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Perspective

The Economic Impact of Space Weather: Where Do We Stand?

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Space weather describes the way in which the Sun, and conditions in space more generally, impact human activity and technology both in space and on the ground. It is now well understood that space weather represents a significant threat to infrastructure resilience, and is a source of risk that is wide-ranging in its impact and the pathways by which this impact may occur. Although space weather is growing rapidly as a field, work rigorously assessing the overall economic cost of space weather appears to be in its infancy. Here, we provide an initial literature review to gather and assess the quality of any published assessments of space weather impacts and socioeconomic studies. Generally speaking, there is a good volume of scientific peer-reviewed literature detailing the likelihood and statistics of different types of space weather phenomena. These phenomena all typically exhibit "power-law" behavior in their severity. The literature on documented impacts is not as extensive, with many case studies, but few statistical studies. The literature on the economic impacts of space weather is rather sparse and not as well developed when compared to the other sections, most probably due to the somewhat limited data that are available from end-users. The major risk is attached to power distribution systems and there is disagreement as to the severity of the technological footprint. This strongly controls the economic impact. Consequently, urgent work is required to better quantify the risk of future space weather events.

KEY WORDS: Geomagnetic storms; power grids; space weather

1. INTRODUCTION

Space weather is of rising importance both as a scientific discipline in its own right(1–8) and as a severe source of risk recognized by governmental agencies and corporations at the national and international level.(9–19) For example, in the United States, it has been the subject of a recent Executive Order issued by President Barack Obama, which directs multiple federal agencies and departments to coordinate their preparation for, and response to, severe space weather.[9] This highlights the fact that space weather is a fundamentally interdisciplinary risk, and has the potential to affect myriad technologies and activities in space and on the ground.

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[9] https://www.whitehouse.gov/the-press-office/2016/10/13/executive-order-coordinating-efforts-prepare-nation-space-weather-events

