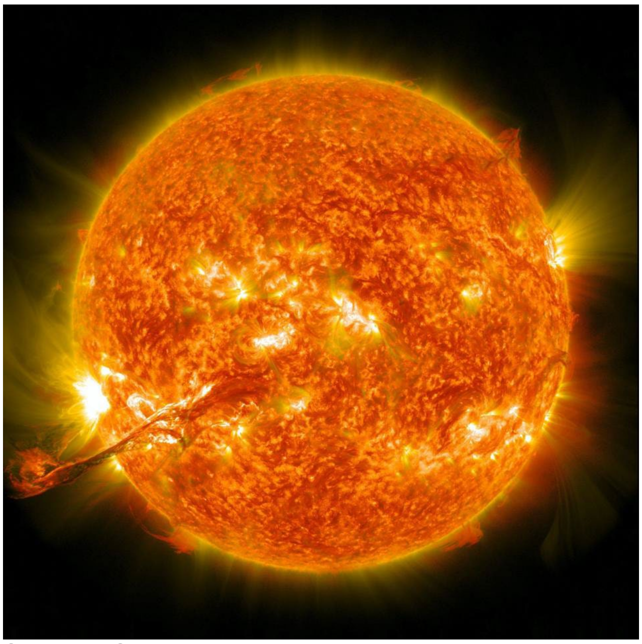
Solar Storms and Cybersecurity



Source: NASA solar storm hitting Earth

When it comes to space weather, Jake Bleacher, chief exploration scientist for NASA's Human Exploration and Operations Mission Directorate, said, "There is no bad weather, just bad preparation. Space weather is what it is—our job is to prepare."[i]

"Solar flares are a significant threat to space-based assets, communication networks, and global power grids. The development of an accurate method to predict coronal mass ejections is not currently available as a tool." Col. David Brewer, USAF AIR FORCE FUTURES[ii]

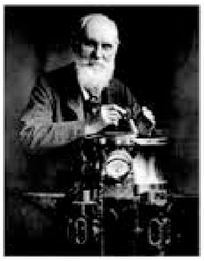
Overview

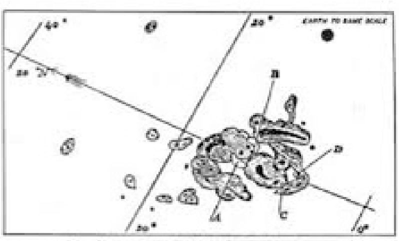
There is uncertainty around the extent of a domino effect on human society should a geomagnetic disturbance from the sun cause a catastrophic solar storm to make direct landfall on earth. Solar flares, say NASA,[iii] will increase and cause problems on Earth through 2025.[iv] History of sun activity events goes back 440 years, with no big event in the space age and digitised world. Climate change and cyber risk dominate the risk register; so as we move to a greener, more data-secure world, a natural catastrophe from the sun, causing power outage and loss of digital services, could catch the world off guard, setting back objectives with widespread business interruption.

The sun is a magnetic star and its gravity keeps the earth in orbit around it. Basic solar physics teaches us that the sun has a greater magnetic field than Earth and a multitude of perils can emerge from disruption of electricity transmission, transportation, and satellites through geomagnetic imbalance.

In May 2018, a global insurance broker launched PathogenRX,[v] a protection product against pandemic risks, utilising an event trigger from epidemic risk specialist data and backed by global reinsurance capacity. The parties warned of the serious business interruption impact infectious disease outbreaks can have, and the importance of bringing risk capital directly to the corporate market via the reinsurance industry to reduce the protection gap. There were no claims filed from this policy because no company bought the cover after the launch in 2018. Post-pandemic demand is now soaring for this type of product.

Must we risk a repeat of this scenario with space weather and geomagnetic storms? Currently, solar storm exposure is not contemplated in insurance policies, nor exists as silent cover as happened with cyber, where the need for stand-alone policies arose. The benchmark and baseline lie in an 1859 event, a near miss in 2012, and predictive activity of the sun from 2019 through 2030. Astronomer Richard Carrington observed the 1859 event in September of that year and made a drawing of the sunspots visible in the event which now bears his name.





Solar sketch, September 1, 1859, by R. C. Carrington

Source: Wikipedia

Another major event in 1921 was also attributed to a geomagnetic storm and caused infrastructure damage—which in 1859 was primarily telegraph equipment, and in 1921, telephone, electrical, and railroad systems. Events in 1989 and 2003 in the space age and internet era resulted in significant damage to power grids, transformers, and satellites. These episodes demonstrate that geomagnetic disturbances can disrupt electrical infrastructure and communication lines; specifically, the 1989 event caused a power outage in northeast Canada[vi] well before the establishment of the modern internet infrastructure.

The latest 11-year activity cycle of the sun peaks in 2025 and there have been numerous small events leading up to this peak, including observed activity as recently as December 14, 2023. There is no reason for alarm, but this activity begs the question of when a severe event does happen—along the lines of climate, cyber, pandemic, and other emerging risks—is there any mitigation and preparedness in place? The documented worst-case scenarios by scientists and researchers show serious economic losses of global power grid interruption into trillions of dollars.[vii] Although a complete “internet apocalypse” as discussed in social media is highly unlikely, considerable episodes of internet downtime must be considered.[viii]

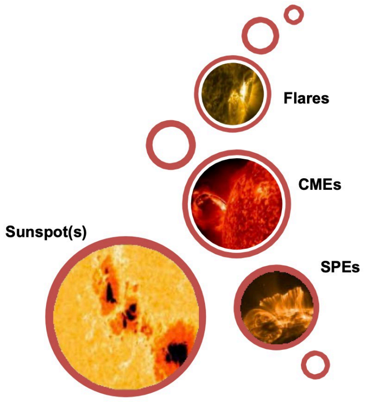
Solar storm events have only been measured for 440 years, but carbon dating identified events before that, with results of a catastrophic level thousands of years ago, greater in magnitude to 1859. The effect of this on today’s digitised world would be concerning to governments, re/insurers, power grid transmission control operators, space agencies, and the transport industry. This paper looks at mitigation, risk transfer, and predictive analysis and how artificial intelligence technology can address early warnings of these solar storms. It also looks at potential insurance-linked securities (ILS)[ix] solutions as solar storms have a severity rating system which can be combined with business interruption losses into a parametric solution.

Despite decades of research, scientists need to know more about sun activity and resulting complexities of the space weather. The occurrence of a high severity-rated solar storm in December 2023, which did not make direct landfall on Earth, serves as a reminder of this emerging risk and the potential impact of solar activity on technologically and satellite dependent societies. As scientists continue to monitor the sun's activity using advanced AI techniques, this event underscores the importance of preparedness for space weather events and the need to fund ongoing research in solar physics. Much of the bibliography dates back to the last solar activity cycle, but governments and insurance industry are now taking note.

Bibliography

Date	Title	Author
2010	Space Weather[x]	Lloyds of London
2011	Future Global Shocks[xi]	OECD
2011	Geomagnetic Storms Evaluation of Risks[xii]	Department of Homeland Security
2014	Space Weather and Financial Systems: Findings and Outlook[xiii]	European Commission's Joint Research
2016	Helios Solar Storm Scenario[xiv]	Cambridge University Judge
2021	Space Weather Preparedness Strategy[xv]	UK Government
2021	Solar Superstorms: Planning for an Internet Apocalypse[xvi]	Sangeetha Abdu Jyothi University of California, Irvine, and VMware Research
2023	Solar Storms: A New Challenge on the Horizon[xvii]	European Council

Definitions



Source: Helios Solar Storm Scenario

Aurora—A substorm in a geomagnetic disturbance that injects energy into the high latitude upper atmosphere, giving rise to coloured lights and arcs across the sky.

