Cambridge Centre for Risk Studies

Advisory Board Research Showcase – 13 January 2016

Solar Storm Helios Scenario

Centre for
Risk Studies

UNIVERSITY OF CAMBRIDGE
Judge Business School

Jennifer Copic
Research Assistant
Cambridge Centre for Risk Studies

Presentation Outline

- Project information
- What is a solar storm?
- Subject matter experts
- The scenario
- Macroeconomic modelling work to date

Solar Storm Project Overview

- Objective: To produce a detailed solar storm scenario with macroeconomic, insurance and investment portfolio impact estimations

- Timeframe: 30 Mar 2015 – 30 Mar 2016

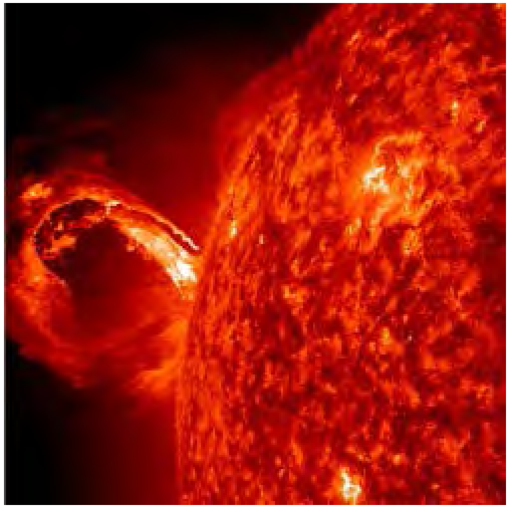
- Important Deliverable:
  - Detailed solar storm scenario
  - Macroeconomic impact estimations
  - Insurance industry impact estimations
  - Investment portfolio impact estimations
  - Report

- Similar stress test exercise run by Bank of England PRA

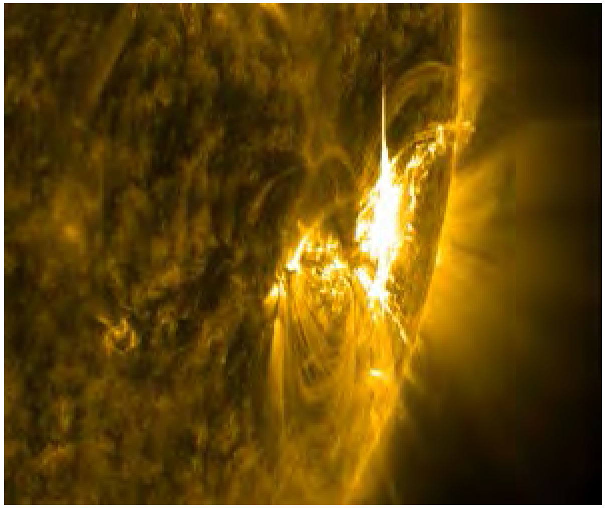
What is a solar storm?

- Coronal Mass Ejections (CMEs)
  - A massive burst of gas, matter, magnetic fields and electromagnetic radiation that is released into the solar wind
- X-class solar flares
  - A solar flare is a sudden flash of brightness observed near the Sun's surface
  - Flares can be accompanied by a spectacular coronal mass ejection
- Solar Proton Events (SPEs)
  - When particles emitted by the Sun become accelerated and enter the Earth's magnetic field

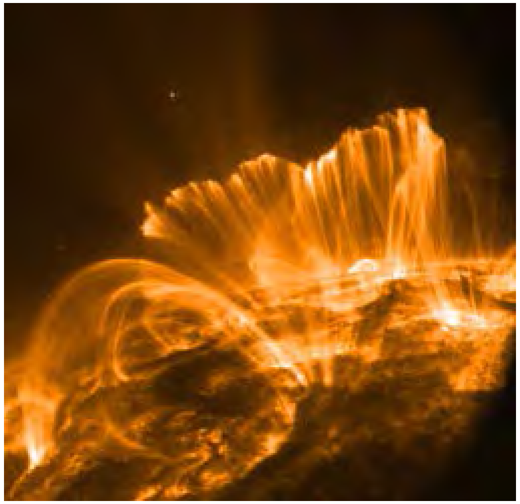
CME



Solar Flare

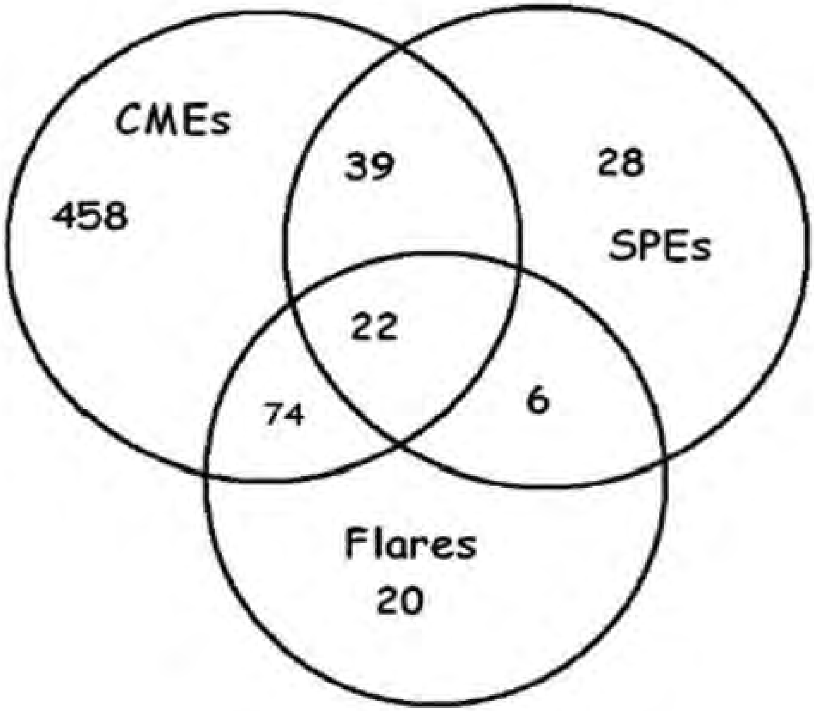


SPE



Space weather events

- Each phenomenon has a different probability and severity
  - It is essential that we decompose ‘space weather’ into these constituents to understand their effects on technology
- CMEs far outnumber the frequency of SPEs and flares
  - There is a higher probability of SPEs and flare taking place along side CMEs
  - There is a lower probability of SPEs and flares taking place in isolation or together
- **An extreme solar storm would feature all three of these phenomena**