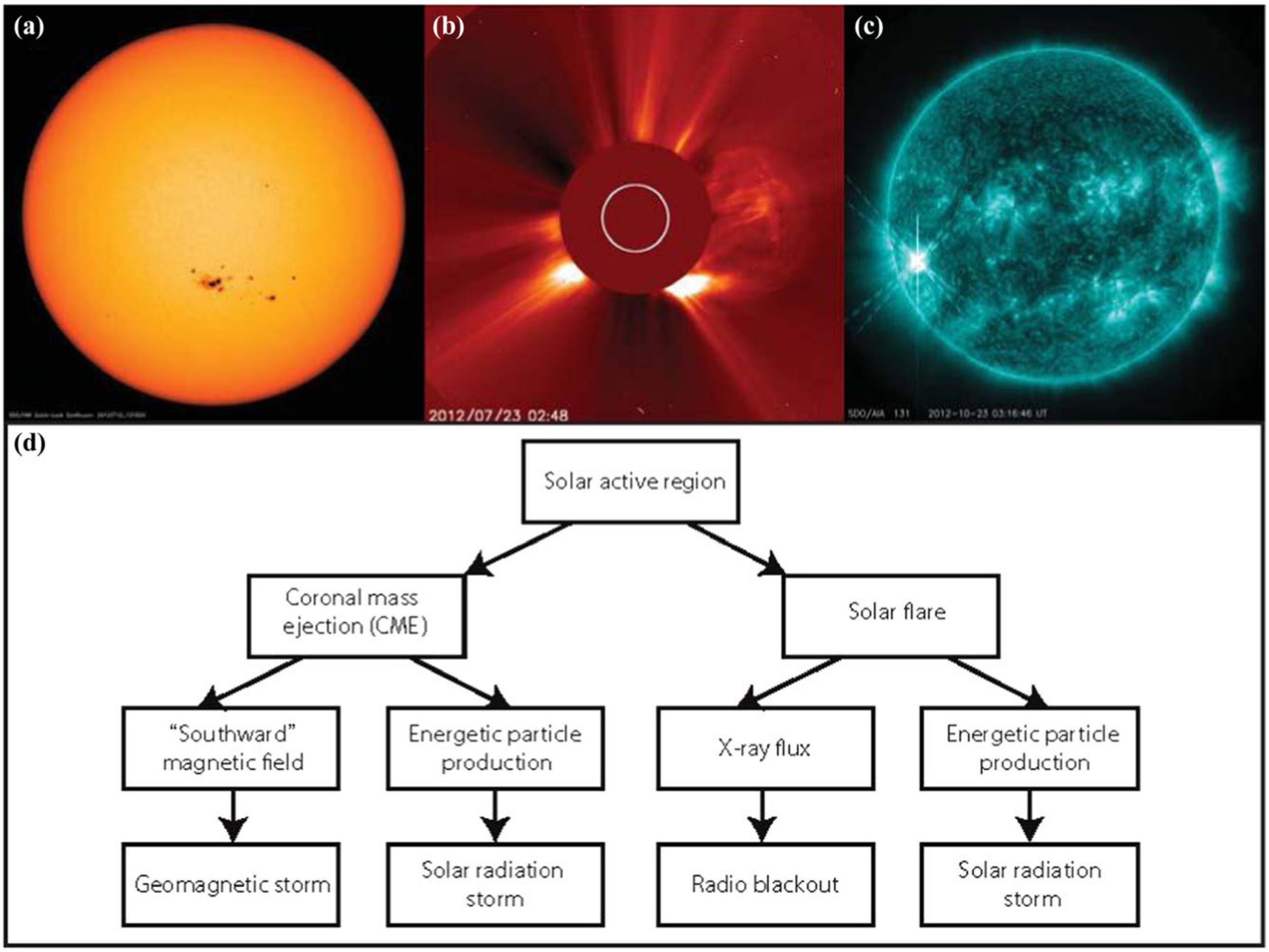

Fig. 1. (a) Image of sunspots on the solar disk from NASA's Solar Dynamics Observatory on July 12, 2012. The grouping of sunspots was associated with active region 1520. (b) CME launched from active region 1520 on July 23, 2012 and observed by the European Space Agency/NASA Solar and Heliospheric Observatory (SOHO) (Image credit ESA/NASA/SOHO). (c) X-class flare observed by NASA's Solar Dynamics Observatory on October 22, 2012 at 131 Angstrom wavelength, which caused an R3 radio blackout (Image credit: NASA/SDO/Goddard). (d) Solar active regions produce CMEs and solar flares, which are subsequently responsible for the three primary categories of space weather as indicated here and in the text.

Although the field is growing rapidly, peer-reviewed work rigorously establishing the economic impact of space weather is still scarce. Here, we aim to briefly summarize what is known to date in this area. We first introduce the physical nature of the risk and notable space weather events, in order to establish the hazard component (event occurrence). We then review documented impacts in several different sectors, (i.e., the loss-severity component), and finally examine attempts to quantify the economic consequences. We conclude with some observations about the current status, the research gaps, and the main challenges characterizing this area of risk analysis.

1.1. Space Weather

The ultimate source of space weather is the Sun. It can sometimes produce bursts of electromagnetic radiation (*flares*) and eruptions of material (coronal mass ejections, *CMEs*) accompanied by solar energetic particles (*SEPs*). The interaction of CMEs with the Earth's magnetic field can lead to a *geomagnetic storm* (see Fig. 1). Three main types of space weather