Carrington Event—The first observed solar storm event in 1859 that involved sunspot formations and auroras. Used as the benchmark when modelling solar storms, but many researchers look at the July 2012 near-miss as a better baseline in the modern era.

Coronal mass ejection (CME)— Large expulsions of plasma and electromagnetic material from the sun's corona that could hit Earth, causing magnetic disturbances.

Electromagnetic pulse (EMP)— An intense pulse of electromagnetic radiation, similar to that generated by a nuclear explosion and occurring high above Earth's surface.

Geomagnetically induced currents (GIC)— Quasi-direct currents resulting from solar storms that can flow into transmission lines, causing surges and damage to transformers.

Miyake events—Use of carbon dating and isotype finding in ice cores and tree rings to identify catastrophic solar events of the distant past that may provide intelligence as to what would happen if this occurred today.

Solar cycle 25—The current solar cycle from 2019 to 2030, where activity on the sun is increasing. The solar maximum is expected in July 2025, with a peak of 115 sunspots.

Solar particle events (SPE)— Energetic particles emitted by the sun in a solar wind become accelerated either close to the sun during a flare or in interplanetary space by a CME.

Solar flare—A burst of intense high-energy radiation from the sun's surface, associated with sunspots causing electromagnetic disturbances on the earth.

Solar maximum/minimum—Beginning of a solar cycle is the minimum when sun has least sunspots and the middle of the solar cycle is the maximum when the sun has most sunspots.

Solar cycle—The sun's magnetic activity follows an 11-year solar cycle where the intensity of the sun's magnetic field manifests itself as increasing numbers of sunspots.

Solar winds—An unrelenting stream of material bearing down on Earth from the sun.

Space weather—Disturbance of the upper atmosphere in near Earth space.

Sunspots—Active solar storm areas on the sun where the magnetic field is about 2,500 times stronger than Earth. Sunspots can affect Earth by solar radiation, solar flares, and CMEs.

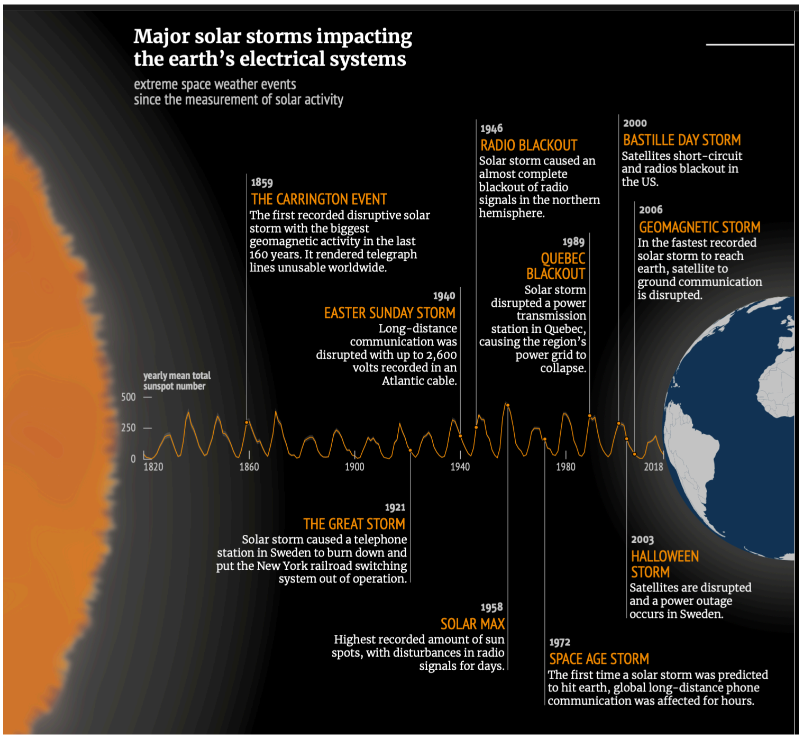
Solar Storm Events of Note (key ones marked in yellow)

Date	Event	Significance
660 BC		Isotopes found under the Greenland ice sheet show high magnitude storm.
775 AD	Miyake Event	Carbon and other isotopes found in tree rings and Antarctica ice cores indicating large early solar storms.
March 1582	The Great Magnetic Storms of 1582	Prolonged extreme geomagnetic storm; extensive aurora.
February 1730		Comparable to 1989 intensity, but less severe than the Carrington baseline.
September 1859	Carrington Event	Most extreme event observed; caused telegraph outage, electrical shocks, and fires. Triggered compass needle fluctuations and aurora. Used as baseline. Depleted the ozone layer by 5 percent.
February 1872	Chapman-Silverman Storm	The Chapman-Silverman event, the most intense geomagnetic storm ever recorded, brought auroras to the Sahara.
October 1903	Solar Storm of Oct.-Nov. 1903	Extreme solar storm occurring in a solar minimum, causing aurora, disruption, and telegraph damage.
September 1909	Geomagnetic Storm of 1909	Comparable in intensity to March 1989.
May 1921	May 1921 Geomagnetic Storm; New York Railroad Storm	Extreme storm, low-latitude aurora, burning out fuses, disruptions to telephone stations, electrical apparatus with fires, and communication blackouts. Knocked out the entire signal and switching system of the New York Central Railroad.

January 1938	Fatima Storm 1938	Massive solar storm with bright aurora. Electrification was in its infancy, so no significant damage.
March 1940	March 1940 Superstorm	Triggered by solar flare; widespread disruptions to U.S. communication systems.
May 1967	Great Storm of May 1967	Blackout of polar surveillance in the Cold War, nearly triggering conflict.
August 1972	August 1972 Solar Storm	Extreme solar particle event hazardous to human spaceflight; interrupted TV signals and detonated U.S. Navy mines in Vietnam War.
March 1989	March 1989 Geomagnetic Storm	Most extreme storm of the space age, causing power outage for 5 million in the province of Quebec, Canada for 9 hours and disrupted U.S. power grid. Radio transmissions were scrambled.
November 1991		Intense solar storm 50% intensity of March 1989; aurora low as Texas.
July 2000	Bastille Day Storms	Caused radio blackout in the U.S.
April 2001		Large solar flare hitting spaceborne solar monitoring equipment; just missed Earth.
October 2003	Halloween Solar Storms X45	Large intensity solar storm that just missed Earth but overloaded satellite sensors measuring it. Blackout in Sweden for 50,000 customers and damage to transformers in South Africa, causing their removal from service.
July 2012	July 2012 Solar Storm	Fast CME directed away from Earth with full characteristics of a super solar storm. Considered a near miss of catastrophic proportions.
March 2015	St. Patrick's Day Storm	Largest geomagnetic storm of solar cycle 24.
September 2017	September 2017 X9.3	Large solar flare. Aviation, ham radio, shipping, and emergency services unavailable for 8 hours.
February 2022	Space-X Starlink Launch Failure	Solar particle and geomagnetic storm that affected the launch and re-entry of low-Earth orbit satellites.
December 2023	Solar 25 Cycle X 2.8	Solar storm causing radio blackout in South America.

Source: assembled by author from Wikipedia

The following diagram summarises the main solar storm events known since 1959. Given this history it can be concluded that these solar storms occur more often than may be realised and the effect of these events occurring today would be underestimation.

