Description of document: National Aeronautics and Space Administration (NASA) Report: A Rigorous Foresight Approach to Understanding and Modeling the Societal and Economic Impacts of Space Weather Events, 2018

Requested date: 28-September-2020

Release date: 29-September-2020

Posted date: 02-November-2020

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September 29, 2020

Office of Communications

REF: 20-NSSC-F-00812

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Sincerely,

Martha Terry
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A Rigorous Foresight Approach to Understanding and Modeling the Societal and Economic Impacts of Space Weather Events

Forecasting the impacts of space weather events under different scenarios of societal and technological development

Report prepared for NASA's Emerging Space Office by Vision Foresight Strategy LLC

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This report and all supporting applications, data, documents and files were created in fulfillment of NASA Research Announcement Solicitation: NNA15ZBP0001N-B1, Economic Research for Space Development, Emerging Space Office

Funded by NASA Emerging Space Grant 80NSSC17K0328

Executive Summary

Purpose

An extreme space weather event has the potential to inflict trillions of dollars of damage to the global economy by disrupting and destroying critical infrastructure and triggering cascading failures in emergency response, governance, and military systems. To improve resiliency in the face of such events, we need to better understand the risks of space weather and our vulnerabilities to it, today and into the future. Much of the existing literature looks at the ramifications should an extreme storm occur today, but less examined is what impact that same storm might have were it to occur in 2050 as opposed to 2018, when technology and society may be very different. Current trends suggest vulnerability to space weather events is likely to increase over time as critical infrastructure systems become ever-more interconnected and governed by digital technologies and as humanity's presence off-world grows. But future vulnerability will depend on current and future policy choices and the particular technological, economic, and societal development pathways followed. This study's purpose is to provide a rigorous foresight approach to aid in our understanding of these future potentialities. Using a blend of qualitative and quantitative foresight methodologies, this study explores several development pathways, charting out society's changing vulnerabilities to space weather events—and the consequences from those vulnerabilities—under different scenarios of global development out to 2100.

Process

This study consisted of four interlinked processes: 1) an in-depth review of the literature regarding the science of space weather, its socioeconomic impact pathways, and the existing methodological approaches for modeling space weather and its impacts; 2) an emerging issues analysis aimed at identifying 'weak signals' of change—new technologies and other on-the-horizon developments with the potential to shape society's vulnerabilities and responses to space weather events; 3) a qualitative scenario analysis using the morphological box methodology to establish a framing set of alternate future pathways of societal development; and 4) a modeling project designed to provide quantitative forecasts of the potential costs and disruptions associated with space weather event occurrence. Each process led into and enhanced the next and all informed the creation of the Space Weather Impact Model. Each process is described in this report.

Major Findings

In conducting the supporting literature review for this study, we traced the main impact pathways by which space weather events can impact society, from direct 1st order impacts on critical infrastructures, and 2nd order indirect impacts stemming from the disruption of infrastructure services, to 3rd order impacts on society at large, and, after a review of various methods, identified system dynamics modeling and disaster impact/inoperability modeling methodologies as the best approaches to model these impact pathways. We also created a listing of past space weather events and gathered estimates of event severity and probability. Extreme space weather events are high-impact, low-probability events, with an estimated probability of occurrence of 1 to 1.2% per year. The poster children for extreme events are the 1859 Carrington Event and the 2012 Coronal Mass Ejection, either of which could cause catastrophic damage should they occur today. But even 'everyday' space weather can disrupt critical infrastructure networks and space-based assets. Thus, the ability to model, forecast, and prepare for all levels of space weather activity is vital.

Our emerging issues analysis identified 20 emerging issues with the potential to shape future vulnerability to space weather. In the process of doing so, we developed a database of over 250 'scan hits' covering developments in the political, economic, social, technological, and environmental space. This report provides the curated results of the emerging issue process—with supporting links to the sources—but a database containing all the scan hits accompanies this report. Some of the issues identified include: the potential for autonomous vehicles to provide alternatives to traditional ICT and satellite infrastructure, the growth of the global space economy, increasing automation and AI deployment, and the race to utilize the thawing

Through our scenario analysis, we crafted five scenarios of alternate societal development pathways that together help frame the factors and uncertainties tagged by our emerging issues analysis and found in the literature:

Tearing Ahead

A greater emphasis on short term growth and a failure of politics and policies to enforce smart, sustainable growth leads to a more crowded and haphazard world.

Resilient Redesign

Climate change and human demands collide, prompting a widespread search for innovative ways to house, feed, and support increasingly vulnerable communities and populations.

Starry Future

A global competition over technological innovation and great power competition propel the widespread digitization and automation of society and launch a new international space race.

Separate Paths

The evolution of a more fragmented world order leads to less integrated global systems and more divergent developmental paths among nations.

Halting Transformations

Spurred by the mounting pressures of climate change, population growth, and economic development, countries begin an uneven but determined push for more innovative and sustainable models of growth.

Using the Space Weather Impact Model, we found that the global economic disruption stemming from an extreme space weather event—depending on the timing and the scenario of societal development—could run in the trillions of dollars, from a low of $1.8 to $4.8 trillion dollars (in constant $2010) should one occur today to a high of $9.8 trillion should one occur in 2050 in a world ill-prepared to meet such a storm. Increasing infrastructure vulnerability and continuing economic growth will likely ensure that storms will become more damaging as time goes on, but the extent of the damage and the time to recovery can be greatly reduced by improving mitigation strategies, increasing defensive investments and improving governance systems. The same storm causes $1.5 trillion less in economic disruption in a world following the Resilient Redesign development path than the Tearing Ahead development path ($3.1 trillion less compared to the 'worst case scenario').

In the United States, the same extreme weather event would cause $340 billion to $780 billion in economic disruption in 2015 (significantly more than the 2017 record-setting hurricane season) and $500 billion to $1.4 trillion in 2050. In a scenario where the US embraces the 'Resilient Redesign' development path, the same storm causes $200 billion less in economic disruption than in a US following the Tearing Ahead development path ($600 billion less compared to the 'worst case scenario.'

In sum, we found that severe space weather events pose a significant risk to modern society—they not only have the potential to inflict economic damage at an unprecedented scale, but can, in the case of long-lasting disruptions, undermine governance systems including emergency response, defense, financial, and health systems from the local, to the global level. It could take years to fully recover from such an event, even in developed nations, and in developing countries, stalled or inadequate recoveries could lead to unrest and government collapse.

Future Directions

The foresight, modeling, and analysis conducted for this study provide a foundation for continuing to enhance our understanding of the economic and societal impacts of space weather. Based on this foundation and our findings to date, a number of potential next steps present themselves:

- Continued enhancement of the Space Weather Impact Module, including:
  - A more comprehensive economics model
  - More detailed space weather dynamics, including a spatial component to allow for different geographic areas of effect
  - Inclusion of additional critical infrastructure systems (governance, defense, finance, etc.) to the critical infrastructure and inoperability modules
  - Treatment of additional countries
  - The addition of a social (and societal) vulnerability index
  - An enhanced user-interface

- Deploying technology foresight and roadmapping methodologies to provide greater detail to the technological and societal development pathways described in this report, including identification of specific technology and policy needs to enhance system resiliency
- Further uniting the myriad literatures around understanding and modeling the impacts space weather events

Introduction

An extreme space weather event the magnitude of the 1859 "Carrington Event" or the July 23rd, 2012 'near-miss', should one occur today, has the potential to inflict trillions of dollars of damage to the global economy, disrupting and destroying critical infrastructure networks and triggering cascading failures throughout society—failures likely to challenge emergency, military, and governance systems, and likely to lead to significant impacts to human health and wellbeing (Baker 2017; Bäumen et al. 2014; Centra 2011; US House Homeland Security Committee 2009). Such an event would be a true global shock, directly impacting multiple countries across multiple continents and indirectly affecting the rest of the world. Recovery from an extreme space weather event would likely require a coordinated international response and, as the case of Puerto Rico and Hurricane Maria suggest, may take months to years to complete (Centra 2011).[1] Extreme space weather events are high-impact, low-frequency events, with an estimated probability of occurrence of 1 to 1.2 percent in any given year, making them the kind of event that is notoriously difficult for governments and businesses to mitigate cost-effectively. But even 'everyday' space weather has the potential to disrupt critical infrastructure networks and space-based assets. Thus, to improve resiliency across society, we must better understand the risks of space weather events and our society's vulnerability to them (Oughton et al. 2017).

It is also important that we better understand how our vulnerability to space weather events is likely to change in the future. Much of the existing literature looks at the potential fallout from an extreme space weather event should one occur today, but this tells us little about the impact the same storm might have were it to occur five, ten, or even one-hundred years from now, when technology and society may be very different. Current trends suggest that our vulnerability to space weather events is likely to increase over time as our critical infrastructure systems become ever-more interconnected and 'smarter' and as our presence in space grows. But this is not necessarily so; future vulnerability will depend on current and future policy choices and the particular technological, economic, and societal development pathways followed.