Table I. Types of Space Weather and Their Properties

Space Weather Category	Physical Cause	Physical Measure	Timing	Impact	Likelihood of Most Severe Event
Radio blackout R1 least severe R5 most severe	Solar flares: X-ray emission causes increased low altitude ionization (60–90 km). UV emission heats and expands atmosphere.	Solar X-ray flux	The electromagnetic emission travels at light speed—no warning time. Impact is almost immediate, but depends on ionospheric response.	Absorption and disruption of high-frequency (HF) radio (3–30 MHz).	The most severe event (R5) would correspond to a GOES peak X-ray flux exceeding X20 (i.e., 20×10^{-4} Wm^{-2}). Such an event is expected to occur less than once a solar cycle.
Solar radiation storm S1 least severe S5 most severe	Solar energetic particles (SEPs) accelerated by flares and coronal mass ejections (CMEs).(20,21)	Energetic particle flux	During "impulsive events" associated with flares, and the launch of CMEs, fluxes can start to rise significantly a few minutes after the arrival of the electromagnetic emission. Gradual events associated with CME propagation through interplanetary space intensify more slowly.	Biological effects on astronauts, aircrew, and airline passengers (if sufficiently energetic). Technological impact on electronic devices on satellites, aircraft, and even on the ground. HF radio blackout in polar regions.	An S5 event is expected to occur less than once a solar cycle. (However, note that S5 is not useful for aviation impact because particles are still insufficiently energetic to penetrate down to altitudes of interest, and so special aviation alerts also exist in addition to S5 warnings.)
Geomagnetic storm G1 least severe G5 most severe	Primarily triggered by earthward-directed coronal mass ejections that travel through space from the Sun. A geomagnetic storm will develop when a CME interacts with the Earth's magnetic field, provided that the CME magnetic field structure is appropriately oriented "southward." Solar wind high-speed streams can also drive geomagnetic storms if their magnetic field is similarly oriented. Fast CMEs with strong magnetic fields produce the largest storms.(22–24) Although geomagnetic storms are a global phenomenon, their regional impact is highly heterogeneous. Geomagnetic storms cause geomagnetically induced currents (GICs) on the surface of the Earth.	Geomagnetic index[a]	A geomagnetic storm may arise after two to four days depending on the time it takes for the CME to travel from the Sun to the Earth. The severity of each particular geomagnetic storm impact can vary considerably in space and time. It is currently not possible to predict if a CME will be geoeffective until it is measured by satellites just before it reaches the Earth.	Power system failure, spacecraft failure, degraded satellite navigation, severe ionospheric disturbances, GNSS degradation (e.g., affecting aviation augmentation systems) and loss of integrity, and HF communication blackout. Geomagnetic storms are considered a primary risk in most assessments of space weather impact.	Storm severity is typically measured according to the Kp index ($Kp_{\max} = 9$), which is designed to capture the severity of the global perturbation to the quiet magnetic field on the surface of the Earth (time resolution of three hours). The physical measure of a G5 event is $\mathrm{Kp} = 9$ and, on average, four such storm days per solar cycle are expected.

[a] Geomagnetic storms are difficult to characterize. Geomagnetic indices condense the properties of a complex nonlinear system with a variety of dynamical processes into a single number. They provide information about the occurrence of geomagnetic storms on a global level, and therefore are a necessary part of understanding geomagnetic storm likelihood. They must be used with care:(2) there are examples of little or no variation in geomagnetic index even when the space weather is "stormy, "(25) and relatively weak storms can have significant effects on technological systems.(26) Furthermore, none of the indices currently in use are directly useful for understanding the most important societal impact—the production of GICs that may affect power grids. Such GIC production is highly inhomogeneous in space and time. There is increased interest in understanding the statistics of extreme events on regional scales,(27) and in the future, it is likely that a global measure of geomagnetic storms will be rendered obsolete in favor of local warnings of specific storm impact.(28)

