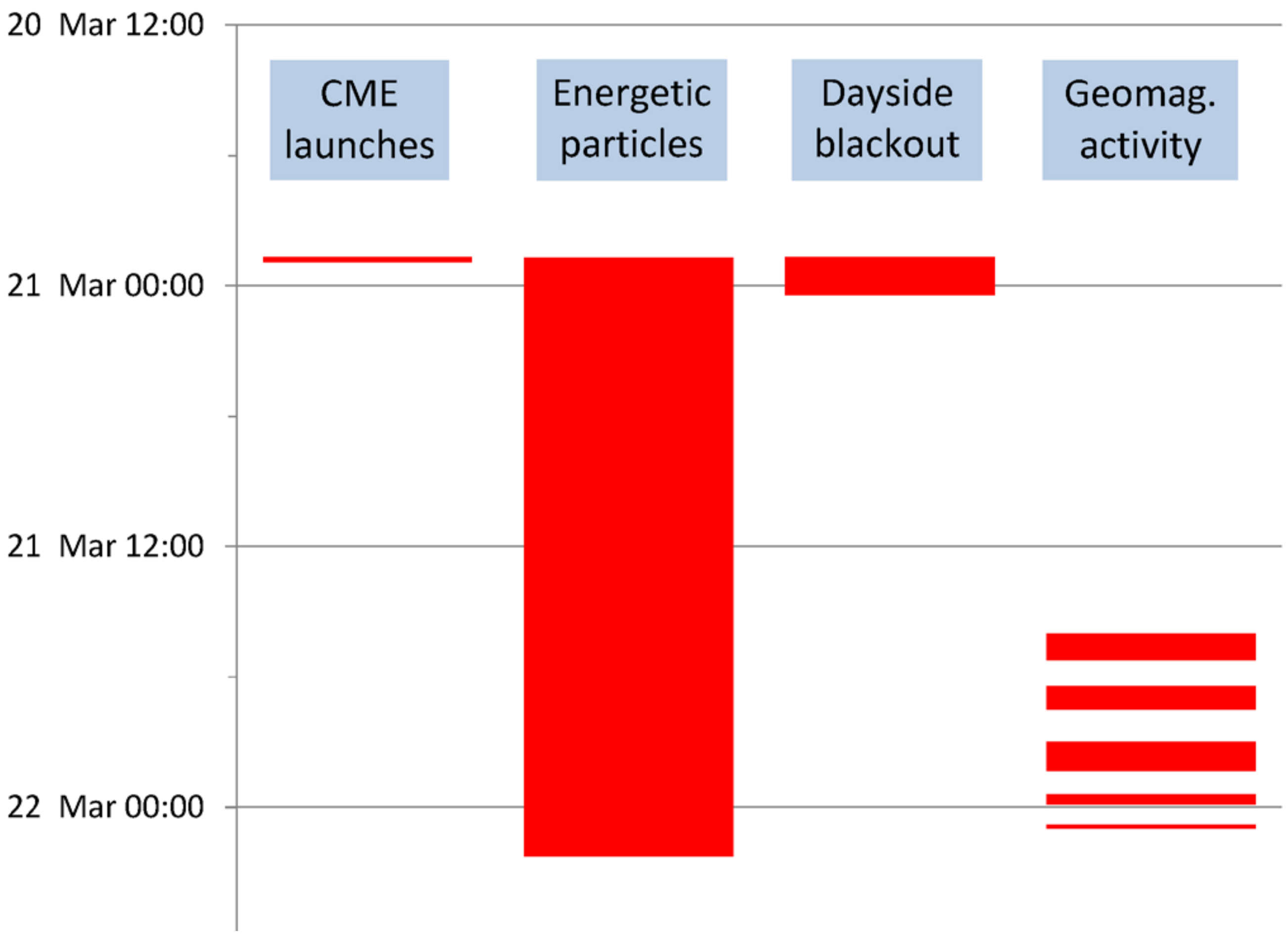
Severe space weather as an ensemble

- Severe SWx typically occurs:
  - as 1 to 2 week-long burst (e.g. Sep 2017) due to active region on Sun
  - multiple CMEs and SEP events as in Nov 1960 event (right) with impacts such as:
- Geomagnetic storms
  - GICs, disruption of many radio systems, satellite drag and charging
- Radiation storms
  - SEEs on satellites & planes, satellite radiation damage, radiation doses for aircrew and air passengers, HF blackout in polar regions



Above: an intense SEP event simultaneous with CME arrival on 12 November 1960

Simulated timeline for SWx event



Simplified version of Figure 7 in 2013 Royal Academy of Engineering report.