This study uses a foresight-driven approach representing a unique blend of qualitative and quantitative methodologies to explore how society's vulnerability to space weather events—and the consequences from those vulnerabilities—may evolve over time (out to 2100) through different scenarios of future global development. To better get at the concept of vulnerability to space weather, we have adapted the framework often used by the Intergovernmental Panel on Climate Change and supporting literature, that of *exposure, sensitivity, adaptive capacity,* and *resilience*, and reorganized the concepts into five categories:[2]

- The Extent of the Built Environment (*exposure*)
- The Nature of Critical Infrastructure Systems (*sensitivity*)
- Short-Term Mitigation and Recovery Capacities (*adaptive capacity part 1*)

[1] https://www.theatlantic.com/politics/archive/2018/04/puerto-ricos-next-public-health-challenges/558896/
[2] See Appendix A3 for definitions; http://www.ipcc.ch/ipccreports/tar/wg2/index.php?idp=650

- Long-Term Adaptive Capacities (*adaptive capacity part 2*)
- Policy Priorities/Societal Development Pathways (*resilience)*

Summary of Deliverables

Final Report

This report includes a review of key literature, details the design and construction of the Space Weather Impact Model, describes a set of qualitative societal development pathway scenarios based on the identification of emerging issues, and provides full analysis of the project's quantitative and qualitative results.

The Space Weather Impact Model (SWIM)

A quantitative forecasting model designed to calculate the extent of global economic disruption caused by space weather events. Users can use the model to examine event impacts taking into account different storm types, strengths, and durations as well as societal and technological developments over time.

Scenarios of Societal Development

Built through the combination of two qualitative foresight methodologies (morphological boxes and Emerging Issues Analysis), the Scenarios of Societal Development includes five different scenarios of realistic future pathways of development, each representing a different vulnerability 'footprint.'

Environmental Scanning Library

Over the course of this project we conducted extensive Emerging Issues Analysis and Environmental Scanning in order to identify some of the up-and-coming technologies and other societal changes likely to impact the five concepts of vulnerability identified above. These 'scan hits' are summarized in the final report while the full collection has been organized into an accompanying database.

Project Database

Includes all of the historical and exogenous forecast data used to initialize the SWIM as well as space weather-related data, including a list of historical events and estimates of storm severities and probabilities.

Literature Review

What is Space Weather?

"Space Weather includes any and all conditions and events on the Sun, in the solar wind, in near-Earth space, and in our upper atmosphere that can affect space-born and ground-based technological systems, and through these, human life and endeavor."–NASA[3]

Space weather is a multipart phenomenon that arises out of interactions between three main systems: activity on the Sun is the source of space weather, when changes in the Sun's magnetic

[3] https://www.nasa.gov/mission_pages/sunearth/spaceweather/index.html#q11 [accessed on 3/18/2018]

field give rise to discharges of energetic particles in the form of solar flares, coronal mass ejections, and high-speed solar winds (system 1). These discharges, in turn, interact with the Earth's magnetic field and upper atmosphere to generate storms (system 2) that can have deleterious impacts on society through disruptions to our infrastructure networks and the many services dependent on them (system 3).

Space weather events are usually divided into different types of storms based on their interactions with the Earth system (and their technological impacts), though a single space weather 'event' can encompass any or all storm types over the course of the event (Eastwood 2017). This report uses the classification developed by the National Oceanic and Atmospheric Administration's (NOAA) Space Weather Prediction Center, which divides space weather into three categories, each with their own scale of severity (see Appendix 5): 1) Geomagnetic Storms (G-Scale); 2) Radiation Storms (S-Scale)—also sometimes referred to as energetic particle storms; and 3) Radio Blackout Storms (R-Scale)—also sometimes referred to as ionospheric storms (Schrijver et al. 2015).

Once they reach Earth, space weather events progress through three main phases: an initial phase, which can last from minutes to hours, where initial interactions with the Earth system being, the main phase, which can last from 30 minutes to several hours and where peak disruptions to the Earth's magnetic field and earthly and human systems occur, and a recovery phase—the longest phase—ranging from days to weeks, where the Earth's magnetic field returns to normal (Centra 2011).

Types of Space Weather

Geomagnetic Storms

Geomagnetic storms can occur when a coronal mass ejection (CME)—a burst of charged solar plasma—collides with the Earth's magnetic field, setting up interactions between the CME's and Earth's magnetic fields, the upper atmosphere (ionosphere and magnetosphere) and the Earth's crust. These interactions generate ground-level variable magnetic fields that, in turn, can induce electrical current flow in the Earth's crust and through susceptible ground-based infrastructure systems. Such storms can also directly affect satellites in low-earth orbit through increased atmospheric drag (Coker 2017; Baker 2016).[4] A geomagnetic storm's strength depends on a number of factors: the originating CME's speed, the orientation of the CME's own magnetic field, and the orientation of the Earth and its magnetic field. In general, the most severe geomagnetic storms tend to result from high mass, fast-moving CMEs with southward-oriented magnetic fields (Oughton et al. 2017). Such storms can cause distortions and disruptions in the Earth's magnetic field lasting for days after the initial impact, increasing vulnerability to any following space weather (Bäumen et al. 2014).

[4] https://www.swpc.noaa.gov/phenomena/geomagnetic-storms

Radiation Storms

Radiation storms, also referred to as energetic particle storms, are the result of emissions from solar flares and high-speed solar wind streams. Collision with these energetic particles can cause ionizing radiation that can be hazardous to human health as well as disruptive to electronics (AMS 2007).

Radio Blackout Storms

Radio Blackout Storms, sometimes also referred to as ionospheric storms, stem from interactions between the intense x-rays and other high-energy photons released by a solar flare and the Earth's thermophore and ionosphere. These interactions can cause additional ionization of particles in the ionosphere, resulting in scintillation that can disrupt various communication systems, including high-frequency radio (HFR) and satellite transmissions (Baker 2016).

Event Severity and Probability

Just how severe can a space weather event be? And how often do extreme storms occur? What about the frequency of relatively weak but still impactful events? Understanding the probability and severity of space weather events is the first step in establishing the risk level posed by space weather. When it comes to space weather events, there are two main ways to measure severity: 1) physical measurement of the event's characteristics—particularly the amount of disruption or deformation the event inflicts on the Earth's magnetic field and upper atmosphere; and 2) the projected or actual impact of the event on human technologies and society. This section focuses on the physical measurement of severity, as a given event's potential technological and societal impacts depends not only on its physical characteristics but also the level of vulnerability of the technologies in question, as a relatively weak event affecting an ill-prepared society might cause significantly more damage than a relatively strong event impacting a well-prepared society (we return to societal vulnerability below).

A space weather event's physical severity depends on multiple factors: 1) the event's own physical characteristics (its mass, charge, magnetic field strength and orientation, and the type(s) of radiation and energetic particles included); the speed of the surrounding solar wind; and the orientation of the Earth (the planet's axial tilt relative to the Sun) and its magnetic field when the event arrives (Cid et al. 2014).

The *Dst* Index is one of the most common methods used to assess physical severity. The *Dst* Index measures the amount of change or disturbance induced by an event in the ring of current surrounding the Earth's middle latitudes. The Index represents a globally-averaged measure of this disturbance, created by averaging the readings from multiple magnetometers located around the Earth (Baker et al. 2013). Reconstructed *Dst* values have also been used to measure the severity of pre-modern events like the "Carrington Event" (Cid et al. 2014). In general, the more severe the event, the lower the *Dst* Index value; depending on the study, index values below -250/-500 nanoTeslas (nT) are considered to be extreme (Cliver and Dietrich 2013). Table 1 provides a sample range of event severity using the *Dst* Index. Severity is also sometimes reported in positive nanoTeslas per minute (nT/min), with higher values being associated with greater potential to cause damage (Centra 2011).

Table 1: Event Severity Based on *Dst* Index	
Severity	*Dst Index* value (nT)
Mild	0 to -49nT
Moderate	-50 to -99nT
Intense	-100 to -249nT
Extreme	-250nT and below/also -500nT and below
Source: Cid et al. 2014	

The four severity levels described in Table 1 are based on the known range of physical severity—that is, they are derived from observations of historical space weather events (examples of which are given below). A final category, 'super storms' is sometimes added, where 'super storms' represent the potential maximum severity of a space weather event based on observations of other Sun-like stars (super flares) and on the geological record here on Earth (Lingam and Loeb 2017).

Extreme Space Weather Events

The "Carrington Event" of 1859 and the coronal mass ejection of July 23rd, 2012 are the two most severe space weather events ever directly observed with *Dst* values of ~-850nT (inferred) and ~500nT, respectively (Baker et al. 2013). They are used in the literature to represent the known upper range of severity and are therefore considered extreme events. A number of studies put the probability of an extreme space weather event of comparable magnitude occurring in a given year at about 1 to 1.2%--the space weather equivalent of a 100-year flood or 9.0 earthquake (Bäumen et al. 2014; Baker et al. 2013; Riley 2012). Lloyd's of London (2013) estimates the frequency of an extreme event to be about once every 150 years (.66% in any given year).

Super Space Weather Events

Geological analysis and the observation of other Sun-like stars both suggest that space weather events of severities many more times those so far witnessed in the modern era are possible. Eastwood (2017) notes that our Sun (like other G-class stars) is potentially capable of producing 'super-flares' (a solar flare roughly ten times stronger than the Carrington Event flare) once ever few thousand years, though this remains controversial. Eastwood draws on this possibility to calculate the probability of a solar flare stronger than any yet recorded (the strongest on record is the 2003 solar flare) occurring within the next 30 years at 10% (roughly .33% in any given year).