Table II. Notable Space Weather Events

Date	Comment
September 1859	The "Carrington" event is the benchmark for extreme space weather studies.(29–33) The solar flare, the geomagnetic storm, and the energetic particle flux associated with this event make it one of the largest on record.(30) Note that many crucial parameters were not measured directly, so its precise properties are subject to uncertainty. In particular, estimating the strength of the geomagnetic storm associated with the Carrington event has attracted some debate; initial estimates(34) should be disregarded in favor of more recent analysis.(35,36)
May 1921	This geomagnetic storm has been estimated to be comparable in size to the current best estimate of the Carrington event.(37,38) Auroras were seen near the equator in Samoa,(30) and geomagnetically induced currents (GICs) caused fires at several telegraph stations in Sweden.(39)
May 1967	An extreme solar flare and coronal mass ejection caused very significant radio blackouts, solar radiation storms, and a major geomagnetic storm. This caused a particularly significant disruption to communications, specifically to the military, and marked the start of a significant U.S. investment in space weather monitoring that continues to this day.(40)
March 1989	The largest geomagnetic storm of the space age(41) causing well-known failure of the Quebec power grid(42) and damaging two transformers in the United Kingdom.(43)
October–November 2003	Very well-observed and measured complex series of events including one of the largest observed solar flares on record.(44,45) The overall technological impact is extremely well documented.(46–49) A 90-minute blackout in 2003 affected 50,000 customers in Sweden. (Although it is now widely recognized that this blackout would probably have been avoided if current operational warning systems had been in place).(50)
July 2012	This CME was not Earth directed, but was measured *in situ* by the STEREO-A spacecraft.(51) If this CME had been Earth directed, it would have generated a very severe "Carrington class" geomagnetic storm.(52,53) It has been argued that this event should be used to create severe space weather scenarios for planning purposes.(52)

are typically recognized: *radio blackouts*, *solar radiation storms*, and *geomagnetic storms* (Table I), and are monitored by various national and international agencies.[10] Since the underlying physical drivers are complex and highly interconnected, all three phenomena can occur multiple times within one space weather "event," with varying temporal and spatial footprints, as well as levels of severity. Table II summarizes the notable space weather events that will be referred to throughout the article.

1.2. Statistics of Space Weather Events and Severe Event Likelihood

All relevant space weather phenomena—solar flare intensity,(54–56) CME speeds,(55,57) and geomagnetic storm strength(55,58)—typically follow power-law distributions.(59) Most studies therefore focus on the study of tail indices, although more complex statistical models have also been developed.(60,61) Solar flare statistics in particular have been interpreted in terms of self-organized criticality. In such models, continual small changes in the evolving magnetic field of the Sun's atmosphere (the corona) are thought to trigger periodic energy release events (flares) whose size follows a power-law distribution, analogous to avalanches occurring on the surface of a sand-pile where grains are continually added.(62–68) Poisson statistics (modulated by the solar cycle) are the standard framework for establishing the waiting time distribution of flares,(69) CMEs,(70) and geomagnetic storms.(71,72) However, there is some evidence for clustering of CME eruptions.(57)

Although there is a growing realization that vulnerability arises not simply due to low-frequency and high-impact events, but also due to continuing degradation as a consequence of many smaller impacts,(18) understanding the *most severe event* that might occur is crucial for disaster planning scenarios.(73) The largest *solar flare* ever recorded in satellite data was on November 4, 2003 (see Table II).(30,45) Given the rarity of very large solar flares, analysis of Sun-like stars using, e.g., NASA's Kepler spacecraft(74,75) suggests that superflares (∼10x Carrington) may occur on millennial timescales, but this is still controversial.(76–79) On this basis, the probability of a flare in the next 30 years whose strength broadly exceeds that observed in 2003 is about 10%.(56)

Direct measurement of *extreme solar radiation storms* is limited to the "space age,"(80) the largest observed being in August 1972.(20) Statistics are therefore very limited. So-called ground-level events in neutron monitor data provide a somewhat longer proxy data set,(81,82) but their geographic variability is unpredictable. Polar ice core nitrate concentrations are no longer considered to be a reliably proxy of

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[10] See, for example, the World Meteorological Organization's list of national and international agencies that provide space weather services: http://www.wmo.int/pages/prog/sat/spaceweather-catalogue_en.php.

event intensity.(56,83) Alternative proxies, Carbon-14 (in tree rings) and Beryllium-10 (in polar ice cores), are of current interest,(84,85) strongly suggesting an intense global atmospheric radiation event occurred around AD775(86–89) due to the Sun.(87,90–92)