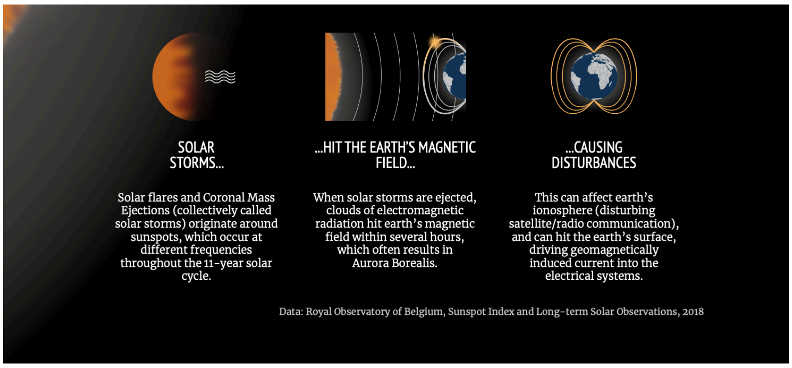


Source: Royal Observatory of Belgium, Sunspot Index and Long-Term Solar Observation, 2018

What Is a Geomagnetic Storm?

The sun frequently experiences solar storms that produce coronal mass ejections (CME), an explosion of billions of charged particles and plasma into space. These move quickly and can arrive on Earth 30 to 60 minutes after the CME is detected. The charged particles cause geomagnetically induced currents (GIC) on the ground and have effects similar to an electromagnetic pulse (EMP) that can cause significant damage to extra-high voltage transformers. The higher northern latitudes are more severely affected but can expand south for larger events. The Carrington Event[xviii] was a massive geomagnetic storm.

The CME interacts with the magnetic field surrounding the Earth, causing it to weaken and leading to distorted behaviour on Earth to electrical equipment and compasses. It also results in aurora borealis[xix] substorms with bright coloured lights, which are often observed in both northern and southern hemispheres, and in big events in low-latitude areas or close to the equator.



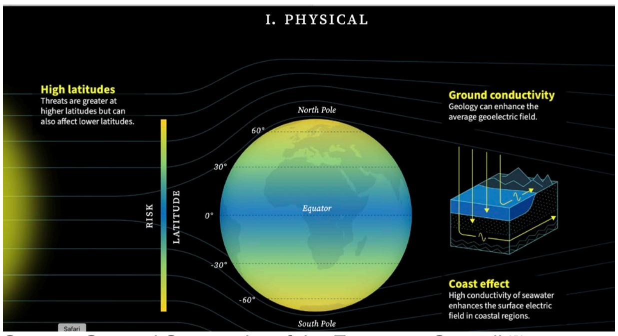
Manifestations of solar wind appear on Earth as aurora substorms at high north and south latitudes (Arctic or Antarctic) where the solar wind-charged particles are funnelled and accelerated by the intense magnetic fields near the poles and collide with the upper atmosphere, emitting visible light. The watching public should understand the severity and consequences of these emissions and realise it is not just a beautiful sight when they travel to observe the aurora. The photo below is from the 1989 Quebec storm.

Source: Stephen Tripp

CMEs have the most effect on Earth as GIC enters unprotected electrical grids. Solar flares and SPEs, which can happen in parallel with CMEs, emit space radiation, which is deflected back into space by the Earth's natural shield but can affect airplanes, drones, and satellites.

Many satellites are hardened to radiation and some probe the sun to measure the storms. However, drag on low-orbit satellites from solar storm density can cause them to fall from the sky unless the orbit is adjusted.

A Miyake or Carrington-sized CME event today could inflict serious damage on Earth as it has an affinity for higher latitudes and coastal and geological conductivity regions covering many of the world's densely populated cities and global supply chains. CMEs can occur close together where earlier ones clear the density in space for faster acceleration to Earth without warning. The downtime caused by such an event in a digitized world can exceed the waiting times of business interruption insurance policies.



Source: General Secretariat of the European Council [xx]

What a Geomagnetic Storm Can Do to the Earth

A 2017 London Economics study suggested that, for the U.K., a five-day disruption to GPS and similar satellite networks would cost £5.2 billion.[xxi] An extreme geomagnetic storm could lead to disruption and social and economic loss affecting electrical systems in daily use. The surge of current into the electrical grid causes component damage, power outage, and reduction of grid capacity, with time needed for repair.

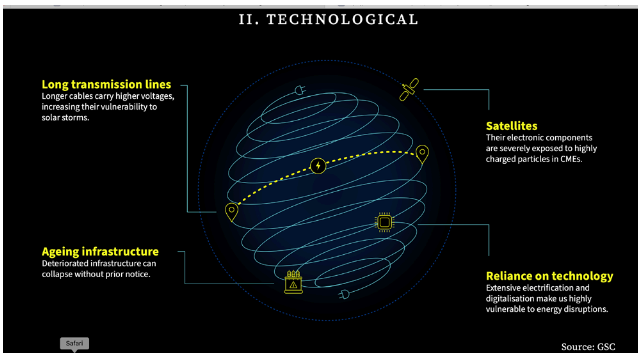
Large solar flares and other space weather events can affect cell phones reliant on satellite GPS communications, lead to radio blackouts, satellite damage, and endanger astronauts. During geomagnetic storms, radio frequencies are absorbed or reflected, leading to rapidly fluctuating signals affecting ground-to-air and ship-to-shore radio. Circuit board damage of orbiting satellites disrupts telephone, internet service providers, television, and transportation from cars, ships, airplanes, and logistics that use GPS for navigation and tracking. Military reliance on GPS can cause national defence issues.

The internet would be affected by a CME, with the impact not fully modelled. Abdu Jyothi researched CME effect on internet mass outages, finding optical fibre connecting regional hubs are unaffected but long undersea cables connecting continents are seriously affected.

Currently no protocol exists to provide resilience here and there is lack of data. Equatorial countries like Singapore and Africa would be at less risk though in extreme events, disruption could reach the equator. Cables that cross the Atlantic and Pacific oceans at high latitude would be at most risk of loss involving internet services.

In February 2022, the effects of space weather caused a failed SpaceX satellite launch as the atmosphere of the Earth became hot where it meets space and expanded the atmosphere. This caused drag, preventing 40 of the 49 launched satellites from making it to orbit.[xxii]

Solar storms could disrupt the rail network's electrical systems and cause signals to switch from red to green. Similarly, the maritime community needs to be advised that availability of global navigation satellite systems (GNSS), which underpin situational awareness, can be adversely affected by increased solar storm activity. GNSS is used in precise manoeuvring of ships (during the navigation of tight channels and docking), the positioning data within the automatic identification system (AIS), and vessel location reports in emergency situations.



Source: General Secretariat of the European Council

GNSS signal propagation is severely degraded during periods of high solar activity when the effect of solar radiation creates particles in the upper atmosphere. Batteries can be affected by a solar flare resembling an electromagnetic pulse (EMP) from a nuclear explosion. Estimates suggest that a Carrington-class storm would lead to some form of outage in a tenth of the 10,300 satellites orbiting the planet.[xxiii] The consequences on Earth would be that anything dependent on a satellite which suffers damage would be disrupted. A large solar radiation storm would disrupt airplane onboard systems, including autopilot and altitude readings.

Power Grid Impact, Mitigation, and Recovery

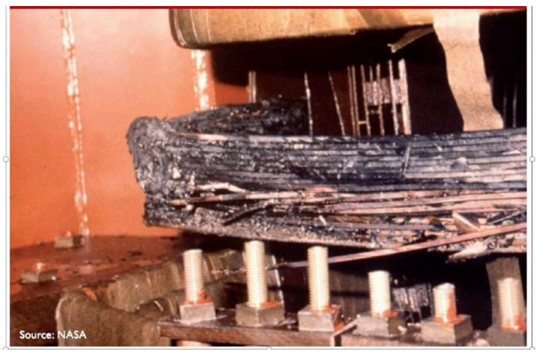
Power utilities must respond to solar storm warnings and understand worst-case scenarios for electricity grids. If a large storm is directed to Earth with alignment of sun and Earth magnetic fields, there will be little warning as when the CME arrives. The Earth's surface becomes an antenna, allowing GIC to flow into transmission lines. Risks to electrical grids are at higher latitudes with electric currents funneled around the poles.