Love and Gannon (2009), meanwhile, provide estimated probabilities for space weather events at many different levels of severity (Table 2).

Table 2: Event Severity and Frequency	
Severity (*Dst*)	Frequency (years)
>100	4.6 per year
>200	9.4 per 10 years
>400	9.73 per 100 years
>800	2.86 per 1,000 years
>1,600	7.41 per 1,000,000

NOAA Space Weather Prediction Center's Space Weather Scales of Severity provide a useful scale for rating storm severity in terms of both physical measurements and expected direct impacts to human systems and probability of occurrence. Ratings provided for the three main storm types, the G-scale for geomagnetic storms (from G1 minor to G5 extreme), the S-scale for radiation storms (S1—S5) and the R-Scale for radio blackout storms (R1—R5).[5] The SWIM system adopts this system for its user-defined storm 'interventions.'

A key takeaway from the literature regarding space weather event severity and frequency is not to focus solely on the most extreme/rare events, as even mild/frequent events can still have measurable impacts on human technologies and therefore society. Schrijver (2015) recommends viewing space weather events as a continuum, running from mild/frequent events to extreme/rare events, and that effective mitigation strategies must address the full spectrum of severity/possibility. Schrijver also points out that efforts to address 'mild' events can help lay the groundwork necessary for preparing to weather extreme events. Another takeaway is the need to consider both physical strength and potential societal and technological impacts when determining whether an event is extreme or not (Cid et al. 2014).

Geographic Distribution

The Earthly severity of space weather events has a strong geographical component, particularly for geomagnetic storm events. All else being equal, higher latitudes—especially above the auroral circles (the zones of electrojet current flows in the ionosphere at the Earth's poles—are most susceptible to geomagnetic storm effects due to the nature of the Earth's magnetic field. But the auroral circles are not static, severe to extreme space weather events can shift the auroral circles to lower latitudes. Recent studies by Ngwira et al. (2013), Pulkkinen et al. (2012) and Thomson et al. (2011) all suggest that geomagnetic latitudes between 50° and 55° tend to be

[5] https://www.swpc.noaa.gov/sites/default/files/images/NOAAscales.pdf [accessed 4/26/18]

particularly affected during extreme geomagnetic storms (a geographic band that includes the cities of Chicago, Washington DC, New York, London, Paris, Frankfurt, and Moscow in the Northern Hemisphere, and Melbourne and Christchurch in the Southern) (Oughton et al. 2017). But even lower latitudes can be at risk from extreme storms: the Carrington Event caused auroral displays as low as 23° North and South (Lakhina et al. 2005).

The two other space weather storm types, Radiation and Radio Blackout, are also most impactful at higher latitudes, with the polar regions especially affected.

But unlike the other two storms, Geomagnetic storm severity also has a major geological component: especially the conductivity of local geological formations and the distance of the affected area to the coast (Bäumen et al. 2014).

Despite the tendency to focus on the world's northern- (and southern-) most areas, a growing list of countries have directly experienced damage from past space weather events: Australia, Brazil, Canada, China, Finland, Japan, New Zealand, Norway, South Africa, Spain, Sweden, Turkey, the UK, and the US (Oughton et al. 2017; Eastwood 2017).

Space Weather's Impacts

As mentioned above, the potential impacts of space weather events depend not only on their physical severity but also on geographic and geological factors, temporal factors (the time of day and season), the specific vulnerabilities and interdependencies of the systems directly impacted, and the level of demand and overall economic and societal reliance on the impacted systems (Centra 2011). This all goes to make the task of tracing specific impact pathways and estimating the extent of impacts a difficult proposition to say the least. It is important, therefore, to frame the significant uncertainties around space weather's societal impacts before pushing on to exploring those pathways and impacts. These uncertainties are particularly large when it comes to extreme and 'super storm' events. This is, in part, due to a lack of experience with extreme events (with even the number of past non-extreme events being rather limited), but it is also due to a lack of established definitions and lingering unknowns around actual infrastructure impacts.

Impact Pathways

The different forms of space weather events (geomagnetic storms, radiation storms, and radio blackout storms) tend to impact different types of infrastructure systems and thus can have multiple direct and indirect impacts on society. For the purpose of this project, we have drawn on the existing literature to identify a number of Impact Pathways by which physical impacts to the Earth system can lead to disruptions in human technologies and society (see Figure 1, below). Each Impact Pathway consists of direct, 1st order impacts (systems directly disrupted by the space weather event), indirect 2nd order impacts (disruptions to additional systems due to dependence on the directly disrupted systems), and indirect 3rd order impacts (the fallout from system disruptions, including overall economic damage, loss of human life, and governance/organizational issues)

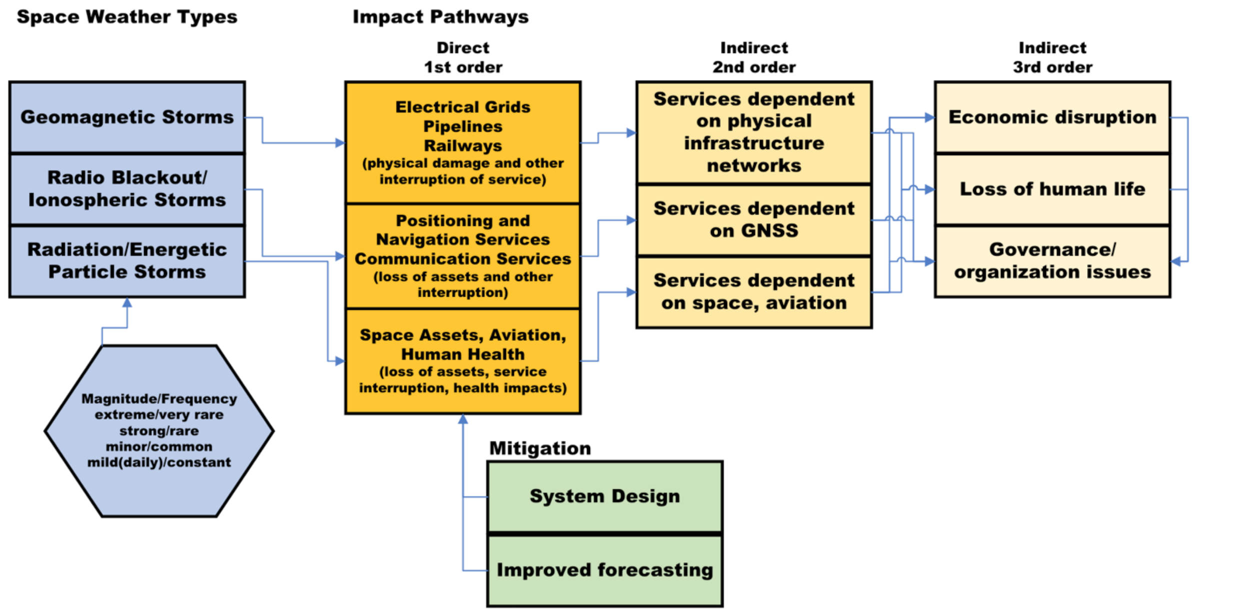

Figure 1: Space Weather Event Impact Pathways
Source: Authors' conception

First Order (Direct) Impacts

Electrical Infrastructure

Electrical infrastructure is often identified as a critical infrastructure[6] as so much of modern society depends on a continuous supply of electricity. When electricity is lost, nearly every other infrastructure will experience either an immediate or subsequent failure as backup power sources run out (Baker 2012). Combined with the fact that space weather's impact on electrical infrastructure is the best documented of all direct impacts and appears to be the most common place, many studies exploring the potential impacts of extreme space weather focus entirely on electricity disruption. In North America alone, space weather (daily emissions and discrete events) is estimated to have been responsible for roughly 4 percent of all electrical disruptions and disturbances between 1992 and 2010.

Space weather disruptions to electrical infrastructure are most often caused by ground-induced currents (GICs) associated with geomagnetic storms. GICs have been known to physically damage electrical infrastructure, especially transformers, through the generation of excess current, but can also trigger blackouts without causing physical damage due to the ability to induce high voltage instabilities and to interfere with protection and fault detection systems (Eastwood 2017;

[6] The term critical infrastructure refers to the "array of physical assets, processes, and organizations" which provide the goods and services upon which "the Nation's health, wealth, and security rely…" This includes physical infrastructure like the electrical grid and governance infrastructures like defense and emergency response (Pederson et al. 2006).

Baker 2016). Today's electrical grids, with their long-distance transmission lines, are particularly vulnerable to GICs (Baker 2016).

A key uncertainty for space weather's impact on the electrical grid is whether and to what extent an event physically damages or destroys EHV transformers due to their long manufacture and replacement times. The Department of Energy (2014) puts the time to manufacture an EHV transformer at between 5 and 12 months (domestic) and 6 to 16 months (international). When transport and installation time is included, the potential replacement time could be well over a year. There are several historical examples of EHVs being damaged by space weather events (see below), but there remains much debate over how vulnerable today's transformers are (Eastwood 2017; Baker 2016).

Energy Infrastructure

The energy sector is also vulnerable to direct impacts from space weather events. In the case of geomagnetic storms, GICs can damage oil and gas pipelines through accelerated corrosion—if there are insulation failures—and or by disrupting corrosion-control circuitry (Eastwood 2017; Lanzerotti 2017; Baker 2016).