Geomagnetic storm statistics are more complex because likelihood depends on both the solar wind driver (typically, but not exclusively, a CME) and the magnetospheric response. The probability of a Carrington-like event occurring in the next decade is estimated to be 12%(55) (50% in the next 50 years).(17) The probabilities of a superstorm event (worse than Carrington) and a 1989 event are calculated as $0 < 6.3\% < 23\%$ and $3.4\% < 17.8\% < 38.6\%$ in the next 10 years, respectively (95.4% Bayesian C2 confidence interval).(58) Finally, although weaker storms are correlated with the strength of the solar cycle, strong storms are not, and so could arise even in epochs where the Sun was quieter, as was the case for both the Carrington event and the 2012 event.(93)

2. SPACE WEATHER: DOCUMENTED IMPACTS

2.1. Power Grids

Geomagnetically induced currents (GICs)(94) associated with geomagnetic storms may damage physical infrastructure (specifically transformers), introduce voltage instabilities that can lead to a blackout without infrastructure damage, and interfere with protection systems and fault detection.(17,35,95–97) It is important to note that the ionospheric current systems that couple to GICs are very structured, and are most intense at relatively high latitudes in the vicinity of the auroral ovals. The aurora and associated current systems descend in latitude during strong geomagnetic storms. Consequently, impacts are not restricted to high latitudes(48,98–101) and have been documented in the United Kingdom,(17,43,102) Finland,(95,103) Sweden,(50) Spain,(104) the United States and Canada,(42) South Africa,(100,105,106) Japan,(107) China,(108) and Brazil.(109) The impact of geomagnetic storms on the North American power grid has been the subject of multiple reviews.(110–113) For example, 4% of the disturbances between 1992 and 2010 reported to the U.S. Department of Energy are attributable to strong geomagnetic activity.(114) Recent technical assessments in the United States and the United Kingdom find that the most likely impact is system collapse due to voltage instability with some transformer damage.(17,112)

2.2. Oil and Gas Industry

GICs can cause changes in pipe to soil voltage that drive enhanced corrosion.(115) Aeromagnetic surveys and precision drilling are affected by magnetic fluctuations during geomagnetic storms.[11] However, it has proven difficult to obtain information on specific documented impacts from anywhere within these industries.

2.3. Communications

Mobile network performance can be affected by solar flare radio noise;(116) these effects are hard to discern among various other variables controlling service quality.(17) Certain mobile networks may be affected by the loss of global navigation satellite system (GNSS) timing information. *Short-wave, high-frequency (HF) radio* is used by aviation and shipping, as well as the military.(17,46,117) During geomagnetic storms, regional and global reductions in the operational HF band occur. Modern HF systems are designed to be resilient, but legacy systems may experience outages. During a Carrington event, HF communication performance could be affected for several days.(17) *Optical fiber networks* require repeater stations to periodically boost the signal; associated power infrastructure is at risk to GICs.(118,119)

2.4. Ground Transportation

Rail networks are in principle susceptible to GICs.(120,121) There is potentially considerable economic benefit to the rail industry in the use of space—e.g., for signaling, communications, monitoring, and Earth observation (landslides, etc.).(122) However, a substantive issue is how geomagnetic storms could interfere with the electromagnetic environment along the railway, including safety critical systems. *Trams and light railways* may be similarly affected, and all mass transit would be severely impacted by power loss (especially for underground mass transit). Finally, a more speculative space weather impact in the future is that on *driverless cars* and *road charging* based on GNSS.

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[11] See, for example, http://geomag.bgs.ac.uk/data_service/directionaldrilling/home.html.