Grids operate on alternating current flows and solar storms generate quasi-direct current flows, causing surges which damage transformers by overheating. Extreme climate events and cyberattacks are taking priority over mitigating power grids related to solar storms. Given recent solar activity, it seems appropriate that preparedness should be applied here due to high impact on critical infrastructure, especially as a large storm can also occur away from solar peak.

Prolonged power outage at scale requires replacement transformers, uninterruptible power supply(UPS), and surge protectors. Many governments have an incident response/recovery planning process to a solar weather event on how to protect and prepare for lengthy power outages. The UPS detects if the grid is out and switches to battery power until primary utility power returns. Surge protection devices detect a voltage surge immediately, diverting excess energy away. Transformers are most at risk due to fast replacement obstacles. Grid loads need to be adjusted, shielded, or hardened when a storm is forewarned. This requires a collection management framework[xxiv] adapted from the cyber playbook to gather and enhance threat intelligence centered around the operations technology and tabletop drills.

Learning from past events such as 1989, when power generation was affected, is a key part of collection management, gathering data outside the baseline for faster recovery. Solar storms can have a prolonged duration, occurring in successive waves, so can strike anywhere over subsequent days. National authorities might keep and not sell spare transformers. Differentiating from cyberattacks is vital as bad actors have a level of anonymity separation disguising an attack.

The following diagram from NASA shows transformer damage at the Salem Nuclear Power Plant in New Jersey from the 1989 geomagnetic storm.

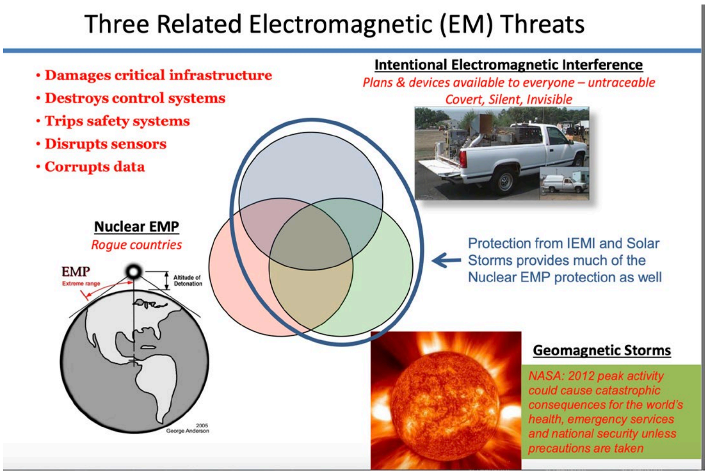


Solar storms can lead to systemic risk across anything electrical and become contagion to the banking system and stock markets, with a collective impact for social unrest. This necessitates close collaboration among governments, academia, and the private sector.

Confusing Solar Storm With a Cyberattack

Power outages can also be attributed to cyberattacks, but many incidents are caused by natural disasters. Solar GICs can resemble a cyberattack due to their ability to take out conducting networks. Recent high-profile cyberattacks have led to an increased focus on malicious actors and impact in cyberspace. Smart cities can malfunction with the smart grid down. Wrongful interpretation could lead to a high risk of miscalculation and cause a cyberwar if intelligence attributes outage to bad actors while solar flares are the cause.

The U.N. Special Commission of Inquiry[xxv] tends to focus on man-made cyberattacks, so the risk of miscalculation and conflict remains high if there is no enforced global standard. In May 1967 a large solar flare jammed U.S./U.K. radar and radio communications, causing blackouts. The U.S. military, in the middle of a cold war, suspected the Soviets and began preparing military action.[xxvi] A conflict was narrowly avoided by intervention of space scientists. A CME can produce similar effects of an EMP, causing damage to solid-state electronics, and could be seen as a nuclear attack. The following diagram from Emprimus[xxvii] shows how these threats look similar.

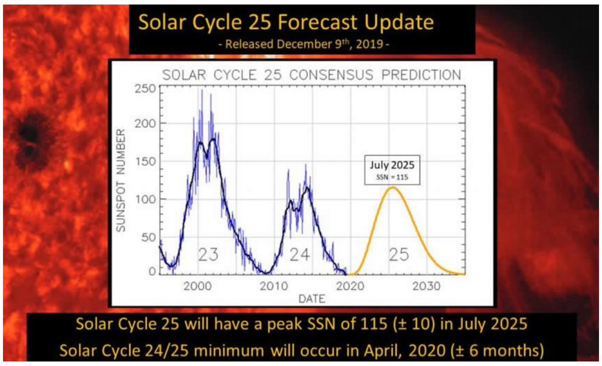


Source: EMPRIMUS

An EMP is the electromagnetic radiation from a nuclear explosion or nuclear device. Non-nuclear weapons can also generate EMP but less widespread. The resulting electromagnetic fields, couple with electrical/electronic systems, produce damaging voltage surges. Depending on the intensity, it can cause power spikes ranging from several hundred to a million volts per meter, with component or subsystem burnout and degradation.

A vehicle test for EMP simulation shows the severity of vehicle damage caused by CME. The U.S. EMP Commission[xxviii] tested vehicles to malfunction, showing that a powerful CME leads to car crashes as electronic components fail. Components that have been hardened against electromagnetic interference can be used as transformers during an extended outage of the power grid. Use of EMP-hardened solar panels supplying electricity directly to consumers not connected to the main power grid is a key mitigation strategy. The chances of a large CME event hitting the Earth are low but can be catastrophic. Steps need to be taken to mitigate the effects and to eliminate it in the case of cyber or nuclear conflict escalation.

Current Sun Cycle 25

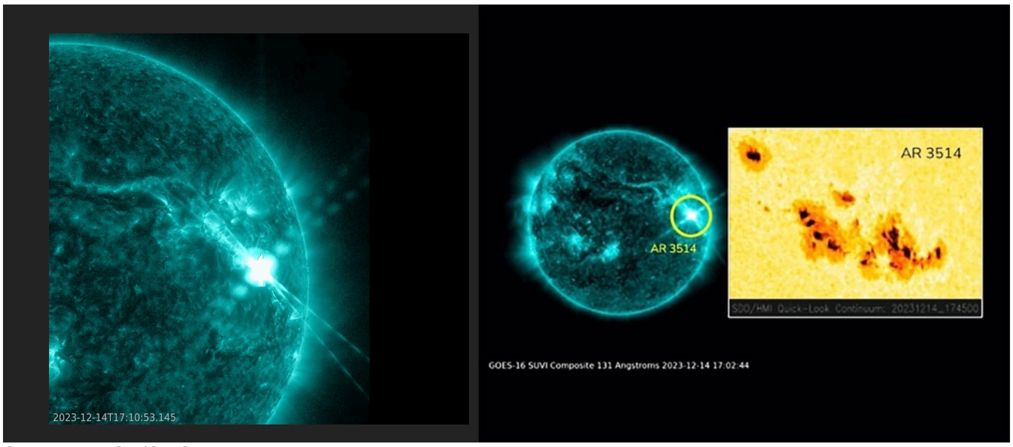


Source: Solar Cycle 25 Prediction Panel co-sponsored by NASA and NOAA

As can be seen, the current in-force solar cycle looks weaker in sunspot data than the previous cycles. A sunspot is a darker, magnetic active region (AR) on the Sun, rotating like a tornado, where solar storms originate and erupt. Only one event is needed to do damage similar to that caused in the 1982 hurricane season, which was mainly inactive until Hurricane Andrew.[xxix]

Solar Cycle 25 started in December 2019 and is the 25th solar cycle since 1755, when sunspot recording began.[xxx] It will continue past 2030, peaking in July 2025. Stronger solar activity tends to occur during odd-numbered solar cycles and frequently close to cycle peak. This will be first peak when the world is at a tipping point of full digitiszation**.** Recurring storms are frequent when the cycle is at minimum as solar winds blow and substorms appear as aurora. However, at the solar maximum, catastrophic, non-recurring storms can occur as the AR is more likely to generate solar flares and CMEs spice up the solar winds past the Earth.