Communications Infrastructure

A space weather event can cause signal degradation and disruption in many communication systems through radio interference and scintillation effects in the atmosphere. High-frequency (HF) radio communications used by aviation, shipping and the military (also UHF), and satellite to ground communications are most vulnerable, especially legacy systems (Eastwood 2017). There is still debate over whether cellular communications are likely to be directly disrupted, and research into the direct impacts remain limited, but the loss of GPS timing and location services and electricity for cellular towers can result in network outages (after onsite batteries run down) (Baker and Lanzerotti 2016). Line-of-sight terrestrial radio may experience increased noise/static as a direct effect but otherwise should remain usable (MacAlester and Murtagh 2014; Perron 2014).

Space-Based Infrastructure

Satellites

The global satellite fleet is naturally vulnerable to conditions in space, and during a space weather event, both hardware and satellite provided services (e.g. GNSS) are potentially at risk. Complete losses of satellites are rare however, due to measures taken to protect satellites from the standard space environment. According to Eastwood (2017), the 2003 Halloween storm adversely impacted only about 10% of the global satellite fleet at the time, with 47 reporting anomalies, 10 suffering full service loss for at a day or more, and only one being a total loss. Temporary faults and signal disruption are therefore the most likely impacts from space weather.

Signal Disruption

Space weather events can cause significant degradation or even disruption to satellite to ground communications (trans-ionospheric signals) lasting up to days. Such disruptions are most often due to distortions in the ionosphere (ionospheric electron-density variability) which can cause scintillation effects and "loss of lock." Augmented GNSS systems (EGNOS and WAAS) may be particularly vulnerable (Eastwood 2017; Schrijver 2015).

Radiation Damage and Single Event-Upsets

The space environment is full of radiation. Energetic particles (ions), whether in the form of cosmic rays, the naturally occurring radiation of the Van Allen Belt, or energetic particle emissions from the Sun, can all cause physical damage to satellites, especially to sensitive electronic components. There are two main forms of radiation damage: dose effects, or the buildup of radiation effects over time, and single particle effects, where a high-energy heavy ion passes through a spacecraft's electronics causing a Single Event Upset (SEU). SEUs are becoming "an increasing concern" to satellite operations as onboard electronics are increasingly miniaturized (Baker 2016).

Spacecraft Charging/Discharging

During a space weather event, the Earth's natural radiation belts can become 'enhanced,' as additional highly-energetic electrons become trapped in the belts. Upon encountering a spacecraft, such particles can cause an electrical charge to build up in one section or subsystem of the spacecraft that is then discharged to another, resulting in material damage, electrostatic noise, and phantom signals (Baker 2016).

Atmospheric Drag

Interactions between space weather events and the Earth's upper atmosphere can cause the uppermost layers of the atmosphere to expand, increasing drag on low-orbiting satellites. Increased drag can alter orbits, and in extreme cases, lead to the deorbiting and reentry of a satellite (Baker 2016).

Human Spaceflight

The International Space Station and any crewed vehicle require protection for both hardware and crew. Outside the protection of the Earth's magnetic field and atmosphere, even minor space weather events can pose a real risk to craft and crew. Emissions of energetic particles are the primary danger, making forecasts and fast detection of space weather essential.

Transportation Infrastructure

Aviation

Aviation, especially transpolar aviation, is vulnerable to both direct and indirect disruption from space weather events. The primary direct impact is the disruption of the high-frequency radio bands used in long-range and transpolar airline communication. Loss of such communications, due to x-ray and other energetic particle emissions, can last from hours to days at polar latitudes (above 78°), requiring transpolar flights to be rerouted to lower latitudes. Such rerouting can cost airlines $100,000 per diversion due to operational and refueling costs (Eastwood 2017; Schrijver 2015). The "Halloween Storm" of October 2003 blacked out transpolar aviation communications for 18 days, causing considerable disruption to the industry (Eastwood 2017). Increased radiation levels from space weather events pose a second, direct impact, again especially for transpolar aviation, affecting both avionics and human health. While unlikely, it is possible that increased radiation from a space weather event could cause flight crews to exceed mandated radiation limits, reducing available flight times (Baker 2016).

Ground Transportation

While not nearly as vulnerable to direct disruption as aviation, several ground transportation systems are at least potentially vulnerable to direct disruption, especially rail and light rail networks, where a severe geomagnetic storm could disrupt critical safety systems along the railway via GICs induced by long stretches of metal track (Eastwood 2017; Baker 2016).

Human Health

While most human-health related impacts from space weather come indirectly from the disruption of critical infrastructures, radiation storms do pose a direct threat to human health via increased radiation exposure. This is a major concern for astronauts above the Earth's protective atmosphere, who are required to shelter during increased emissions to avoid exposure—and will likely become more important as human spaceflight moves once again beyond Earth orbit. It is a lesser concern though still a reality for airliner crews and passengers, particularly those traveling polar routes. It is unlikely a single space weather event would cause enough radiation exposure to cause a direct health impact in air travelers, but for crew, dosage effects can add up (AMS 2007).

Second Order (Indirect) Impacts

Infrastructure Interdependencies

Many infrastructures are becoming increasingly reliant on other infrastructure services for their operation. Transportation systems, for example, especially mass transit, are particularly vulnerable to indirect disruption due to their dependency on electricity and GNSS for operation. Eastwood (2017) suggests that transportation infrastructure is likely to become more vulnerable to indirect disruptions in the future as space weather events could disrupt the electrical, ICT, and GNSS infrastructures supporting driverless car networks (smart highways) and road charging services. Energy exploration and production efforts can also be indirectly impacted through degradation of Global Navigation Satellite Services (Schrijver et al. 2015). Other sectors of the global economy, like finance and agriculture, are also becoming increasingly reliant on GNSS

Emergency Response

Studies suggest that much of the communications equipment (HF radio) as well as the GNSS signals used by emergency response services could be disrupted by atmospheric scintillation effects during radio blackout storms, hampering ability to respond to both storm- and non-storm-related emergencies (MacAlester and Murtagh 2014).

Businesses

The disruption of critical infrastructure networks is likely to have many knock-on effects for businesses both within and outside the direct impact zone. For those businesses within the main area affected by the storm, the loss of electricity and ICT services can lead to long periods of inoperability. For those businesses outside of the directly impacted area, the disruption of supply chains is of primary concern, particularly those reliant on just-in-time inventory and shipping.

Military

Space weather has been an important operational concern for the military for some time now, as a number of military systems are susceptible to disruption by space weather events, including space-based assets, over-the-horizon radar systems, HFR communications systems, and GNSS reliance for navigation and targeting. While affected military hardware may represent a direct impact, the indirect geostrategic fallout from a degradation in military effectiveness is also important to consider. For example, on may 23rd, 1967, a solar flare and the resulting geomagnetic and radio blackout storms disrupted US radar systems across the polar latitudes, leading to an initial assessment of the outage being due to Soviet jamming prior to attack. The storm also disrupted radio communications across North America for almost a week. In another example, in Afghanistan in March 2002, solar activity is believed to have disrupted US military UHF SATCOM systems leading to the downing of a US helicopter and three casualties (Kelly et al. 2014).

Going forward, the world's militaries are likely to only increase their use of space-based assets to provide communications, navigation, and intelligence services, suggesting that military vulnerability to space weather will grow over time (Baker and Lanzerotti 2016; Perron 2014).[7]

Similarly, as the thawing Artic ocean gains in geostrategic importance, military operations at polar latitudes are almost certain to increase, while the Arctic region is particularly vulnerable to space weather events.

Third Order (Indirect) Impacts

The Economy

The global economy looks to become increasingly vulnerable to supply chain disruptions as the spread of automation and "just-in-time" manufacturing and shipping lead to greater dependency on ICT and GNSS-based services (Oughton et al. 2017). Bäumen et al. (2014), for example, demonstrate how critical infrastructure disruptions in one region can ripple through the global

[7] American Geophysical Union. "1967 solar storm nearly took US to brink of war." ScienceDaily. ScienceDaily, 9 August 2016.
www.sciencedaily.com/releases/2016/08/160809145123.htm [accessed on April 17th, 2018]

economy through the use of inoperability input-output tables—as production, distribution, and consumption are disrupted across sectors and countries.

Governance and Instability

Extended outages of critical infrastructure services, especially electricity, can prove challenging for local, regional, and even national governments in terms of both immediate response and long-term after effects. The OECD project on Future Global Shocks sees the failure of critical infrastructure as a potential source of civil and political unrest and provides a model for tracing out such implications based on measures of social vulnerability, including personal wealth, age, density of the built environment, single sector economic dependence, housing stock, dependency on infrastructure, occupation and race and ethnicity (Centra 2011).

Historical Examples

Past Space Weather Events

The following are a sample of past space weather events, see Appendix 5 for the complete list.

- **September, 1859 "Carrington Event"**
  The most severe space weather event to have directly impacted the Earth in at least the last few centuries, the Carrington Event was a powerful geomagnetic storm spawned from a major solar flare and CME. The storm disrupted telegraph communications across North America and Europe, triggered fires in telegraph stations, and caused visible auroras down to 23° of the equator in both hemispheres. Estimated severity: ~-850 nT *Dst* (Bäumen et al. 2014).