- Fast CME towards Earth launched late on 20 March
- Solar radiation storm from CME shock quickly reaches Earth
- Rad storm continues as the CME + shock travel to Earth
- CME takes 17 hours to reach Earth => geomagnetic storm
- Magstorm produces pulses of activity (substorms) as Earth's magnetosphere stores and releases energy from the CME.
- Solar flare associated with CME launch causes HF radio blackout (but UK on nightside, so not directly affected)

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Any questions so far?

And finally: … outcomes and thoughts for future

Outcome: SWx in National Risk Register

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Position of risks derived by Government on basis of expert advice, e.g. SWx scenarios

Impact					
Catastrophic (E)			Pandemics		
Severe (D)			Coastal flooding River flooding		
Moderate (C)		Droughts Animal diseases	Surface water flooding **Severe space weather** Poor air quality Antimicrobial resistance High consequence infectious disease	Storms Low temperatures Heatwaves Volcanic eruptions	
Minor (B)		Wildfires		Environmental disasters overseas	
Limited (A)			Earthquakes		
Probability in next year	< 1in-500	1-in-500 to 1-in-100	1-in-100 to 1-in-20	1-in-20 to 1-in-4	> 1-in-4

- Risk matrix from 2020 NNR
  - Environmental hazards & health
  - Wider assessment includes accidents & malicious events
  - Impact scale is logarithmic,
  - Position of risks guides investment in risk mitigation

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The future: Innovation and space weather

- Technological innovation is central to modern societies
  - at least since the advent of the Industrial Revolution
  - has delivered vast improvements in human well-being
- But has also opened up vulnerabilities to space weather
  - Initially had limited impacts on everyday life, e.g. electric telegraph (1847), telephones (1894), HF radio (1928), power grid (1940)
- But society now dependent on vulnerable technologies, e.g.
  - Electricity, not coal, in homes, offices and factories
  - Electronic communications, not paper mail
  - And many others ….
- Innovation will continue … so will space weather risks

Some important innovations

Autonomous navigation

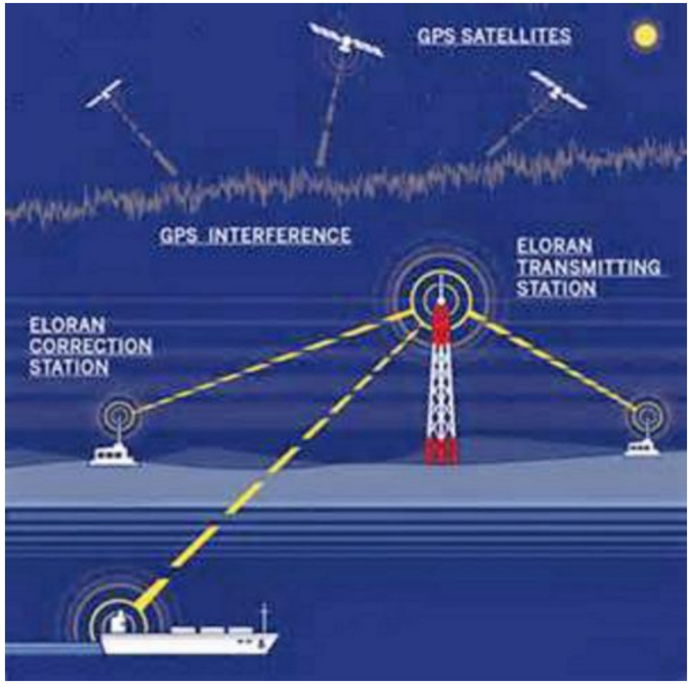
Green power?

5G

Cashless payments?

But need also to expand on what we know


Civil aviation



Resilient PNT
(position, navigation & timing)

Interconnects for electricity

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