The sun emitted a strong solar flare (AR3514), peaking at 12:02 p.m. EST on December 14, 2023. NASA's Solar Dynamics Observatory (SDO),[xxxi] which watches the sun constantly, captured an image of the event, shown below. This flare, classified as a X2.8 flare, was considered by the Space Weather Prediction Centre (SWPC)[xxxii] to be a notable event and the largest of this solar cycle since the X 8.2 flare observed by GOES-15 satellite in September 2017.[xxxiii]



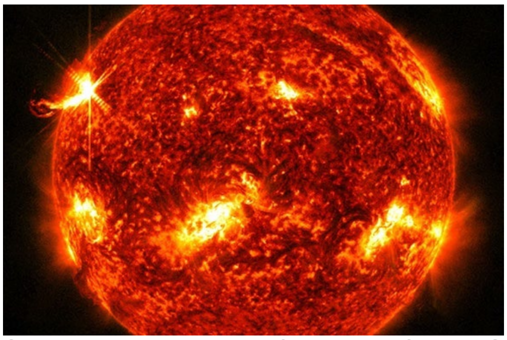
Source: NASA/SDO AR3514

A NOAA advance warning announced that this AR3514 strong solar storm event would cause auroras and disruptions, resulting in widespread high-frequency radio blackouts across South America, with activity continuing for four days. SWPC monitored a CME associated with this event which could have led to a geomagnetic storm making landfall on earth.

Satellite Data Collection

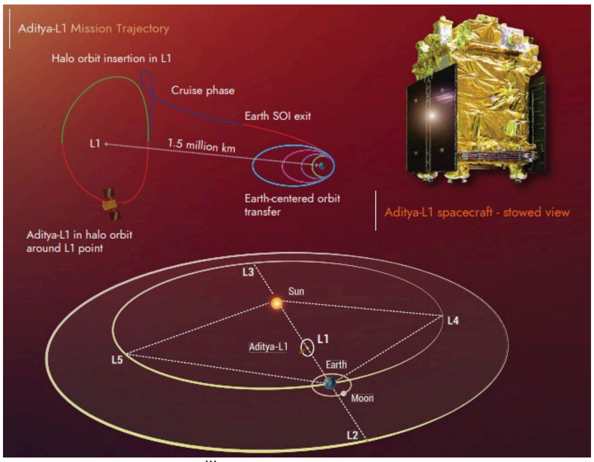
Mutations, disturbances, and phenomena occur in and around the sun's atmosphere, collectively known as solar activity. Solar storms or solar flares occur when there is a sudden, large release of plasma and magnetic fields from the sun's outermost layer, known as the corona. Unlocking the physics of solar eruption may come from satellites such as SDO, which observes the sun around the clock and takes pictures in high resolution every one-tenth of a second in multiple wavelengths. SDO cannot predict when flares or CMEs happen but can assist in forecasting space weather by using time-series data consisting of AR magnetic field parameters over several years.

Classification models use machine learning and AR data as input to predict the flare occurrences, establishing robust dataset and baseline models domain expert studies. Astrophysics does not have a particular physical theory explaining the mechanisms behind occurrences of solar flares but is researching to unfold a definitive theory to forecast flares. With AI and machine learning, a data-driven approach using the AR parameters observed by the SDO can develop a model to find a causal relationship between AR and flare occurrences.


On 10 January 2023, a solar flare erupted from the Sun (upper left edge)—a sign of increasing magnetic activity.
Source: NASA/GSFC/SDO[xxxiv]

Sun activity has surpassed the cycle forecast and the peak could arrive earlier than scheduled. The 2019 NASA-NOAA-ISES prediction panel meeting analysed multiple forecast models[xxxv] estimating the sunspot peak numbers and arrival prediction. Some models are statistical, making forecasts by extrapolating centuries of sunspot observations; but others use causal AI to determine correlation with the solar cycle and strength of magnetic fields at the sun's poles at solar minimum. A flare, captured by SDO on March 28, 2023, ionised the top layer of the Earth's atmosphere, affecting radio communications across Southeast Asia, Australia, and New Zealand.[xxxvi] Predicting solar flares helps mitigate damage and monitoring of solar events is crucial to accurately forecast space weather. NOAA has constellations of geostationary environmental satellites sending a continuous stream of data for this purpose.

India launched the Aditya-L1 probe,[xxxvii] with a mission to monitor the sun for CME, flare activities, and particle analysis and is operational January 6, 2024. It is positioned at LaGrange L1 point with an uninterrupted view of the sun and important satellite position for this purpose.



Source: Livemint[xxxviii]

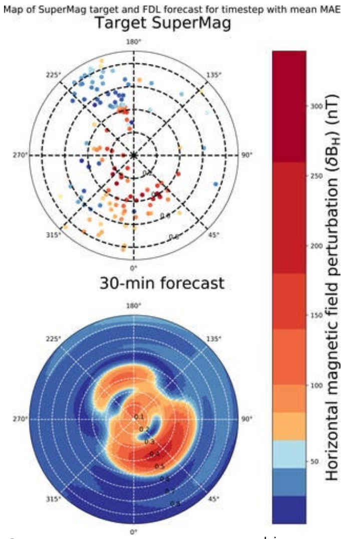
The European Space Agency (ESA) will launch Vigil[xxxix] around 2025 with a mission to get better speeds and direction of CMEs. A satellite mission called RADICALS[xl] from the University of Alberta is studying solar radiation high in the atmosphere, 50 km above Earth. This will make high-resolution and accurate measurement of the radiation entering the atmosphere and the data ingested by climate models to find causality with space weather and climate. The mission will be operational by 2027, capturing the end of the current solar cycle, and may predict how severe the climate change emergency could shift as a result of the ongoing prodigious levels of greenhouse gas emissions in the atmosphere.

Project Helios[xli] is a solar flare prediction tool for events that could damage space-based assets, communication networks, drones, and global power grids. It uses an algorithm to predict solar flares more than 36 hours in advance. Exposing more data points to a machine-learning solution calculates and improves the predictive nature of solar flares. Helios will not prevent solar flares but helps to operationally respond by predicting communication breakdowns, loss of data links, and internet downtime on future events.

Using AI for Solar Storm Predictions

AI and ensemble satellite data models sound 30-minute early-warning alarms for dangerous space weather by analysing spacecraft measurements from solar winds to predict where a storm will strike and trigger a power grid preparedness program. In 2003 NASA's Solar and Heliospheric Observatory (SOHO)[xlii] picked up the Halloween Storm,[xliii] which triggered a blackout in Sweden and generated transport disruptions, including SOHO itself.

The Frontier Development Lab[xliv] used deep learning models searching for previous event patterns with an AI tool, DAGGER,[xlv] to compare the model's predictions to measurements made during previous solar storms. Colours show the intensity of geomagnetic disturbances that cause GICs in electric grids, with orange and red indicating the strongest effects. The 30-minute forecast for that same time shows intense activity in roughly the same location around the North Pole.