(Odenwald, 2014)

Key Solar Storm Metrics

- Dst (Disturbance storm time) index, units of nano-Teslas (nT)
  - A measurement of earth geomagnetic activity and is widely used to characterise geomagnetic storms (Banerjee et al. 2012)
  - Thus a negative Dst index value indicates that the earth's magnetic field is weakened which is specifically the case during solar storms.
- Rate of change of magnetic fields, units of nT/min
  - The magnitude of the geomagnetic field change per minute is a better measure of ground effects, such as GICs
  - Also measured as dBh/dt
- There are many other metrics used in physics, maths and other sciences, such as Kp, Ap, G

Impacts of Space Weather on Earth

Impact of Space Weather on Earth	Warning Time	Duration	Primary Extreme Event Impact
Radio Blackout	None (speed of light)	Minutes to 3 hours	• Loss of HF radio communications on Earth's daylight side • Short-lived (minutes to an hour) loss of GPS • Interference on civilian and military radar systems
Radiation Storm	30 minutes to several hours	Hours to days	• Satellite operations impacted. Loss of satellites possible. • HF blackout in polar regions. • Increased radiation exposure to passengers and crew in aircraft at high latitudes
Geomagnetic Storm	17 to 90 hours	1 to 2 days	• Possible bulk electricity power grid voltage collapse and damaged to electrical transformers • Interference or loss of satellite and sky wave radio communications due to scintillation • Interference or loss of GPS navigation and timing signals • Satellite operations impacted

MacAlester, M. H., and W. Murtagh (2014), Extreme Space Weather Impact: An Emergency Management Perspective, Space Weather; 12, doi:10.1002/2014SW001095.

Historical Solar Storm Events

- 1859
  - Called the Carrington Event, a -850 nT CME hit Earth's magnetosphere and caused telegraph systems to fail
- 1989
  - CME and solar flare, knocked out power to large sections of Quebec for 9 hours
- 2000
  - Bastille Day Event, a very large CME and flare caused radiation storm on Earth
- 2003
  - The Halloween Event, a mix of CME and flares caused a one hour power outage in Sweden
    - The SOHO satellite failed temporarily during this storm and the ACE satellite was damaged[1]
- 2012
  - Similar size storm as the Carrington event, but it just missed Earth

1. http://www.nasa.gov/topics/solarsystem/features/halloween_storms.html
2. http://www.ourenergypolicy.org/wp-content/uploads/2014/01/Geomagnetic-Storms-Information-Sheet.pdf
3. http://www.leif.org/EOS/swe20162-Extreme-Space-Weather.pdf

Frequency and Severity

- Estimates of the likelihood of geomagnetic storms are not robust because of the short time-series (Hapgood, 2011)
- Riley (2012) suggest that the Carrington event has a 12% probability of occurring every 79 years
- Love et al. (2015) recommend
  – A storm larger than Carrington (-Dst = ≥ 850 nT) occurs about 1.13 times per century:
  – Moreover, a 100-year geomagnetic storm is identified as having a size greater than Carrington (-Dst = ≥ 880 nT)

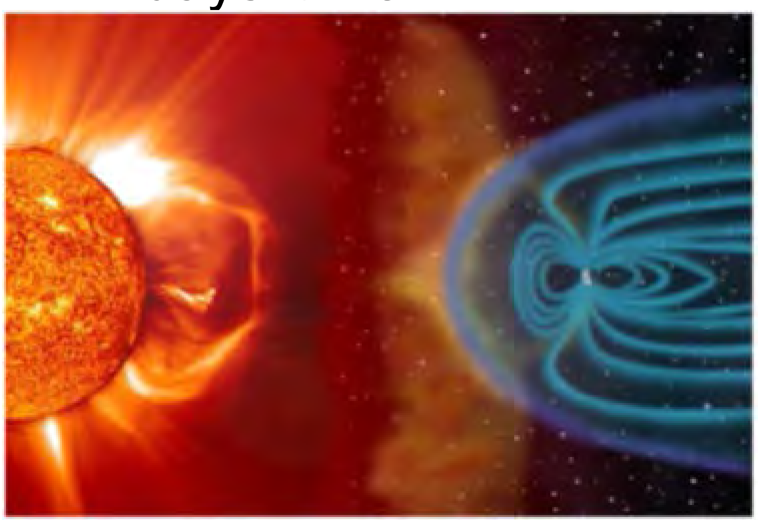
Subject Matter Experts on Space Weather and Impacts

- Hosted scenario development workshop on 29 July 2015

- Impacts on Satellites: Dr Richard Horne, British Antarctic Survey
- Space weather specialist, Heliophysicist: Dr Helen Mason, DAMPT
- Impacts on Earth, GICs: Dr Alan Thompson, British Geology Survey
- Impacts on Electricity Systems: Dr Andrew Richards, National Grid
- Impacts on rail transportation assets: Atkins
- US mitigation plans: NERC, DOE, Southern Co, Hydro One, Canada

Sequence of Events - Activity at the Sun

- Large group of sunspots show heightened activity
- STEREO A satellite detects activity and NOAA scientists take special interest and monitors
- Relatively moderate CME and flare emitted
  - CME speed = ~450km/s ± 500km/s
  - Flare size (M5) = $<5 \times 10^{-5}$ W/m^2
  - NOAA estimates a G2 category geomagnetic storm in 4 days' time