2.5. Satellite Infrastructure

Satellites are at risk from the space environment.(123,124) Energetic electrons trapped in the outer radiation belt cause electrostatic charging and discharging, which can damage sensitive electronic equipment and solar panels.(125–129) SEPs can cause displacement damage (reducing device performance) and single event effects (SEEs),(130–132) which are a growing issue as devices are miniaturized.(17) During the 2003 Halloween storms, 47 satellites reported anomalies (out of 450 in orbit, i.e., ~10%), one scientific satellite was lost, and 10 satellites lost operational service for more than one day.(17,46,47) Complete losses have thus been rare since satellites are designed to tolerate a total dose over some lifetime, with good safety margins: temporary outages and fleet aging are both more likely.(17)

2.6. Global Navigation Satellite Systems: Disruption to Service

Space weather causes signal distortion (scintillation and loss of lock) in the ionosphere and does not have a significant impact on GNSS satellites themselves.(17,133) Disruption to *positioning and timing* services would occur during a major space weather event, affecting many sectors (e.g., communications, financial trading, energy networks, etc.). Augmented GNSS systems (e.g., EGNOS and WAAS aviation systems(17)) may be particularly vulnerable when very large geomagnetic storms cause signal scintillation and physical differences between the conditions at the receiver and the reference station. During a major storm, complete loss of GNSS service for one day is estimated, with extended loss of service for three days.(17) Although many systems can revert to backup technologies, the impact of the reduced accuracy over a prolonged multiday outage is not well understood or verified.

2.7. Aviation

Solar radiation storms enhance the cosmic-ray-generated radiation environment at flight altitude.(134–137) A perhaps counterintuitive effect is that energetic particle radiation can diminish during/after a geomagnetic storm (a Forbush decrease) because the CME can block Galactic Cosmic Rays, which leads to a complex balance of effects.(138) Radiation storms have a technological(134,139–141) and biological impact (due to the fact that the radiation is ionizing).(142,143) While unlikely, mandated crew dose limits could be reached in part due to severe space weather;(141) the wider impact has also been examined.(17) Reduced flight time at high altitude may be required should a severe energetic particle event to occur during flight,(134) and this would have a commercial/operational impact, including delays and increased fuel use,(141) since events arrive without warning and may persist for several hours.

A severe loss of HF radio may lead to communications with most aircraft in the north Atlantic being lost. Aircraft already in flight would continue, but those on the ground would probably not be allowed to take off.(17) At high latitudes where satellite communications are unavailable, HF communication is mandatory. Polar routes have been disrupted by space weather and lost HF communications.(16)

3. ECONOMIC COST OF SPACE WEATHER

The literature studying the vulnerability of different industry sectors to space weather rarely extends the analysis to the actual quantification of economic losses resulting from space weather events. The few contributions available mainly focus on power grid losses. Some studies either present the views of the insurance sector or rely on its pricing models. Insurers' pricing models offer a robust methodological approach to economic cost quantification,[12] but details on data and methodology used are typically undisclosed. Very few scientific studies go beyond a scenario-based quantification of direct economic losses of specific sectors and exposures. When they do, they usually focus on a specific sector's vulnerability (e.g., power grids), and explore its propagation across other sectors via input–output analysis.(146)

3.1. Broader Impact

The National Research Council's Committee on the Social and Economic Impacts of Severe Space

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[12] Insurers decouple loss occurrences into a hazard component (event occurrence) and a loss severity component (damage conditional on the hazard event occurrence). The hazard event is translated into *direct* economic/social losses via a vulnerability function, which depends on the characteristics of the risk exposure (rating factors in the language of (re)insurance pricing models). The quantification of *indirect* losses (e.g., business interruption) instead typically relies on econometric models, input–output analysis, or equilibrium models.(144–146)

Weather Events report summarizes a 2008 workshop and participants' views on current and future risks and vulnerabilities across different industry sectors.(16) Although no holistic quantification of economic costs is attempted, the report collects information useful across a number of sectors, and provides suggestions for sector-specific risk mitigation techniques. It supports quantification based on approaches similar to insurance pricing models and catastrophe risk models. A 2011 OECD report supports the use of a threat-vulnerability-consequence template, but suggests that efforts should be aimed at going beyond insurers' focus on replacement costs to capture broader societal costs.(9) The latter should rely on estimates of consumers' willingness to pay and opportunity costs. The report also emphasizes the importance of systemic risks arising from interconnected economies and sectors. However, no estimates of economic costs arising from compounding of losses via network interlinkages are provided.