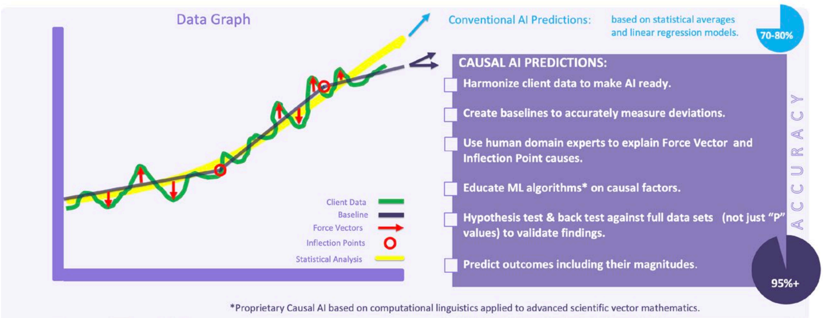


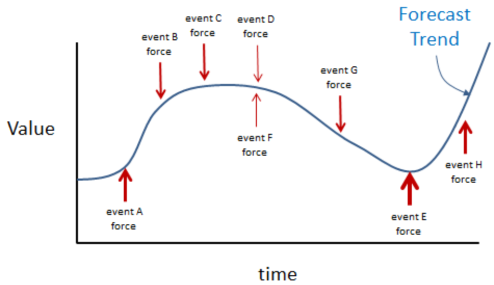
Credits: V. Upendran et al.[xlvi]

Open-source approaches allow input from energy and telecommunication companies so they can take grids offline or move satellites to different orbits. The NASA Parker Space Probe,[xlvii] launched in 2018, gathers information on solar winds that is fed into AI models.

The consequences of false negatives or false positives are significant. When predicting bull markets for stocks using Golden Cross,[xlviii] precision is important to avoid losing money. In solar flare prediction, false negatives can cause crucial damage to satellites and power grids while false positives can trigger expensive mitigation measures. Logic says not detecting will cause more damage than false alarms, so a prediction recall of flaring activity will be part of a suitable model.

Applying causal and explainable AI to space weather will increase accuracy and granularity of the models and enable usage in ILS insurance products. This is shown in the below diagram courtesy of Eumonics.[xlix] Causality lies at the core of human reasoning, enabling understanding the world and making informed decisions. Using causal analysis to develop understanding of forces involved in solar flares using domain experts is more impactful and explainable than using statistical correlations.





Applying upward force events causes the value of the forecast trend to increase over time and applying downward forces cause it to decrease. The magnitude of the event forces is indicated by size of their respective arrows. If these forces are known, the value of the forecast trend can be determined at any point in time and predicted for future periods.

Rating for Solar Storms (Parametric Indicators)

The ESA[i] defines a solar flare as a tremendous explosion on the sun that happens when energy stored in twisted magnetic fields unwinds like elastic bands. Such active areas are labelled AR and used to number the flare. Solar flares are ranked from A to X, with X being the most powerful, and further divided by numbers, indicating relative strength where an X2 flare doubles the strength of an X1. The 2003 Halloween storm was the largest recorded at X45. The ESA classifies solar flares in three categories according to their brightness in the X-ray wavelengths: X-class, M-class, and C-class. They are exponential so X is 10 times greater than M.

An X-class flare can release as much energy as a billion hydrogen bombs[ii] due to the complex interaction of the sun's magnetic field. X-class flares do not directly harm humans, as Earth's atmosphere protects; but X-class solar flares (like AR3514) represent some of the most powerful phenomena in the solar system. Understanding them will mitigate technology impacts and provide insight into broader workings of the sun.

No.	SXR Class	Date	Solar cycle	Active region	Time (UTC)			Notes
					Start	Max	End	
1	>X28	2003-11-04	23	10486	19:29	19:53	20:06	Associated with the 2003 Halloween solar storms
2	X20.0	2001-04-02	23	9393	21:32	21:51	22:03	
3	X17.2	2003-10-28	23	10486	09:51	11:10	11:24	Associated with the 2003 Halloween solar storms
4	X17.0	2005-09-07	23	10808	17:17	17:40	18:03	
5	X14.4	2001-04-15	23	9415	13:19	13:50	13:55	
6	X10.0	2003-10-28	23	10486	20:37	20:49	21:01	Associated with the 2003 Halloween solar storms
7	X9.4	1997-11-06	23	8100	11:49	11:55	12:01	
8	X9.3	2017-09-06	24	12673	11:53	12:02	12:10	
9	X9.0	2006-12-05	23	10930	10:18	10:35	10:45	
10	X8.3	2003-11-02	23	10486	17:03	17:25	17:39	Associated with the 2003 Halloween solar storms

Source: Wikipedia

The disturbance storm time (Dst) index is a metric of space weather about the strength of the magnetic ring around Earth caused by solar storms. A negative value means the Earth's magnetic field is weak and vulnerable to disruptions. The July 2012 solar storm was picked up by Solar Terrestrial Relations Observatory (STEREO)[lii] spacecraft showing a Dst of -0.80 to -1.75. Had this storm hit Earth, the impact would have been a catastrophe-level event. A CME can take several days to reach Earth, but a solar flare takes minutes. The Carrington event took 17.6 hours to make the 150-million-kilometre journey to Earth, with the high speed made possible by prior CME events clearing the way in the density of space.

Solar storms can disrupt by geomagnetic, radio, or radiation emissions. A scale is used by NOAA to describe the severity of each (G1-G5, R1-R5 and S1-S5, respectively).

NOAA Space Weather Scales

Category		Effect	Physical measure	Average Frequency (1 cycle = 11 years)
Scale	Descriptor	Duration of event will influence severity of effects		
Geomagnetic Storms			Kp values* determined every 3 hours	Number of storm events when Kp level was met; (number of storm days)
G 5	Extreme	Power systems: widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. Spacecraft operations: may experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. Other systems: pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).**	Kp=9	4 per cycle (4 days per cycle)
G 4	Severe	Power systems: possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. Spacecraft operations: may experience surface charging and tracking problems, corrections may be needed for orientation problems. Other systems: induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).**	Kp=8	100 per cycle (60 days per cycle)
G 3	Strong	Power systems: voltage corrections may be required, false alarms triggered on some protection devices. Spacecraft operations: surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. Other systems: intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).**	Kp=7	200 per cycle (130 days per cycle)
G 2	Moderate	Power systems: high-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. Spacecraft operations: corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. Other systems: HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).**	Kp=6	600 per cycle (360 days per cycle)
G 1	Minor	Power systems: weak power grid fluctuations can occur. Spacecraft operations: minor impact on satellite operations possible. Other systems: migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).**	Kp=5	1700 per cycle (900 days per cycle)

A geomagnetic storm is considered extreme with a Dst of less than -500 nT and the March 1989 event had a Dst of -589 nT. An estimated Dst of -850 to -1050 was derived for the Carrington event rated G5. The December 2023 flare emerged from an active sunspot (AR3514) visible on the solar surface, categorized as X2.8, causing radio blackouts and classified as an R3 event. A geostationary orbit satellite, GOES-16, detects X-ray level increases with resultant impacts to a radio blackout, affecting the dayside of Earth facing the sun.

Return period calculations are varied as determining the frequency of extreme space weather events is extremely difficult; but estimates suggest that relatively strong events happen about every 50 years, and anything between 150 to 500 years for extreme storms such as the Carrington event.[liii] Research in 2012 by Peter Riley[liv] determined there was a likelihood of a 12 percent chance of a Carrington-class event occurring in the next 10 years.