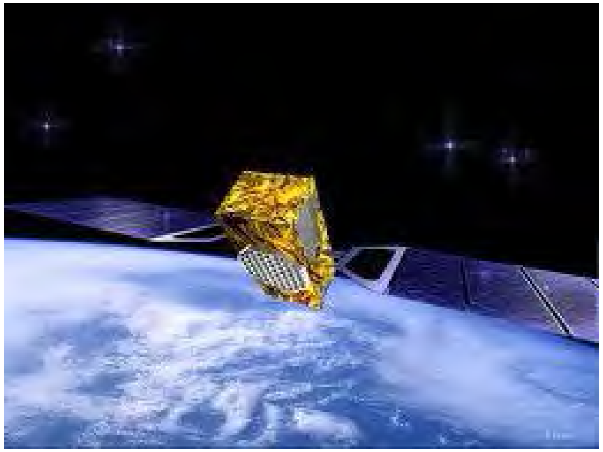
Kp Scale	NOAA G-Scale	National Grid Scale
Kp 9	G5	Category 5
		Category 4
		Category 3
		Category 2
Kp 8 to 9-	G4	Category 1
Kp 7	G3	
Kp 6	G2	
Kp 5	G1	
Kp < 5		

Source: Richards, Andrew. "Impacts of Extreme Space Weather on GB Electricity Network." 18 September 2015.

Sequence of Events - Activity at the Sun

- Sunspot group continues to be highly active
- Three days later, a large build up of energy due to an efficient magnetic reconnection process, leads to a giant high-mass CME being discharged towards Earth
  - CME speed = ~2000km/s ± 500km/s
  - Flare size (X20) = $2x10^{-3}$ W/m^2
  - Solar radiation storm = 10^4 MeV
- The interaction effect between the moderately-sized CME a number of days earlier, preconditions the interplanetary space
  - This lowers the ambient solar wind density, producing very little deceleration

Sequence of Events – Arrival at Earth



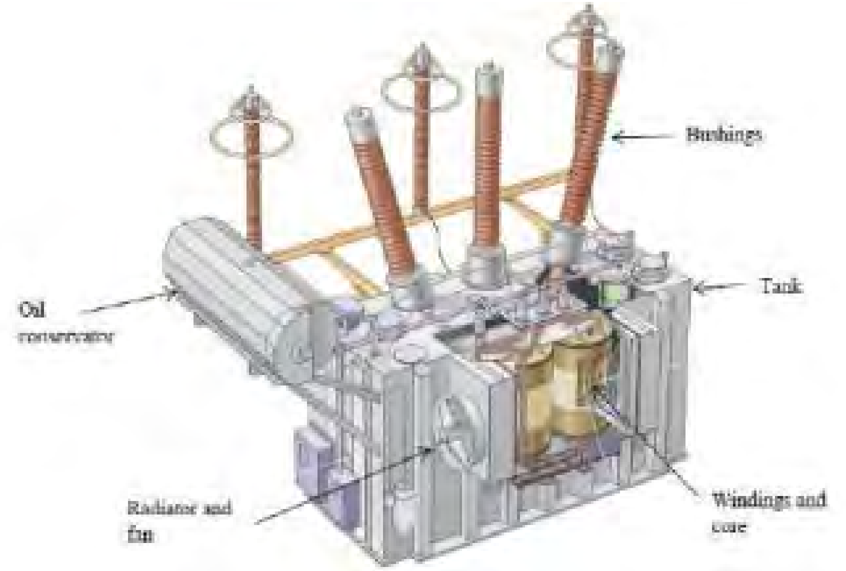
- Satellite systems provide 60 minutes warning of incoming CME
  - Bombards Earth's magnetosphere, forcing a reconfiguration between the southward-directed interplanetary magnetic field and Earth's geomagnetic field
- The second CME reaches Earth in only 20 hours
  - Consequently billions of tonnes of gas containing charged particles intensify the shock compression
  - Particles are accelerated along the magnetotail, back towards Earth being deposited in the auroral ionosphere and magnetosphere on the night side of the Earth, directly above North America
  - Dst measurements = ~-1000nT
  - dB/dt measurements = ~5000nT/m at 50° magnetic latitude

Sequence of Events – Arrival at Earth

- Auroral oval forced equatorward by 15° magnetic latitude
- Numerous substorms
  - Take place every few hours on the dawn-to-dusk side of the Earth due to the highly dynamic nature of the auroral electrojet roughly 100km above ground
- Geomagentic effects
  - Rapid change in the magnetic field rate-of-change down to 50° magnetic latitude
  - Ring current intensifications take place down to 20° magnetic latitude

Sequence of Events – Effects on the Ground

- Intense electrojet and ring current activity
- Key electricity network assets are placed under significant strain due to ground induced currents (GICs)
  - For the UK, the RAE (2013) report estimates 11 transformers could be damaged from this size storm
    - Out of a total of 600 transformers, this corresponds to roughly 2%
- Manufacturing of replacement transformers take 8-16 weeks to replace (if available)
- Additional damage affects engineered systems
  - Damage caused to oil and gas pipelines
  - Increased corrosion rapidly reduces asset lifetime



Note: Workers move wires, lights, and poles to transport a 340-ton power transformer, causing hours of traffic delay.

Source: Pittsburgh Live News, December 2011.

Image Source:
DOE. Large Power Transformers and the US Electric Grid. April 2014 Update. Page 5.