The impact of severe space weather events on global supply chains and the global economy has recently been studied, explicitly considering both direct and indirect losses and adopting the input–output methodology for the first time. Restricted to the systemic effects of the power transmission system failure and interruption, "[f]or a 1989 Quebec-like event, the global economic impacts would range from $2.4 – $3.4 tn over a year."(147) This analysis examines the implications of such an event occurring at different locations around the world (e.g., North America, China, and Western Europe) and assumes an outage of one-year duration based on the presumed long-lead times needed to replace destroyed transformers, as described in the next section.

3.2. Power

The estimated economic impact of the most severe events strongly depends on the assumed technological impact footprint, where there is some controversy. Several studies have assumed that a one in 100-year event (i.e., worst-case Carrington class) would cause catastrophic impact, with major transformer damage/failure and permanent loss of generator step-ups, taking a considerable length of time (4–10 years) to recover from. Generator step-ups are important because of compounding difficulties arising from network effects (loss of output of vital and usually baseload nuclear, coal, and hydroelectric generation resources for the power grid). The consequent economic impact is in the range of trillions of dollars because of the lack of power for a very prolonged period.(16,113) In a separate assessment that assumes extended power outages lasting from 16 days to one to two years, and minimum transformer replacement lead times of five months it has been suggested that the estimated total economic cost of a Carrington-level storm is $0.6–$2.6 tn(12) in the United States. This is based on an affected population of 20–40 million. However, data and methodology are not fully disclosed.

A recently completed study also focuses on losses resulting from damages to transformers and associated power outages in the United States, resolved to the level of individual U.S. states taking account of geomagnetic latitude, ground conductivity, and the number of transformers in each state.(148) Three different "stress test" scenarios are presented to help inform the insurance industry about the possible range of impacts a severe space weather event may cause, including a plausible worst-case scenario where there is significant transformer damage causing prolonged power outage. The difficulty of procuring and installing replacement extra high-voltage transformers is discussed in detail. For each scenario, direct and indirect costs are calculated, the latter being quantified via input–output analysis. The total economic loss varies between $0.5 tn and $2.7 tn based on calculations examining disruption to the global supply chain. An alternative methodology finds a total loss of $140–$613 bn. This is lower as it accounts for the "dynamic response of the global economy." Losses to U.S. GDP are estimated to range between $136 bn and $613 bn over five years following the space weather event, with the worst affected states being Illinois and New York. It also indicates significant knock-on impacts on the global economy with China, Canada, and Mexico being the worst affected (as they are the United States' largest trading partners), but also significant impacts on the United Kingdom, Japan, and Germany. The report(148) also develops analyses of impacts on insurers' payouts and investors' portfolios. The losses to the U.S. insurance industry are estimated as $55.0–$333.5 bn, and it is noted that this upper limit is "similar to the total insured losses from all catastrophes in 2015."

The assumptions that lead to a very severe worse-case-scenario impact footprint are not universally accepted. Both the North American Electric Reliability Corporation (NERC) and the U.K. Royal Academy of Engineering (RAE) specifically find that the more likely impact is system collapse due to voltage instability rather than catastrophic infrastructure destruction.(17,111,112) The NERC report examines past transformer failures, as well as experimental data concerning transformer heating as a function of applied direct current. It is argued that during a major geomagnetic storm, design thresholds are unlikely to be exceeded. While transformers that are near end-of-life or employ older designs may be more at risk, it is nevertheless concluded that voltage instability is the most likely primary impact. The RAE report focuses on the United Kingdom in particular, and its conclusion is reached on the basis of studies and assessments undertaken by the National Grid. In particular, it is noted that since 1997, newly installed transformers have employed a more GIC-resistant design, which strengthens resilience. Outages are therefore measured in hours to days, rather than months, but such events still have a considerable economic impact through primary and secondary losses.(149) As examples, the economic impact of Hurricane Katrina was estimated to be \$81–\$125 bn(150) and the August 14, 2003 northeast blackout was \$4–\$10 bn.(151) Analyses of historical blackout events in the United States indicate that even short blackouts, which occur several times during a year in the United States, sum up to an annual economic loss between \$104 bn and \$164 bn.(152) These figures are based on insurance industry pricing models for business interruption insurance. (Details on data and methodology are not publicly available.)