The Gray scale for radiation absorption, where any human absorbing over 5 can be fatal, would apply to astronauts on missions or people in high-altitude aircraft during an extreme solar storm. This shows the importance of early warnings to flights and space missions. In October 2021, a CME sent energetic particles to Mars, the Earth, and the moon simultaneously, enabling satellite data comparisons across the three planets,[lv] especially as the moon and Mars do not have magnetic fields leading to important research on space exploration.

Close Solar Storm Miss of 2012

A space probe satellite STEREO showed that an extremely powerful CME crossed Earth's orbit in July 2012.[lvi] The Earth was at a different point in its orbit at the time; but a week later would have been a direct hit. The estimates of a landfall would have generated a geomagnetic storm measuring a Dst of around -1200 nT, larger than the Carrington event. STEREO was placed in orbit to observe and withstand solar storms and it survived the storm; but without it, no one would have known of such a storm, let alone the magnitude. Scientists calculated the Earth had missed it by a 9-day margin and it would have inflicted catastrophic damage worth $2 trillion+ and take years to repair, leaving millions without power. This should erase any doubt about the need for mitigation of space weather and preparedness before 2025.

The Insurance Industry and Solar Storms

Geomagnetic storms are low-probability, high-impact events but highly directional and can miss Earth entirely, make direct landfall, or partially strike. In 2013,[lvii] Lloyds of London and Atmospheric and Environmental Research (AER) in the U.S. used data from the Carrington Event to estimate the economic cost of a similar event occurring today. They found in the U.S. alone, $600 billion to $2.6 trillion (equivalent to $747 billion to $3.24 trillion in 2022), equating to roughly 3.6 percent to 15.5 percent of annual GDP. Current underwriting will unlikely include exposure to space weather because there is no standard model and minimal loss experience.

From a re/insurance industry perspective, space weather events are just as plausible as climate change, cyber, and pandemics, but with no way of eliminating the risk. Cost to the industry is high across all sectors but mainly physical property damage, business interruption, transportation, and power grid failures, with potential systemic social unrest. As mostly higher latitudes are affected, a winter event would add to the chaos.

In 2021, Verisk estimated the cost of insurance geomagnetic storm loss using high and low estimates.

Coverage type	Low estimate of losses (Million, USD)	High estimate of losses (Million, USD)
Property damage EHV transformers	$466	$1,845
Property damage satellite	$218	$645
Business interruption	$50,980	$318,860
Household contents	$449	$720
Commercial contents	$1,079	$1,790

Source: Verisk [lviii]

X-class flares create the most concern. Recent interconnected events that the insurance industry was arguably unprepared for were COVID-19, the Tōhoku earthquake/tsunami, and the Thai floods, both in 2011.

D&O claims could arise if companies were judged as not having taken preventative action to secure continuity. The insurance industry must alert clients to the risks that solar flares present to their operations, provide mitigation advice, and coverage/risk transfer solutions. Evidence shows that a 1-in-200-year solar storm would resemble the 1859 event, leading to major power blackouts affecting millions of people for protracted periods.

Mitigation measures recommended to power utilities operators are through reliability standards imposed by grid regulators (NERC).[lix] Space weather cover is silent, so care is needed when underwriting contingent business interruption (CBI) policies and service interruption extensions due to accumulation risk and ambiguous policy wordings driving a parallel with cyber.

Insurance contracts seldom mention a loss occurrence by extreme solar weather but covered by all-risks policies, not named perils, unless they indirectly trigger a named peril. Solar storms must be a monitored emerging risk. Regulators will likely ask reinsurance companies to include a 1-in-200-year solar storm as part of Solvency 2/RBC-compliant internal models. When underwriting power grids in higher geomagnetic latitudes, mitigation measures need to be applied to reduce vulnerability to solar storms, following available standards including managing accumulation risk linked to service interruption extensions along digital supply chains during prolonged blackout and internet downtime.

Cyber insurance policies may exclude space weather events, electrical power interruption, surge or blackout or even exclude space weather events directly by citing electromagnetic fields. Cyber insurance policies often cover only non-physical damage from a cyber event so revenue interruption, loss of profits, and the increased costs of working following a major space weather event may be excluded unless the impacted infrastructure is owned and operated by the policyholder. However, the capital markets seem the best approach to space weather as it is difficult to see traditional reinsurance provide capacity to handle trillion-dollar economic losses and bespoke solutions are required for the organizations involved.

Insurance Industry Insurance Linked Securities (ILS) Solutions

The Cambridge Helios Storm Scenario insurance loss estimates double the loss volume of both Hurricane Katrina[lx] and Superstorm Sandy,[lxi] close to overall insured losses from all global catastrophes in 2015, suggesting a severe space weather event could become the largest insured loss event in history**.** Reinsurance brokers warn of large economic and insured losses from solar storms underlining the need to develop specific protection products. With the space weather satellite data and the rating parameters, an indexed solution is feasible and parametric by nature,[lxii] triggering a claim payout based on solar activity levels. Drawing parallels with cyber, the understanding and modelling of the risk needs to be done but once in place will lead to solar storm catastrophe bonds and other derivative covers.

Solar and geomagnetic storms are low-probability events with high economic consequences to the re/insurance industry and broader economy. The re/insurance industry must take the lead in risk management and risk transfer as existing reinsurance treaties likely carry the clauses and legal liability triggers for a major space weather event but were not drafted for solar storms.

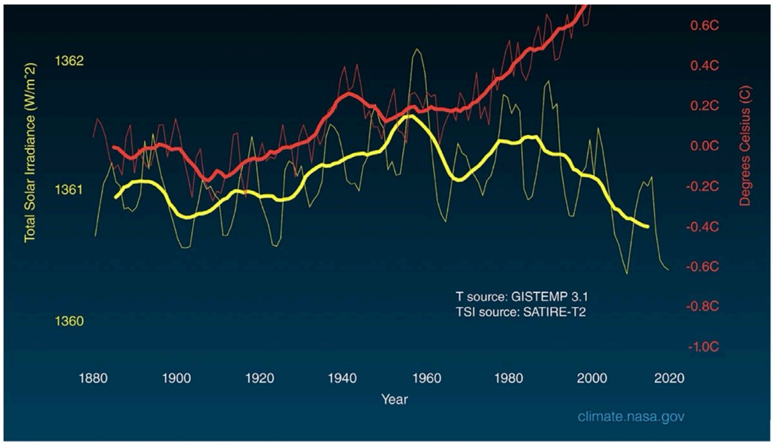
The satellite industry faces a challenging insurance renewal season after extensive launch losses in 2023. Specific space weather contracts could be written as standalone cover for losses directly attributed to solar weather. Artemis covered this in 2011[lxiii] but not many products have emerged, if any, but solar activity levels can be hedged as in weather events.

With the exposure size and low probability, a parametric hedging approach would suit satellite operators or electrical transmission owners with a dual trigger approach, linking the space weather event occurrence to the ultimate net loss of an insurer or corporation. This is attractive and could also be applied as an industry loss warranty (ILW) suitable for insurer protection.

Investment would come from capital markets and pension funds as risks of this magnitude require investors with an appetite for rare, uncorrelated risks. The X-class solar rating could be used as the storm parametric trigger in conjunction with the G5 geomagnetic storm rating, with the ILS being issued around the solar maximum period. The agencies ESA, NASA, and NOAA would be third-party verification for the payout based on satellite data. An ILW for the satellite and power industry may be appropriate against an agreed level of total industry insured loss with a specified limit if the warranty is triggered.

Solar Storms and Climate Change

All weather on Earth, from the surface of the planet and into space, begins with the sun. Many climate scientists agree that sunspots and solar winds play a minimal role in climate change; most attribute Earth's warming primarily to greenhouse gases, backed up by evidence. The United Nations Intergovernmental Panel on Climate Change (IPCC)[lxiv] incorporates effects of the sun's variable degree of brightness in their overall calculations. Once the carbon emissions have been reduced it will be clearer to see how much impact sunspots and solar wind have on climate change.