Sequence of Events – Aftermath

- Electricity failure leads to
  - Transportation disruptions
  - Intermittency in digital communications
  - Interrupted food production and processing
  - Lack of potable water
  - Lack of waste processing
- Electromagnetic bursts from the solar flare (NOAA R5 radio blackout) and severe (S4) radiation storm cause
  - Interruption of HF radio communications on the sunlit side of the Earth for a number of hours
  - Unavoidable radiation absorption by astronauts and aviation flight crews
  - Radio absorption and wireless interference, disrupting a range of communication systems
  - Low-frequency navigation signals to cease on the sunlit side of the Earth, causing a loss of positioning
  - The aviation and maritime sectors to lose contact with planes and vessels for a number of hours
  - Two large container ships navigating close to shore run aground as a consequence of these interruptions
  - Chaos at airports around the world

CRS Solar Storm Scenario Variants

Scenario	CME Number	Activity	Size	Length of Power Outage (to return to 100% capacity)
S1	1	Only one large and fast CME hits Earth	dB/dT = ~3000nT DST= ~ -600nT	3 months
S2	1	A moderate-sized CME first hits Earth	dB/dT = ~1500nT DST= ~ -400nT	6 months
	2	A very large and fast CME then hits Earth	dB/dT = ~5000nT DST= ~ -1000nT	
X1	1	A moderate-sized CME first hits Earth	dB/dT = ~1500nT DST= ~ -400nT	12 months
	2	A very large and fast CME then hits Earth	dB/dT = ~5000nT DST= ~ -1000nT	
	3	27 days later a moderate-sized CME hits Earth	dB/dT = ~1500nT DST= ~ -400nT	

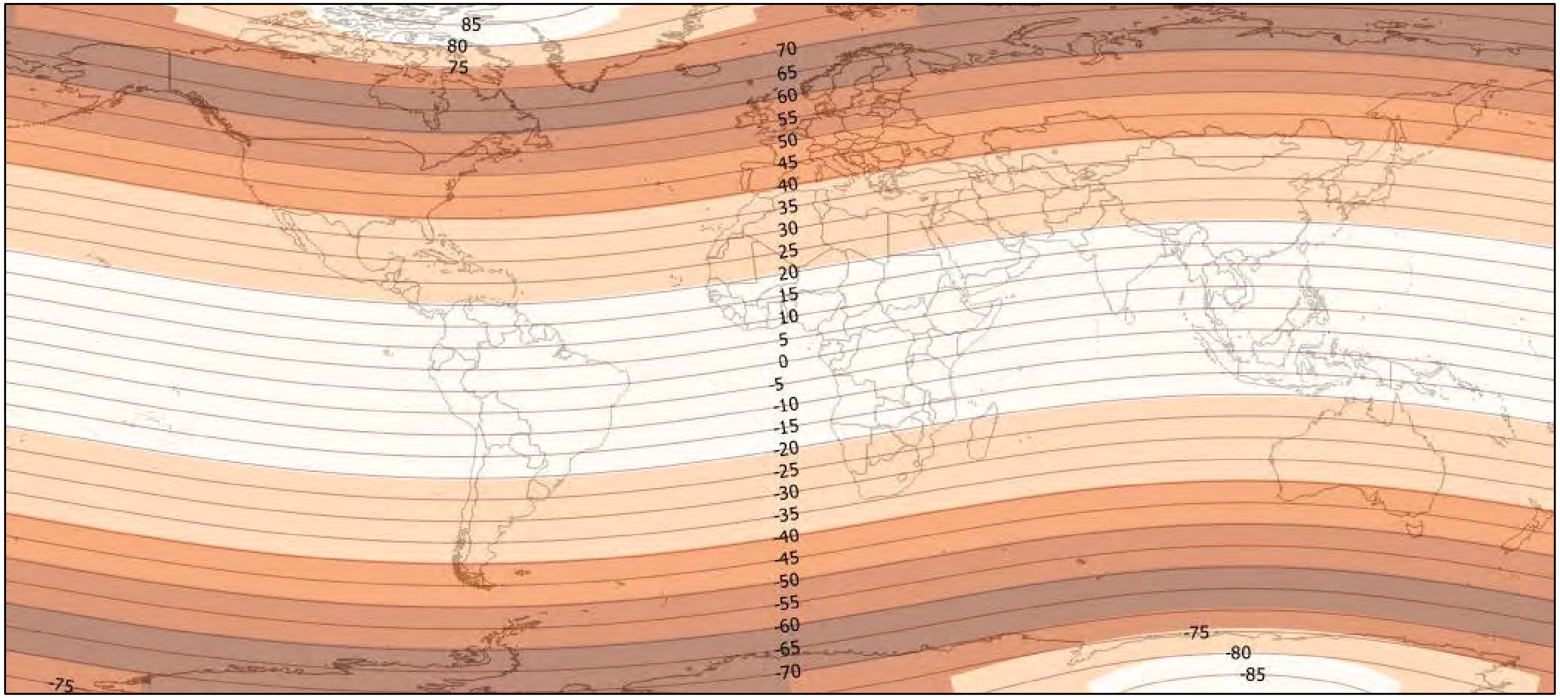
Historic Geomagnetic Latitude of Aurora Observations

- Several papers by Silverman analyse historic aurora observations for geomagnetic storms
  - To determine the minimum geomagnetic latitude where sightings occurred

Date	Estimated minimum Dst index values	Geomagnetic Latitude of Aurora Observations, most equartorward latitudes unless otherwise stated
Aug-Sept 1859	-850 nT	22-23°, through must activity was observed in this range 30-35° (Silverman, 2008) or around 41-48° (Pulkkinen, 2012)
Oct 1870		28° (Silverman, 2008)
Feb 1872		20°, though an aurora was seen as low as 10° (Silverman, 2008)
Sept 1909		30-35° (Silverman, 1995)
May 1921		30-35° (Silverman and Cliver 2001) or around 40° (Pulkkinen, 2012)
March 1989	-589 nT	40° (Pulkkinen, 2012)
Oct 2003	-383 nT	30-35° (Pulkkinen, 2012)

- From this we see that lowest equatorward latitude where auroras are observed is 20°
- Pulkkinen (2012) suggests that the threshold geomagnetic latitude is set at 50° for conservative estimates and 40° for less conservative estimates