- **May 14th–15th, 1921**
  Strongest geomagnetic event of the 20th century, damaged telegraph networks and facilities, generated an aurora visible over Samoa (Bäumen et al. 2014).

- **March, 1989**
  Geomagnetic storm that caused significant damage to electrical infrastructure in Canada, the US, and UK—but particularly in Quebec, Canada—triggering a 9-hour-long blackout affecting up to six million people. The storm lasted more than 12 hours but only took 90 seconds to shut down the Hydro-Quebec power grid. Estimated severity: ~-589 nT *Dst* (Oughton et al. 2017; Bäumen et al. 2014). Total cost to Hydro-Quebec was estimated at $13.2 million, with $6.5 million due to equipment damage.

- **October 31st–November 4th, 2003 "Halloween Storm"**
  The so-called Halloween Storm was the largest solar flare ever recorded (Eastwood 2017). Accompanied by a fast-moving coronal mass ejection. Left 50,000 in Sweden without power due to GICs and even had impacts at latitudes as low as South Africa, where it caused significant damage to at least twelve EVH transformers. Estimated severity ~-353 nT *Dst* (Oughton et al. 2017; Bäumen et. Al 2014).

- **July 23rd, 2012 "Near-miss"**

Potentially the most severe CME on record—stronger even than the Carrington Event. This event did not impact the Earth, but thanks to detailed observation, this near miss has become the go to example for calculating the impacts of an extreme space weather event (Baker et al. 2013). Baker et al. estimate that had the storm hit the Earth, it would have had "devastating consequences for many technological systems."

Examples from Other Natural Disasters

- 2003 Northeast US Blackout

  Estimated economic impact of $4 to $10 billion

- 2005 Hurricane Katrina, US

  Estimated economic impact of $81–125 billion to US

- 2011 Earthquake and Tsunami, Japan

  Because of Japan's importance in many international supply chains, the devastation wrought on Japan had significant indirect ripple effects on industries around the world (Oughton et al. 2017).

- 2017 Hurricanes Harvey, Irma, Maria, US and Caribbean

  The most expensive Atlantic hurricane season on record, the trio of major hurricanes, Harvey, Maria and Irma inflicted an estimated $202 billion in damages, though the 'final bill' is still being tabulated. Puerto Rico and several Caribbean islands are still dealing with the aftereffects of Hurricane Maria, some seven months after the storm hit.[8] The significant damage done to Puerto Rico's electrical infrastructure should be a case study for the potential impact of a severe space weather event, particularly should such an event affect one or more developing countries.

Existing Forecasts and Impact Estimates

Existing Space Weather Scenarios

A Reasonable Worst-Case (Global) Scenario

Baker et al. (2013) argue that the July 23rd 2012 storm should be seen as representing a "defensible worst-case" space weather event scenario. Their conclusion is that, based on the storm's severity and the current level of societal vulnerability, we'd *"still be picking up the pieces"* if the storm had struck the Earth back in 2012. In a latter publication Baker (2016) calls for the July 2012 storm to *"be adopted as quickly as possible as the prototypical extreme event scenario for emergency preparedness purposes."*

The OECD report by Centra Technologies, Inc. describes a 'reasonable worst-case' scenario for a geomagnetic storm. The modeled storm was a G5 on the NOAA space weather scale (maximum

8 https://news.nationalgeographic.com/2017/11/2017-hurricane-season-most-expensive-us-history-spd/; https://www.bloomberg.com/news/articles/2017-11-26/the-most-expensive-u-s-hurricane-season-ever-by-the-numbers [accessed on April 18th, 2018]

strength of 3,000nT/min at 50° latitude. The scenario primarily explored first and second order impacts on critical infrastructure systems, the most significant of which was to the electrical sector—the report cites other estimates of 130 million without power in the US due to the loss of multiple major transition lines. But it also looked at the potential governance implications of prolonged outages (see above) (Centra 2011).

Country-Level Scenarios

Should the 1921 storm occur today and impact the US, estimates cited by MacAlester and Murtagh (2014) suggest that the storm could cause a large-scale, extended blackout (through voltage instability and collapse leading to widespread damage to EHV transformers) affecting upwards of 100 million people across the country, with the East Coast, northern Midwest, and Pacific Northwest being most vulnerable. Full restoration of the electrical grid back after such a storm could last months (Centra 2011).

Existing Impact Estimates

Estimates of the impacts of "everyday" space weather

Most studies of the potential cost of space weather focus on the impact of major storms, but as several authors point out, it is also important to look at more 'modest' events to produce a realistic range of damage estimates. Estimation of the impacts of minor space weather events is most often done through industry insurance claims. Eastwood (2017) points to insurance claim information from the US suggesting that disruptions from 'everyday' space weather may cost the US electricity sector $5 to $10 billion per year. Schrijver (2015)—who originally came up with that estimate (2014)—later expands the insurance method to estimate impact costs to the US and EU electrical grids summed over the span of a century. He finds that such costs would add up to $1.3 to 2.1 trillion dollars over the century, certainly not a trivial amount.

Estimates of the impacts of "severe" space weather

Bäumen et al. (2014), use a global economic model—designed to capture both direct country impacts and indirect impacts through trade disruption—to calculate the cost to today's economic of an event ranging from the magnitude of the 1989 Quebec storm to the 1859 Carrington Event. They find that the global impact from such an event would range from $2.4 to $3.4 trillion dollars over the course of a year, with about 50% of the cost incurred by countries not directly impacted. In all, the direct and indirect impacts of such an event would result in a loss of about 3.9% to 5.6% in global GDP, which, according to the authors, is about the same magnitude as wars, extreme financial crises, and potential costs of future climate change.

Eastwood (2017) suggests that a 100-year level event would cause major damage to the electricity sector, including loss of transformers and generator step-ups. Eastwood estimates a 4–10-year recovery period with economic impacts in the trillions of dollars due to prolonged electricity outages.

Odenwald et al. (2006) estimate that a Carrington-level event could cost the global satellite industry alone $70 billion from damage to hardware and lost revenue due to service disruption.

Lloyd's (2013) estimates the total economic cost of a Carrington-level event to the US at $.6 to $2.6 trillion, depending on the duration of the triggered blackouts, which in their scenarios last from 16 days to 1 to 2 years (accounting for full EHV transformer replacement). Their scenarios assume, however, that only 20–40 million people (about 10% of the US's population) are directly impacted by the blackouts.

Modeling Space Weather Events and Impacts

Modeling Space Weather

Most attempts to model the impact of space weather focus on calculating the direct and indirect economic costs of infrastructure disruption and loss. Depending on the level of detail, economic costs can include estimates of unserved demand, lost income, lost goods (like food spoilage), lost production, and other opportunity costs of service failure. Models also tend to include scenario specific storm parameters and infrastructure operations (mitigation strategies) (Centra 2011).

Existing Quantitative Models of Space Weather and its Impacts

Bäumen et al. (2014) use a global economic input-output model coupled with a physical model of storm severity to calculate the direct and indirect economic costs of a severe space weather event on today's economy. Bäumen et al. first calculate the storm's footprint—the geographic area impacted—and then quantify a specific impact for each country, in terms of reduced electricity production capacity, based on the overlap between footprint and country. Electricity production is used as an input for the production of goods in the input-output model and so the model is able to quantify the ripple effects of the disruption between sectors of a single economy as well as between economies. The model uses a "multi-regional input-output" database encompassing 187 countries with 25–400 sectors per country, enabling the model to capture ~99% of global trade. In the model, the output of economies undergo forced changes based on storm severity and location that impact final demand (or consumption) possibilities—the technique most often used in disaster-impact analysis. Only sectors considered significantly impacted by the loss of electricity production are disrupted in the model in order to account for substitution of inputs. The authors use the model to run a number of scenarios of different storm locations (using a severity equivalent to the 1989 Quebec event), to explore the impact of disruptions to different global supply chains (as well as direct impacts to shared international power grids, where they occur). Bäumen et al.'s modeled costs are quite close to other existing estimates.

Lingam and Loeb (2017) use a mathematical economic model to calculate the economic cost of severe space weather events over time. They first model the wait time between extreme solar flares and then calculate global GDP at the time an extreme flare is set to occur. The relationship between GDP and economic damage is fixed but grows over time as wait time (and therefore flare severity) increases. The model also accounts for increases in technological sophistication during the wait time. Technological sophistication is modeled in terms of a logistic growth function that saturates over time. The model assumes that greater technological sophistication means greater vulnerability to flares and thus greater economic damage (but with saturation the damage from sophistication stops increasing). The model suggests that society is likely to be most vulnerable during the period of exponential growth in technological sophistication during the mid-decades of this century. Lingam and Loeb (2017) find that, by 150 years in the future, the economic damage from an extreme or super flare could equal the current GDP of the US.

Oughton et al. 2017 describe four steps to calculating the economic impact of space weather events: 1) determine the geographical location of the blackout zone (electricity disruption), where different geographies have different vulnerability levels; 2) calculate country-level direct economic impacts from production disruptions (input-output); 3) aggregate country-level costs; 4) estimate indirect and global economic impacts. As with Bäumen and the SWIM, Oughton et al. use the World Input-Output Database. The authors analyze four scenarios of increasing storm severity and geographic footprint. In S1, 8% of the US is directly impacted, with a direct, US economic disruption of $3.2 billion and a total (direct and indirect) global impact of $7 billion. In the most severe scenario, S4, the storm impacts 66% of the US population, costing the US $28.2 billion dollars and the globe $48.5 billion.