Space weather impacts are not necessarily restricted to catastrophic effects. Insurance claim information suggests that the losses to the U.S. power grid from noncatastrophic disturbances from GICs "may be \$5 – \$10 bn/year."(153) The effect of space weather on generation outages, transmission congestion, wholesale real-time electricity prices, and resulting day-ahead prices has been examined,(154) as has its effects on electricity prices and spinning reserves using regression analysis to compute sensitivities.(155) A follow-up study examined GIC impact on different power grids using a variety of metrics, but translation into economic losses, however, was not addressed.(156) Finally, a study of South African power system impacts indicates that interruption costs correlate with business activity levels according to the seasons and time of day, and both this and the cost of interruption can be represented by β probability density functions.(101)

3.3. Satellites

It is likely that many encountered problems remain undisclosed due to commercial and security sensitivities.(17) An initial attempt to quantify losses from the bottom up by modeling factors well known to affect satellite resources (solar power erosion, orbit decay, etc.) led to an estimated \$70 bn cost from lost revenue and satellite replacement for a 1859-calibre superstorm.(157) The failure of Intelsat's Galaxy-15 spacecraft in April 2010, probably due to space weather, provides a useful case study.(11) It is indicated that the satellite builder is spending around \$1 m on remedial actions and is facing the loss of payments linked to in-orbit performance worth \$7 m. As it was not even four years into its 10–15-year operational life, the potential total loss is estimated to be \$100 m based on a satellite cost of \$250 m.(11) Consequently, direct and indirect economic costs of space weather damage should be recoverable from publicly available information on length of satellite outage or replacement cost in case of total loss.(17,123)

3.4. Other Sectors: GNSS, Aviation, Pipelines, and Transport

While there is no specific literature available on the economic cost of space weather impacts on GNSS, aviation, pipelines, or transport, initial efforts have been made that may aid analysis: for example, attempts have been made to quantify the fraction of U.S. economic activity dependent on GNSS services.(158) In aviation, it is reported that United Airlines closely monitors this risk dimension given its high numbers of polar routes.(16) However, no estimates of economic/health costs are available beyond anecdotal evidence of operational costs ranging from flight delays and fuel stops resulting from diversion from polar routes following space weather events.(16) Models have been developed to obtain spatial information about the distribution of pipeline GICs,(159) and this framework could be used to determine space weather economic cost from the bottom up. Finally, information on Russian and Swedish railway failures due to space weather events(120,121,160) should be rich enough to estimate the associated economic costs based on transportation networks literature, and extrapolate to other countries.

4. CONCLUSIONS

Although space weather is now a widely recognized risk, its economic impact remains quite uncertain. Further work is required to comprehensively assess both direct and indirect losses across a diverse range of sectors. While the physical nature of space weather is the best-understood aspect of the problem, there is a lack of agreement in the realistic technical footprint of the most severe space weather event, and this leads to dramatically divergent cost estimates. Therefore, a second research gap is to accurately quantify the technical impact of space weather in a variety of industries (power, satellite, aviation, GNSS, etc.). Given its rising importance, GNSS may be a particularly important sector to analyze. Two challenges stand out. First, modern society is yet to experience a Carrington-level space weather event, and so projections of economic impact will inevitably be subject to uncertainty. Second, quantifying technical impacts fundamentally relies on the participation of industry by providing appropriate data, and this often conflicts with commercial sensitivities. Since exposure to space weather risk is only likely to increase, urgent effort is required to address this tension.

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