Cambridge Global Geomagnetic Storm Threat Map

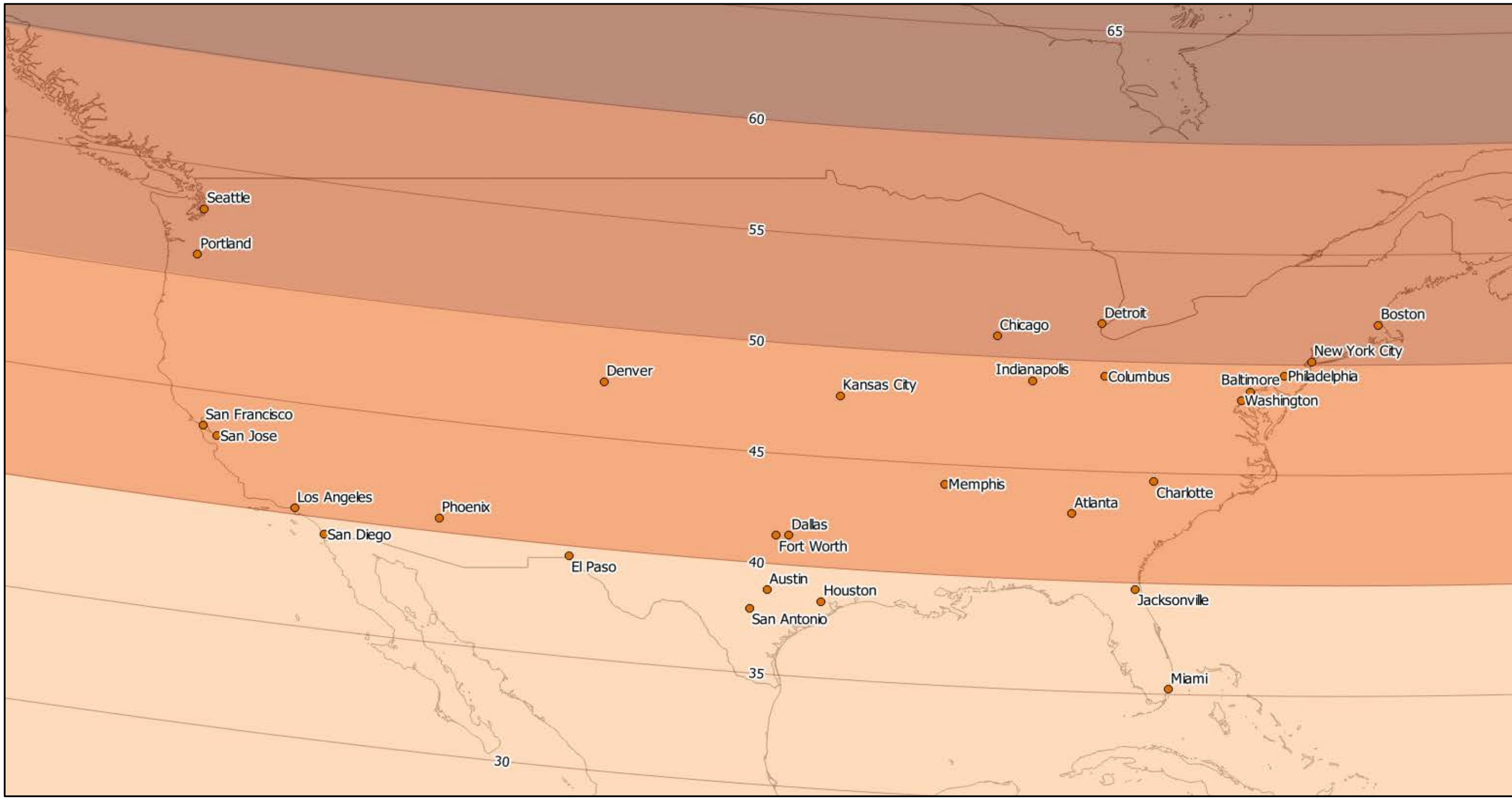


World population	S1	S2	X1
Exposed to storm	11%	22%	62%
Not exposed to storm	89%	78%	38%

- 38% of the world population is not exposed to the storm in any scenario variant

Notes: The contour lines on this map were generated using the World Magnetic Model (WMM) 2015 shape file from NOAA (Chulliat, 2014).