Modeling Infrastructure and Critical Infrastructure Interdependencies

Modeling Infrastructure Futures

Taking the broadest view, two factors—and the balance between them—drive change in infrastructure over time: the demand for infrastructure services, and the ability for infrastructure providers (public and/or private) to meet that demand. Technological change, under this conception, acts on both demand and provision rather than existing on its own, altering the type of services demanded (new forms of infrastructure), reducing the cost of existing infrastructure for providers, and enabling alternative development pathways (leapfrogging, for example). Thus, to model infrastructure, we need to map out the drivers of demand and provision (Rothman, Irfan, Malin 2014).

As people and firms tend to be the end users of infrastructure services, the drivers of infrastructure demand primarily come from economic and demographic change. As the population and economy grow and shift, infrastructure requirements change: a more urbanized population requires more public transport, a growing IT sector requires more robust ICT networks, and so on. There are two main indicators used in the literature to measure economic change: GDP and GDP per capita. Demand for infrastructure services, particularly electricity, is closely linked to changes in GDP (Stevens et al. 2006)—although there is growing evidence that this relationship is changing,[9] but the precise mix of infrastructures demanded also depends on the structure of the economy (agricultural, manufacturing, service, etc.) and how that structure

[9] The exact relationship between GDP and electricity demand depends on a country's level of development, as with pollution levels, it appears economies follow an inverted U pattern of demand where electricity demand increases rapidly during a country's development and then levels off and even decreases as more efficient technologies are deployed (Rothman, Irfan, Malin 2014).

shifts over time (the current trend from manufacturing to service to information economies), which is, again, closely linked to growth in GDP (Yepes 2008). Rising GDP per capita is also linked to increased demand for all types of infrastructure services. For demographic change, the primary indicators used are population density and urbanization, which are not only important drivers of demand but can also impact the types of infrastructure deployed. A denser, more urban population will generally favor more public transport, and more centralized power, water and communication systems, while a less dense, more rural population may favor more private road transport and distributed generation systems. Family size and population aging are two other demographic drivers of infrastructure demand. As average family size around the world shrinks (due to a decline in multigenerational homes, large numbers of youth in developing countries entering adulthood, and delayed age of marriage and falling fertility rates), the number of households around the world will continue to grow, outpacing overall population growth, and increasing the demand for many different forms of infrastructure as each new home will require municipal services (Jong and Riet 2004). The growth in households, particularly in developing countries, also suggests continued growth in demand for consumer goods and hence the infrastructure needed to support the manufacture of those goods. Migration can be another driver of infrastructure demand, particularly of communication networks as migrants seek new methods of communication and ways to transfer funds to their families back home (Stevens et al. 2006).

Modeling Critical Infrastructure

A significant literature exists around the definition and modeling of critical infrastructures and their interconnections, in addition to more general infrastructure forecasting (see above). Critical Infrastructure networks (CIs) are the backbone of modern society, underpinning the functioning of our economic, governance, security, and social systems. Their disruption or destruction, therefore, can have dire consequences. Understanding CIs' vulnerability to hazards, natural and manmade, is thus key to ensuring the safety and stability of society. But identifying such vulnerabilities is not easy; each infrastructure is a highly dependent and interdependent complex system, where disruptions in one infrastructure is likely to have ripple or cascading impacts across others (Ouyang 2014; Eusgeld et al. 2011; Conrad et al. 2006). It is because of these complex interdependencies that the literature on CIs often characterizes them as representing a "system-of-systems"—a conglomeration of multiple, distributed, heterogeneous, systems embedded in a network of interconnections across multiple levels of scale, with internal structures and interconnections that evolve over time (Eusgeld et al. 2011). The exact list of CIs tends to vary from country to country, but those infrastructures most commonly considered critical to society are: electrical; information communication technologies (ICT); energy (oil and natural gas); transportation; water; banking and finance; government services; and emergency services.

Mapping Critical Infrastructures

Mapping the interconnections between Critical Infrastructures is a prerequisite step in attempting to model CIs and their vulnerabilities. This section provides a brief overview of the important dimensions for mapping (and modeling) critical infrastructure. The interdependencies between the various Critical Infrastructures can take many forms. Rinaldi (2004) identifies four main "classes" of system-level interdependencies/dependencies (a number of studies either use Rinaldi's classes directly or expand upon them):

- Physical Interdependencies
  - Infrastructures are physically interdependent, most obviously, if there are physical linkages between elements of different infrastructures, but also if the state of each infrastructure depends on the material output(s) of the other.
    - *Example: a city's water system requires electricity while the power plant providing that electricity depends on that water system for providing water for cooling*
- Cyber Dependency
  - Infrastructures have cyber dependencies if their operation depends on the flow of information (transmitted through information infrastructure)—the automation of modern infrastructures has led to pervasive cyber dependencies. Overlaps with Pederson et al. (2006)'s use of Informational Interdependency, where information flows support decision processes among interconnected infrastructures.
    - *Example: digital control systems of a smart electricity grid*
- Geographic Interdependencies
  - Infrastructures are geographically interdependent if they share a close spatial proximity and can all be damaged by a local event. Also referred to as being collocated.
    - *Example: fiber optic cables and telephone lines sharing the same right-of-way*
- Logical Interdependencies
  - Infrastructures are logically interdependent if the state of each infrastructure depends on the state of the other via some form of policy, legal, or regulatory regime governing the infrastructures. The Logical Interdependency category also covers things like Pederson et al. (2006)'s Policy/Procedural Interdependency.
    - *Example: regulations addressing climate change that govern both electricity and transport infrastructures*

Along with the different classes of interdependencies, Petit et al. (2015) (and others) identify five additional dimensions important for the mapping (and modeling) of Critical Infrastructures:

- Infrastructure operating environment
  - Business/Economic concerns
  - Public policy and legal/regulatory concerns
  - Technical/Security concerns
  - Health and Safety concerns
  - Social/Political Factors
- Coupling and response behavior
  - Adaptive versus inflexible response—an adaptive infrastructure is more likely to continue to function adequately in the face of a disturbance while an inflexible infrastructure is unlikely to respond well to a disturbance

- Loose versus tight connection—in a loose connection, the state of one infrastructure is only weakly correlated to the state of another. A tight connection is characterized by time-dependent processes that have little margin for error.
- Linear versus complex processes—expected and familiar production/maintenance sequences versus unfamiliar, unplanned and unexpected sequences

- Infrastructure characteristics
  - Organization—how the organization of decision and control structures impact how a disruption is managed
  - Operational—emergency and business continuity measures that affect the importance of impacts generated by failures
  - Temporal—duration of outrages and recoveries, can have substantial implications for importance of impacts generated by failures
  - Spatial—geographical extent of critical infrastructure system
- Types of failures
  - Cascading failure—a disruption in one infrastructure causes disruptions in other infrastructures
  - Escalading failure—a disruption in one infrastructure exacerbates an independent disruption in a second (e.g. recovery of one infrastructure is impacted because services from another infrastructure is not available) (Peerenboom and Fisher 2007)
  - Common cause failure—a disruption in two or more infrastructures at the same time as a result of a common cause (Peerenboom and Fisher 2007)
- State of operations
  - Normal—operations at or near optimal level
  - Stressed/disrupted—operations at a reduced capacity due to increased demand or damage/degradation of critical assets
  - Repair/restoration—operations have been voluntarily or forcibly halted and repairs or new equipment are needed to resume operations

Eusgeld et al. (2011), draw on theses interdependencies and dimensions to create a general model architecture for mapping and modeling Critical Infrastructure consisting of three layers:[10]

- The System-of-Systems Level (highest level)
  - A macro-level that arises emerges from the interactions between lower-level systems
- The Middle Level

[10] Eusgeld et al. (2011) also introduce the notion of Input, Shared, Mutual, and Exclusive categories of dependence/interdependence, where Input covers infrastructures reliant on information from another infrastructure; Shared, where multiple infrastructure systems underlie another infrastructure system (CI and SCADA systems of water supply both requiring electricity); Mutual, where the operations of each infrastructure is dependent on the other; and Exclusive, where the services of one infrastructure can be substituted for another in the case of disruption.

- The Middle Level contains the interactions and interdependencies between infrastructure networks
- The Low Level
  - Consists of system models of single infrastructure networks (including control systems)

Despite all of this emphasis on interdependencies, when it comes to the restoration/recovery of Critical Infrastructure, the process is most often treated as a linear one, where infrastructure elements move in a straight line from damaged to fully recovered. But as Eusgeld et al. (2011) point out, recovery from a cascade of nonlinear impacts can require nonlinear recoveries, as interdependencies lead to the need to restore one infrastructure before the failures in another can be addressed.