This NASA graph and its following explanation[lxv] compares global surface temperature changes (red line) and the sun's energy received by Earth (yellow line) since 1880. The lighter/thinner lines show yearly levels while the heavier/thicker lines show the 11-year average, highlighting underlying trends.

The solar energy amount Earth receives shows no net increase since 1978, but global temperature has risen, indicating the sun has not caused the Earth global temperature warming trend. Scientists would expect warming from the surface to the upper atmosphere but there is surface warming and cooling at the top, consistent with accumulation of heat-trapping gases near Earth's surface.

Scientists agree greenhouse gases cause climate change, but space weather affects Earth climate as an interaction between weather and space, not climate change.[lxvi] Populations in 1645 to 1715 across the Northern Hemisphere experienced a long period of minimal solar activity, the Maunder Minimum,[lxvii] which triggered the Little Ice Age.[lxviii] in 1650, the first of three cold intervals with the last in 1850. Satellites observing the sun since 1978 indicate the amount of energy the Earth receives from the sun is stable with little fluctuation.

Historical Solar Storm Warning (Pre-Measurement)

Artists and research unveiled evidence of a super solar storm that hit Earth in 1872.[lxix] Below is a Japanese drawing showing solar aurora at Okazaki in February 1872.

Source: Shounji Temple[lxx]

A solar flare in AD 775 produced radiocarbon (c-14)[lxxi] recorded in the upper atmosphere. Ice-core samples and tree rings reveal events of Miyake and Carrington intensity occur every 150 to 500 years. Miyake produced a 1.2 percent increase in c-14, but Carrington only <1 percent,[lxxii] so Miyake was a super solar storm.

Cosmic radiation or high energy particles from the sun can strike Earth's atmosphere, causing nuclear-type reactions. Radiation converts nitrogen in the upper atmosphere into radiocarbon which is detectable in plants, animals, people, oceans, and trees, preserving records for thousands of years and enabling scientists to explain solar physics at that time.

This radiocarbon spike was detected by analysing tree rings and Greenland ice cores containing beryllium-10 isotope from cosmic rays. The sun's magnetic field shields Earth from cosmic rays, but when the sun's activity is at a solar minimum, more radiation reaches Earth—hence more radiocarbon production and space hurricanes[lxxiii] over the Artic threaten satellites at this time. Fusa Miyake,[lxxiv] a Japanese physicist, discovered the radiocarbon spikes in 2012, known as Miyake events. Sedimentary rock porosity conducts electricity, more than metamorphic/igneous, so regional geology factors in solar storm intensity.[lxxv]

Wildfires, Volcanos, and Solar Flares

Wildfires destroy forests and other assets. There is a possible connection between forest fires and solar activity. Fires emerged in Europe in August 2005 and analysis has shown a presence of strong electromagnetic from highly energetic regions that were in position before the fires.[lxxvi] There is a strong causal relationship between solar activity and the ignition of these forest fires taking place.

It is difficult to estimate how changes in solar activities affect dynamics of environmental processes, so causal AI is used to establish the functional relationship between weather and solar parameters. Statistical connections between the occurrences of forest fires in various regions worldwide and the emissions from the sun exist. Studies also show there is a strong indication that the same solar effect enhances the frequency of volcanic eruptions in periods of high solar flare activity of the solar cycles.[lxxvii] Many major volcanic events occurred during inactive phases of solar magnetic activity (solar minimum), well indexed by the group sunspot number. The association between volcanic eruption timing and the solar minimum is statistically significant to a confidence level of 96.7 percent.[lxxviii]

Conclusions

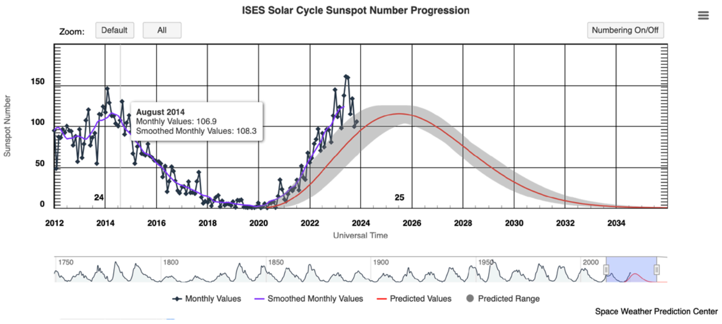
A solar storm of the same magnitude of the Carrington Event hitting Earth is inevitable as historical records indicate that extreme storms of that magnitude occur every 150 years. The total economic cost of such an event is estimated between $600 billion to $2.6 trillion.

The world is in the midst of a polycrisis that fragments global order. Governments and multinational corporations must manage long-tail geopolitical risks across many geographies and can be caught off guard. Warnings that the world needed to prepare for a pandemic were largely ignored and threats from space weather in a technology-dependent world are only getting patchy attention. Space-based technologies are crucial to industry and a shutdown of satellite communications from a cyberattack or severe geomagnetic storm would be chaotic.

Climate change has shown that not listening to scientific advice has consequences. Risks posed to human activity by extreme space weather should be added to the lessons from pandemic, cyber, and climate change. State nations can destroy power grids by cyberattacks, but the sun could similarly destroy through a natural event. The 1962 Starfish Prime high-altitude nuclear test[lxxix] generated an EMP that caused unexpected electrical surges on Earth when electrical and communication grids relied on solid-state systems that were better protected. Now with silicon-based microprocessors they are more vulnerable. Governments do not understand the threat of EMP caused by CME, focusing almost entirely on cybersecurity, largely ignoring the other major threat vectors against electric grids.

The probability that all satellites in space fail simultaneously is stated by experts as highly improbable but not excluded. Extreme solar storms, cyberattacks, and space debris chain reaction (Kessler effect[lxxx]) are all satellite risks. As satellite dependency is now irreversible, even a low probability of an event must be explored. Cyberattacks on satellites have already happened and satellites have been damaged by solar storms and space debris. Implications are broad as in high-speed financial trading where the GPS systems are used to place time stamps on financial transactions where precision timing is critical.

Just like pandemics, Carrington-sized solar storms are judged to be 1-in-150-year events and few scientists would be surprised if one hit tomorrow. Because the sun, which moves in 11-year cycles of volatility, will enter its most active phase known as solar maximum in July 2025, sunspots are increasing; but storms can also occur in a solar minimum.



Despite decades of research, scientists know relatively little about the activity of the sun and the intricacies of the resulting space weather. The occurrence of a Class X2.8 solar flare at the end of 2023 serves as a reminder of the sun's immense power and the potential impact of solar activity on a technologically dependent society.

As scientists continue to monitor the sun's activity, this underscores the importance of preparedness for space weather events and a need for ongoing research in solar physics. Solar storms threaten an electricity-dependent world and society needs expertise to cope without power for long periods. Decarbonization heightens that dependency, as world trends electrify transport.

The Earth's geomagnetic field is weakening, which could increase solar storm frequency as the Earth's magnetic field is a natural shield against solar interference. The movement of the magnetic North Pole toward Siberia[lxxxi] and the rise of a radiation hotspot (South Atlantic Anomaly)[lxxxii] could indicate the first stages of a magnetic pole shift, exposing Earth to higher levels of radiation. Resilience comes in maintaining good battery power reserves and quantum computing will play a great role here in quickly finding new battery innovations.

The re/insurance industry has a major role to play in risk transfer and will likely come from the capital markets via ILS, parametric insurance, and catastrophe bonds. This risk cannot be ignored, the science should be understood, and the necessary mitigation put in place.

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