Cambridge USA-Focused Geomagnetic Storm Threat Map



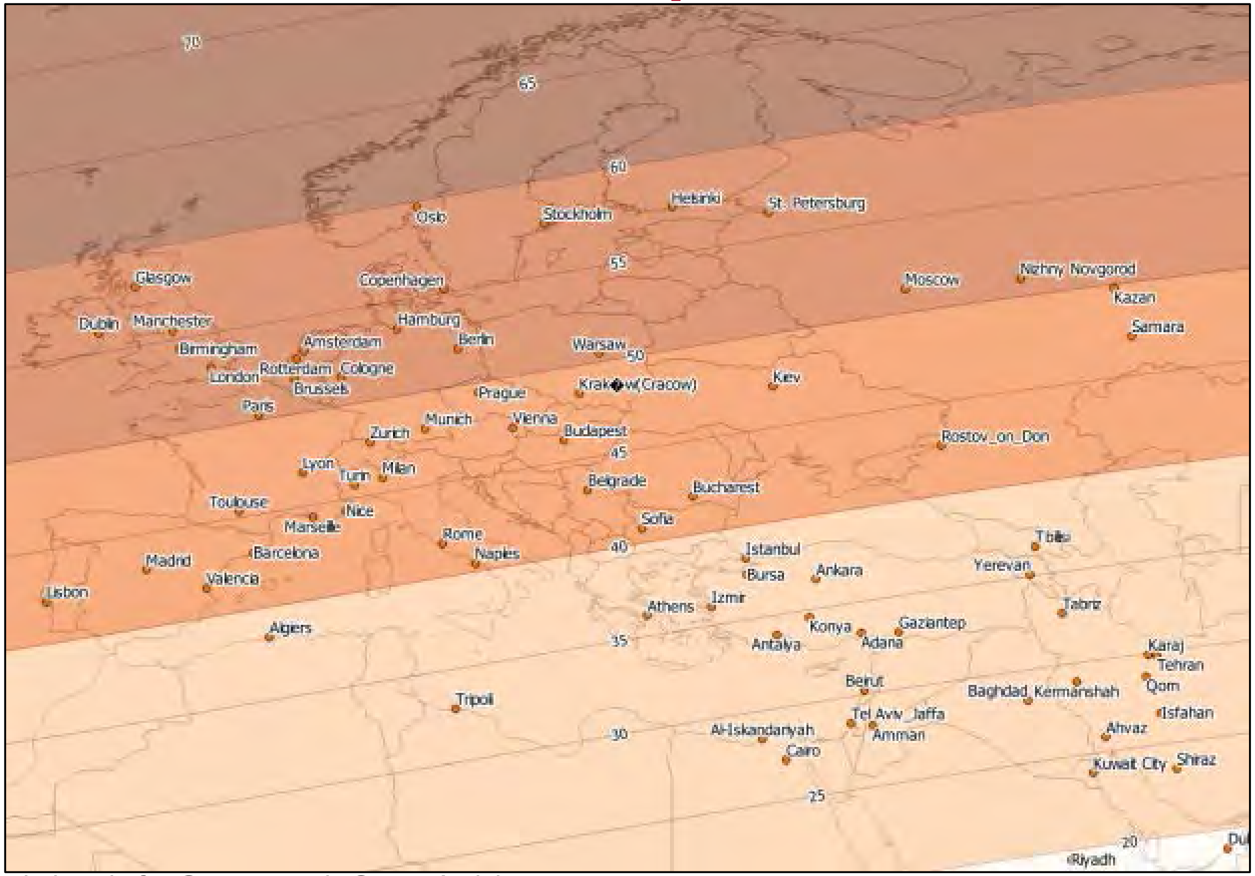
Geomagnetic Latitude bands for Geomagnetic Storm Activity

- Auroral Oval Zone – S1
- Severe Geomagnetic Storm Activity – S1
- Extreme Geomagnetic Storm Activity – S2
- Very Extreme Geomagnetic Storm Activity – X1
- Unlikely Zone for Geomagnetic Storm Activity

UNIVERSITY OF CAMBRIDGE Judge Business School | Centre for Risk Studies

Notes: The contour lines on this map were generated using the World Magnetic Model (WMM) 2015 shape file from NOAA (Chulliat, 2014).

Cambridge Europe-Focused Geomagnetic Storm Threat Map



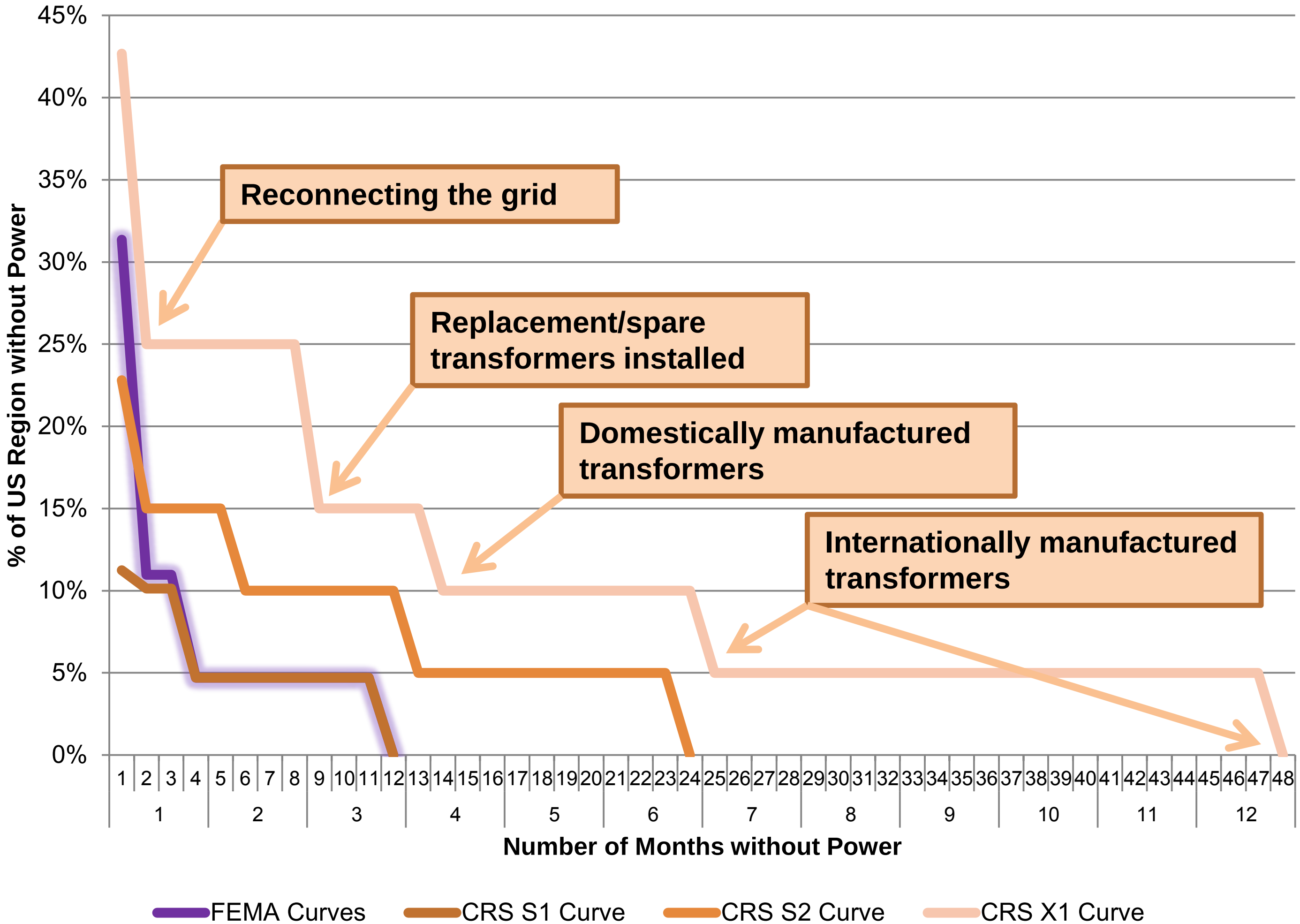
Geomagnetic Latitude bands for Geomagnetic Storm Activity