Critical Infrastructures and Vulnerability

The mapping of the interdependencies between Critical Infrastructures also speaks directly to their vulnerability to natural and manmade hazards (Stapelberg [no date], for example, directly recasts the list of interdependencies as vulnerabilities). The standard framework for vulnerability analysis breaks vulnerability down into three components:

- Exposure
  - The extent to which a given system is exposed to a hazard
- Sensitivity
  - The degree to which the system in question could be harmed by the hazard
- Adaptive Capacity
  - The degree to which potential harm to the system can be mitigated by taking action to reduce exposure and/or sensitivity

The interdependencies between Critical Infrastructures fall across all three components; depending on the nature of the disruptive event, multiple infrastructures can be exposed due to their interconnections, the extent of damage across the infrastructures (sensitivity) also depends on the nature of their interdependencies, and the ability to adapt to and recover from a disruptive event is similarly impacted by the extent to which infrastructures are intertwined (Hasan and Foliente 2016).

Most of the literature points to the centrality of electricity and telecommunications infrastructures, both in terms of interdependencies (and the potential for cascading impacts) and for targeting for mitigation strategies (Conrad et al. 2006). The increasing role of ICT as control systems and as an infrastructure in its own right is seen as making other critical infrastructures more vulnerable, at least to certain kinds of disruption—increasing Cyber interdependencies (Peerenboom and Fisher 2007; Rinaldi 2004).[11] Peerenboom and Fisher suggest that logical

[11] Interestingly, while telecommunications are frequently cited as being a key CI, the role and possible disruption of satellites is not directly discussed…

independencies are also increasing over time, due to “increased reliance on the open market for purchasing and selling of commodities and services.”

In terms of measuring CI vulnerability, Iuliani (2016) suggests using variability in the overall level of supply or service provided (the combination of remaining capacity and output).

Approaches to Modeling Critical Infrastructures

Ouyang’s 2014 survey of the literature identified six dominant approaches to modeling CIs: agent-based approaches, system dynamics-based approaches, economic theory-based approaches, networked-based approaches, and other. This section gives a brief overview of each approach, while the following section highlights some of the existing models using these approaches.

Agent Modeling

Agent-Based Modeling (ABM) is an increasingly popular approach to addressing CIs’ complexities. Individual, physical infrastructure components are modeled as agents and given performance behaviors and operational/physical statuses. ABMs can also model the decisions involved with infrastructure operations, markets, and consumers (Rinaldi 2004).

Strengths: able to provide very fine resolution models that capture system behaviors down to the component level, able to capture nonlinear and even unexpected behaviors through emergence.

Weaknesses: requires strong assumptions about agent behavior; requires large amount of detailed data to calibrate behavior and parameters (Hasan and Foliente 2015)

System Dynamics Modeling

System dynamics-based modeling approaches (SDM) are often used to map out and simulate the connections between individual infrastructures and to link those infrastructures to larger socioeconomic systems. SDMs of Critical Infrastructures usually follow the model structure laid out by Eusgeld et al. above, with the bottom layer(s) representing each infrastructure as a system or set of sub-systems made up of stock and flow diagrams, and with upper layers linking those systems to each other and to non-infrastructure systems via causal loop diagrams (Ouyang 2014). SDM are especially attractive for modeling infrastructure disruptions as real-life infrastructures are likely to respond in a dynamic manner (Hasan and Foliente 2015).

Strengths: able to capture dynamic, nonlinear behavior; easily integrated with other modeling methodologies (Iuliani 2016).

Weaknesses: From Hasan and Foliente (2015) SDMs require making assumptions (usually based on expert knowledge) to establish causal relationships; requires extensive data to calibrate parameters and functions; lack the ability to capture component-level dynamics; can only be validated at the conceptual level because of data requirements; does not (usually) account for component level performance; does not usually account for spatial structure of infrastructure elements

Economic Theory Modeling

Input-Output Modeling

One of the most common approaches for determining direct and indirect economic impacts of infrastructure disruption. The standard model is the Leontief Input-Output Model, which provides an aggregate level, linear and time-dependent analysis of the generation, flow, and consumption of commodities and services between sectors of the economy (Rinaldi 2004). When dealing with Critical Infrastructures, the standard IO model is reframed to consist of a system of interconnected infrastructures (sectors) with the output the risk of their inoperability due to failure, where inoperability is defined as the "inability of a system to complete its intended function…" This variant IO is often referred to as the Inoperability Input-Output model (IIM) (Iuliani 2016). Iuliani describes a series of further refinements to this model that take into account demand reductions in response to an event; integrates sector-specific resilience coefficients; and expansions to the model that take advantage of geospatial datasets (Iuliani 2016).

Strengths: Accuracy in forecasting high-level error propagation among interconnected infrastructures; benefits from widely available existing datasets at multiple scales;

Weaknesses: relationships between sectors are linear and do not capture dynamics like the interdependencies between infrastructures (Hasan and Foliente 2015); provide only a high-level snapshot of the economy and only at a discrete point in time (Iuliani 2016); equilibrium-seeking behavior implied (Dauelsberg and Outkin 2005)

Computable General Equilibrium Modeling

CGE modeling approaches tend to build from IO models. CGEs tend to be macroeconomic and multi-market in nature; capturing the individual behavior of consumers, households, and firms in response to price signals and resource constrains (Vischio 2012). In CGEs, the standard production function and used by produces is modified to incorporate economic resilience—the substitution of inputs should one source/type become inoperable (Iuliani 2016).

Strengths: able to capture more dynamic behavior than IO models; able to incorporate resource constraints and input/import substitution

Weaknesses: provide only a high-level snapshot of the economy and only at a discrete point in time; cannot model dynamic interdependences at lower levels (Iuliani 2016); equilibrium-seeking behavior implied (Dauelsberg and Outkin 2005)

Network Modeling

Network-based modeling approaches use nodes/vertices to represent individual components of an infrastructure system and lines/edges to represent their interconnections. The infrastructure system is mapped out on a graph… Network-based modeling allows for analysis across multiple scales, from a full infrastructure network to tracing the failure of individual components. There are two types of Network modeling methods: topology-based, which is used for vulnerability assessments drawn from large-scale datasets and flow-based methods, which capture the flow characteristics of interdependent infrastructures (Hasan and Foliente 2015).

Example Critical Infrastructure Model

Critical Infrastructure Protection/Decision Support System (Daulesberg and Outkin 2005)

Designed to inform decision-making process regarding infrastructure protection by modeling the full system of Critical Infrastructures and their primary interdependences. Uses a series of system dynamic "consequences" models to compute the impacts of various infrastructure disruptions to human health, public safety, the economy, national security, and the environment. Model outputs are captured in a "consequence database" from which a set of "decision metrics" are calculated. The SD consequence models (national and metropolitan) are constructed using Vensim.

Responses to Space Weather: Forecasting, Resilience, and Recovery

"Resilience is not just about lessening the likelihood that outages will occur, it is also about limiting the scope and impact of outages when they do occur, restoring power rapidly afterwards, and learning from these experiences to better deal with future events."– National Academies of Sciences, Engineering, and Medicine *2017*

Forecasting Space Weather

Forecasting systems are designed to provide advanced warning time, allowing for taking sensitive hardware offline, for airliners to be diverted to safer latitudes, and for astronauts to enter storm shelters. NOAA's Space Weather Prediction Center provides such forecast. Such systems are receiving increasing attention by industry and governments, but funding remains inadequate.

Policies

Estimates of the cost of extreme space weather events can be used to 'stress test' asset exposure in the insurance industry (Oughton et al. 2017).

Political action must accompany scientific and engineering progress to meet the challenges posed by space weather (Baker 2017).

Requiring a strategic reserve of EHV transformers (Coker 2017) and better management of transformer lifecycles against all forms of stress and aging as strong GICs can significantly age transformers (Schrijver 2015).

Environmental Scanning and Current Trends

Introduction

As part of the research for this project, we conducted an environmental scan and emerging issues analysis. An environmental scan looks for "weak signals" of change out in the world. Emerging issues analysis uses those disparate signals to identify potential "emerging issues" (EI). An emerging issue can be a new technology still under development, a potential future public policy issue, or a new concept or idea that might be considered fringe thinking today. If, however, these things continue to mature, they could play important roles in shaping the future.

Emerging issues analysis uses the standard s-curve of issues/technology development as its backbone framework for understanding and plotting the emergence and maturation of future issues. Using this development curve as a guide, futures researchers help to frame many of the potentially disruptive future issues that are not immediately apparent through traditional practices such as extrapolation of current trends or by running quantitative models of well-defined systems.

The emerging issues analysis conducted for this project was based on an environmental scan consisting of over 250 scan hits covering developments in the political, economic, social, technological, and environmental space. The goal of the environmental scan was to identify key emerging issues that point to current and potential future vulnerabilities to space weather. A sample scan hit list can be found in Appendix 4. See the SWIM Emerging Issues Database file accompanying this report for the full list of EI scan hits.