- Auroral Oval Zone – S1
- Severe Geomagnetic Storm Activity – S1
- Extreme Geomagnetic Storm Activity – S2
- Very Extreme Geomagnetic Storm Activity – X1
- Unlikely Zone for Geomagnetic Storm Activity

UNIVERSITY OF CAMBRIDGE Judge Business School | Centre for Risk Studies

Notes: The contour lines on this map were generated using the World Magnetic Model (WMM) 2015 shape file from NOAA (Chulliat, 2014).

Solar Storm Scenario Electricity Restoration



Scenario Variant	Outage, months
S1	3
S2	6
X1	12

Note: US curves only, by all scenario variants

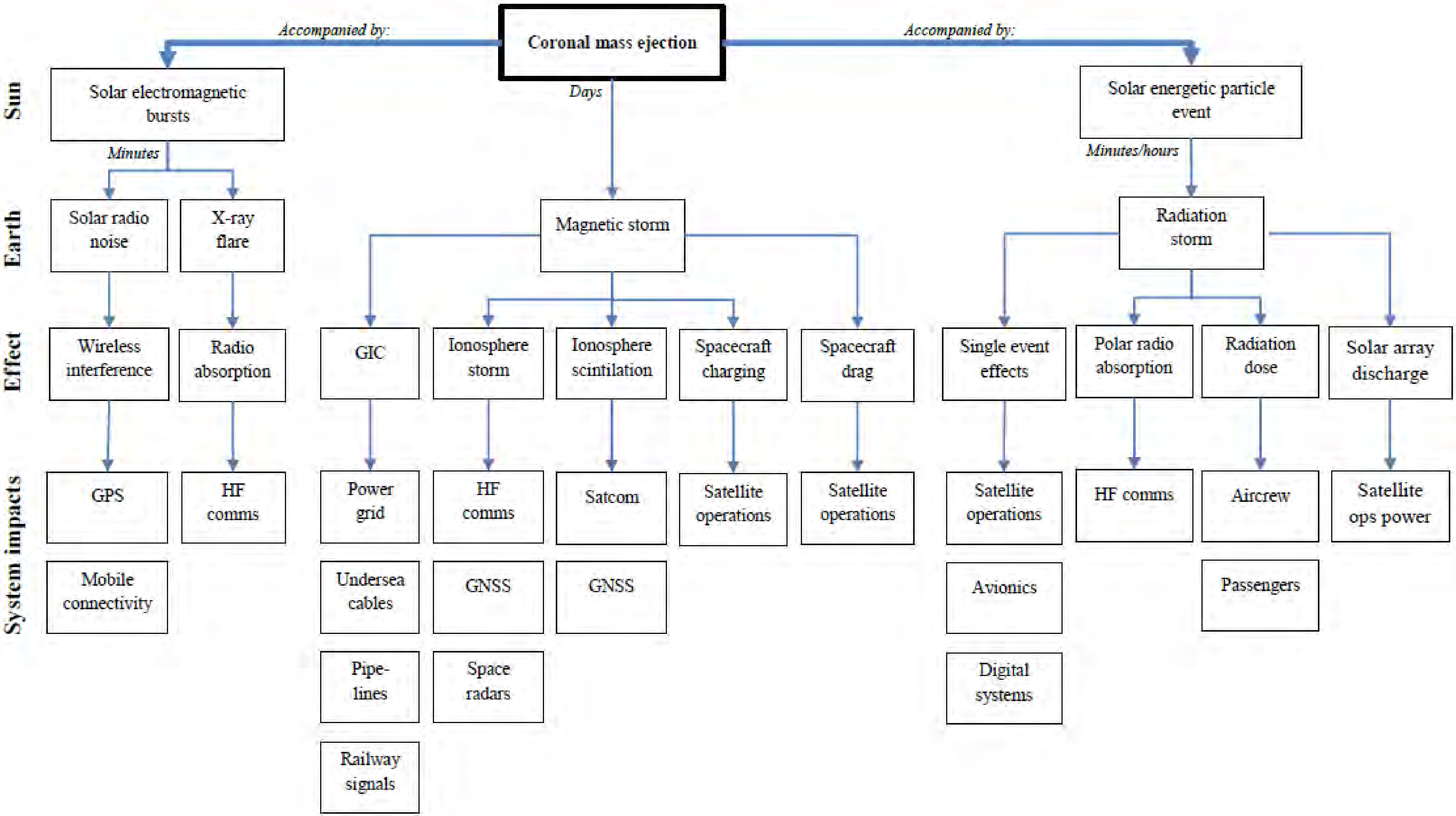
UNIVERSITY OF CAMBRIDGE Judge Business School | Centre for Risk Studies

Factors Influencing Outage Severity

Factors increasing outage time	Factor decreasing outage time
Decreased warning time / ability to prepare	Increased warning time / ability to prepare
Transformer design (highly specific) (some more at risk than others)	Stock of spare transformers (onshore and offshore)
Transformer manufacturing bottleneck	Expedited response due to strong governmental intervention
Transformer transportation time	Reconfiguring the electrical grid Expedited transport permits
Large indirect critical infrastructure failures	Few indirect critical infrastructure failures
Unanticipated damage to electrical assets	GIC effects take place where anticipated

Based on subject medium experts interviews and literature review

Extreme Space Weather Impact Tree



(Adapted from Hapwood et al. 2012)

UNIVERSITY OF CAMBRIDGE Judge Business School | Centre for **Risk Studies**

Modelling the Impacts of Solar Storms

Macroeconomic

- Estimate the loss to the global and US economies
- General Equilibrium Model (GEM)
- IO Interdependency Model
- Global and US specific estimates

Insurance Industry

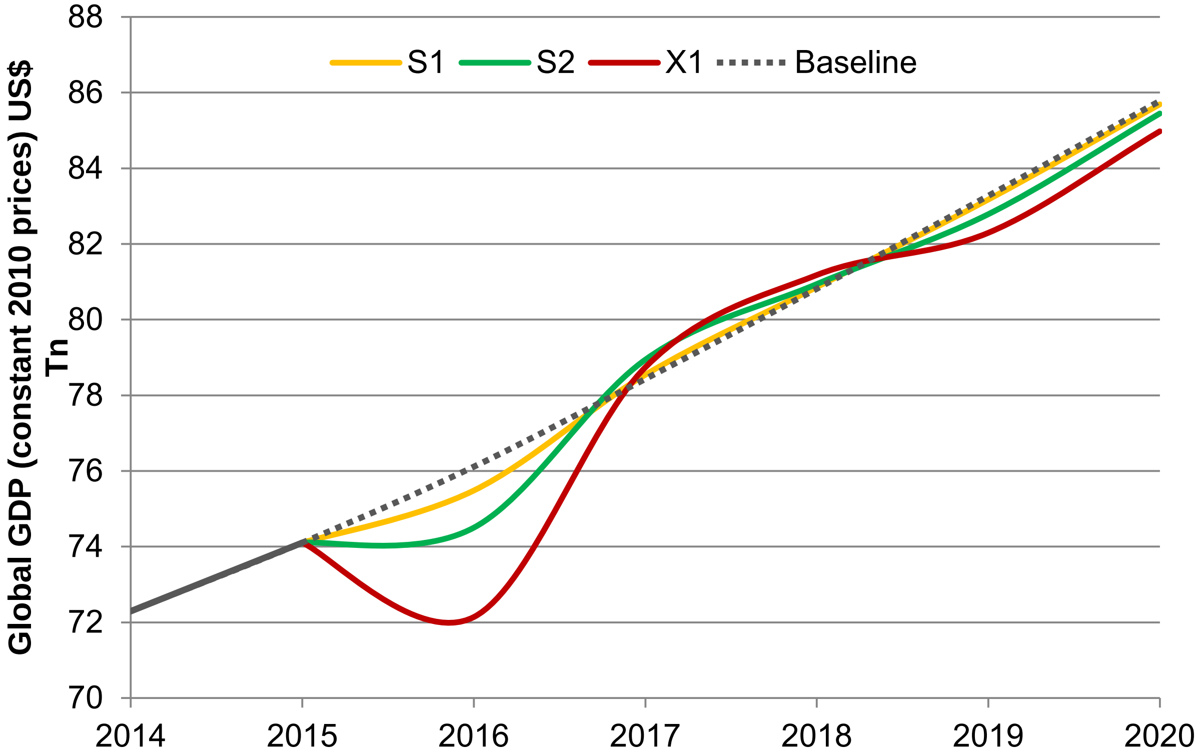
- Estimate the loss for various lines of business from scenario
- US industry focused loss estimates

Investment Portfolio

- Estimate the loss for various investment portfolios using results from the GEM model
- Diversified and non-diversified portfolio loss estimates

Macroeconomic Modelling

- *Oxford Economic Model - Initial results*



Scenario Variants	5-year Global GDP@Risk, US$ Tn (From OEM analysis)
S1	$0.7 (0.2%)
S2	$1.8 (0.4%)
X1	$5.1 (1.3%)

- Input-Output Modelling
  - US focused interdependency loss estimation
  - Development of supply-side global macroeconomic input-output model
    - See Miller & Blair (2009) for a comprehensive overview
    - Utilises the World Input Output Database for 41 global regions

Insurance Industry Loss Estimation

Claimant Type	Coverage
Power transmission companies	Property damage (EHV transformers)
	Business interruption (EHV transformer damage)
Power generation companies	Property damage (step-up transformers)
	Business interruption (step-up transformer damage)
Rail transportation companies	Property damage (step-down transformers)
	Business interruption (step-up transformer damage)
Companies that loss power	Perishable contents
	Contingent business interruption – suppliers extension/service interruption
	Liability
Companies indirectly affected by power loss	Contingent business interruption – critical vendor
	Liability
Satellite owners	Property damage (satellites)
	Business interruption (satellites)
Companies that loss satellite service	Contingent business interruption – suppliers extension/service interruption
	Liability
Companies indirectly affected by satellite loss	Contingent business interruption – critical vendor
	Liability
Accident and Health	Bodily injury (during the storm or increased radiation?)
Workers Compensation	Bodily injury (during the storm or increased radiation?)
Homeowners	Household contents
Speciality	Event cancellation

Insurance loss estimation data components:

- Policy structure
- Deductibles
- Limits
- Exclusions
- Examples of claims
- Etc.

Mitigation Plans

- Operational mitigation
  - Relies on early notification systems
  - Increase spinning reserve and reactive power
  - Reduce/remove the load on key transformers
  - Unlikely that equipment will be turned off
- Engineering mitigations
  - Hardening the transmission equipment to prevent GICs from flowing through it, more resistive transformers
    - Requires expensive capital improvements/replacements
- Progress by geography
  - UK: replacing about 10 transformers per year, currently have 50% more resistive
  - US: NERC is still in review period of the engineering/thermal assessments requirement
  - Australia: has recently done solar storm studies of its electricity system
  - Nordic Countries: well prepared
  - Japan: just starting to look into engineering improvements, but very concerned of the threat
  - China: just took first geomagnetic measurements this year
- Improving solar storm forecasting and upgrading solar storm early warning/alert systems
- Use smarter grid technologies to improve situational awareness such as automatic voltage stabilisation and other automatic protective measures
- Coordinated policy action

Centre for
Risk Studies

UNIVERSITY OF
CAMBRIDGE
Judge Business School