The 20 emerging issues identified through this environmental scan include:

- Expansion of distributed power generation
- Rising energy demand driven by bitcoin and similar technologies
- Deployment of new infrastructure for clean energy
- Drones replacing satellite fleets
- Autonomous shipping
- Rising anti-globalization sentiments
- Next generation of satellites providing advance warning of space weather events
- Reversal of the Earth’s magnetic poles and associated implications (potential for long-term weakening of the Earth’s magnetic field)
- New tracking technologies to complement / compete with GPS systems
- Growth of the global space economy
- Next generation of radiation proof electronics
- Man-machine interface
- Next generation of communication and computing systems
- Potential limitations to scalability of batteries for renewable energy storage
- 5G Communication networks and the advent of the internet of things.
- Quantum computing and the next wave of technological and societal transformation
- Automation and AI transforming the corporate world
- Rising volatility, unpredictable conflicts and impacts on sensitive infrastructure
- Construction of underwater cities
- The race to utilize the Arctic

Curated Scanning Findings

Spike in energy demand driven by bitcoin and similar technologies

The huge amounts of energy currently consumed by blockchain applications such as bitcoin might hold back the widespread adoption of such technologies. Will they become less power-hungry in the future?

Blockchain is an algorithm and a distributed data structure where financial, business, healthcare transactions and public records can be managed by anonymous individuals without the interference of a central authority. Blockchain was originally designed for *bitcoin* – the digital crypto currency developed by an anonymous cryptographer Satoshi Nakamoto – but has wider applications in various industries beyond finance.

Since its genesis, bitcoin's main promise has been to democratize the highly centralized and global financial system by making it transparent and accountable. To deliver on its promise, the technology allows *bitcoins* to be generated by miners (individual users with powerful computers) who process and validate financial transactions that are recorded on a *distributed ledger*. Originally a fringe development, bitcoin (and cryptocurrencies more generally) are now entering the mainstream with big companies and banks trying to make use of the new technology which has led to the price of a single bitcoin reaching over $17,000 in December 2017.

Currently, the slow processing of transactions (due to the growing user base) and the high energy intensity required for processing are the main obstacles preventing wider adoption of bitcoin. A recent article by IEEE Spectrum suggests that "the ever-expanding racks of processors used by bitcoin miners already consume as much electricity as a small city." If computations accelerate further, bitcoin power demand is expected to balloon 20-fold—to 14 gigawatts—by 2020 in which case bitcoin will be using as much energy as Denmark.

The developers of other distributed platforms such as Ethereum are already working on devising much less energy-intensive mining models, based on a Proof-of-Stake (POS) vs Proof-of-Work (POW)[12] used by bitcoin. Other cryptocurrencies such as Dash and Cardano are also experimenting with POS, but whether POS will become the dominant mining model for cryptocurrencies is currently unknown.

How will energy required for bitcoin mining and transactions be produced in the future if demands continue to increase? Will new technology developments –e.g. application specific integrated circuits – or new mining methods – e.g. POS - allow for less energy intensive crypto currency mining? Will other blockchain applications intended for healthcare, business and government will be energy intensive like bitcoin?

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[12] POS – Cryptocurrencies mining approach based on the Proof of Stake Concept – allowing an individual to mine or validate block transactions according to how many coins he or she holds, thereby requiring less computing power and energy

POW – Cryptocurrencies mining approach based on the Proof of Work Concept –where the probability of mining a block is dependent on how much work is done by the miner in terms of calculations, requiring high amounts of energy.

How will quantum computing affect bitcoin and other blockchain technologies – while it will undoubtedly increase the speed of calculations and improve scalability, will it also make these technologies more vulnerable to hacker attacks?

Deployment of new infrastructure for clean energy

Full utilization of clean energy requires the construction of new transmission infrastructure

Clean energy sources are expected to contribute a larger share to electricity generated globally. According to the New Energy Outlook report, renewables (wind, solar and hydro) will produce 51% of global power generation in 2040 whereas natural gas, which is also considered to be a clean source, will supply 16% of electricity produced in the same period. A more positive scenario by Energy Factor estimates that natural gas will account for 30% of electricity produced by 2040.

The production of clean energy is becoming cheaper as the capital costs required for building and installing solar and wind farms are decreasing. Thus, the single major challenge to utilizing the full potential of clean energy (in cases where it is not consumed locally) becomes transmission infrastructure.

The infrastructure existing today was built to serve fossil fuel and nuclear power plants, but wind and solar farms in particular are not usually located in the vicinity of such plants. The construction of new infrastructure is therefore needed.

One solution for wind and solar energy are high-voltage direct current (HVDC) transmission systems. Arguably, HVDC is rising in popularity around the globe for its ability to interconnect grids across borders. The global HVDC market is currently valued at $6.2 billion according to a report by Future Market Insights, cited in Greentech Media. Examples of current projects:

- The Plains & Eastern Clean – a U.S.-based project connects the Oklahoma Panhandle region to Arkansas, Tennessee and other states in the Mid-South and Southeast U.S.
- The Dolwin offshore wind HVDC project is based in Germany and scheduled for completion in 2018. It will increase wind power use in Germany by 50%.
- GE's Rio Madeira 10-gigawatt hydroelectric HVDC project in Brazil transports two-thirds of the energy produced from the hydro plant in the Amazon basin across more than 1,475 miles.
- China has numerous HVDC projects such as Gezhouba – Shanghai, Tian-Guang and Zhou Shan in various regions of the country.

Natural gas faces similar challenges as it is situated in a few geographical regions with Russia, Iran, Qatar and the US holding some of the largest reserves. The concentration of natural gas reserves requires the development of infrastructure for its export and transportation. After the gas has been liquefied and transported in ship tankers, the construction of import terminals and pipelines is required to transport it in demand markets. Mexico is constructing cross-border pipelines to import natural gas from the U.S. Similar projects exist in Europe. Yet, the largest demand for liquefied natural gas (LNG) is expected to come from Asia and will require infrastructure investment of $80 billion to construct LNG terminals, pipelines.

What might derail the completion or further funding of HVCD transmission infrastructure?

What impacts will a prolonged geomagnetic storm have on precision drilling equipment for shale gas extraction, thereby impacting US export activity? What will be the associated economic losses? Geomagnetically-induced currents are likely to cause pipe corrosion due to changes in pipe to soil voltage. How big will associated damage in demand markets be?

Drones and aircraft replacing satellite fleets

The flexibility and lower cost of technologies with satellites functionality such as aircrafts and drones might be crucial for decreasing dependency on satellites infrastructure

Satellites are critical infrastructure on which modern societies run. Everything from communications to navigation and business operations is enabled and directly dependent on reliable satellite operations.

Severe space weather events such as solar storms can massively disrupt satellite operations and could potentially bring our daily lives to a standstill. While governments are considering how to mitigate such effects and reduce our dependency on satellites, the private sector and academia may have found potential solutions to this problem.

In 2016 Airbus declared that it had developed a drone – Zephyrus T – that in the foreseeable future could spend years roaming the stratosphere powered by solar power. Zephyrus – T will be able to provide the same functionality as a modern satellite at a much lower cost and could replace the fleet of existing satellites orbiting the Earth. It can be used for communication, military monitoring and high-speed internet connection in emergency situations.

In addition, researchers at the University of York are working on a £3.9m EU-funded project that aims to develop High Altitude Platforms (Haps). These will be solar-powered aircraft and airships which can be kept stationary at a height of about 20 kilometers. The launch and maintenance of such craft are expected to be much cheaper than satellites. The main benefit of Haps will be that high-capacity communications can be achieved with less communications infrastructure and can be quickly deployed once the obstacle of energy storage has been overcome.

What role could autonomous drones and aircraft play in addressing the space weather problem in the near and longer term? Will such technologies dramatically decrease vulnerability to space weather events – e.g. to be brought down to earth in case of a solar storm warming and re-deployed afterwards?

How easy will the replacement of satellite infrastructure be given that the satellite industry is worth more than $200 billion?

Expansion of distributed power generation

Various initiatives around the world indicate a push towards distributed power generation

Distributed power generation has been technically possible for a long time, but it is finally becoming more widespread. In an article for IEEE Spectrum, Robert Hebner, the director of the Center for Electromechanics at the University of Texas, argues that we are in the early stages of an expansion of distributed generation, which in turn will reduce the need for costly long-distance electricity transmission.

For example, numerous initiatives across the US, such as the Department of Energy's SunShot Initiative and ENERGISE Program, are aiming to make solar energy cost competitive. In addition, utilities are experimenting with alternative ownership options such as community solar, enabling individual ownership of a small number of panels in a relatively large system, or schemes where equipment is owned by an agency but consumers are paid for the use of their roofs. Such ownership models will allow greater number of consumers to benefit from locally produced clean energy, even if the solar panels are actually owned by the energy provider.

New technologies such as compact and smarter electrical inverters, advanced control systems, smart electricity meters and IoT will likely make it possible that the grid evolves into series of adjoining microgrids. This will be a favorable development in the context of space weather because microgrids can operate independently and isolate themselves if disturbances destabilize the larger grid to which they are connected.

Other countries such as China, Japan as well as the European Union have their own distributed energy initiatives. Similar to the US, the evolution of distributed energy and the microgrid will depend on further technology development, regulation and adequate financing.

What other strategies exist for accelerating the evolution of distributed power systems?

Will a transition to distributed power generation increase societal resilience in the face of extreme space weather?

Autonomous shipping

Aside from the advantages such as operational and cost efficiencies, autonomous shipping will make trade highly if not entirely dependent on technology, thereby posing challenges for policy-makers.

90% of world trade is carried by ships, and global seaborne trade will continue to expand, according to the International Chamber of Shipping. Currently 50,000 ships are trading internationally, manned by over a million seafarers. In an article for IEEE Spectrum, Oskar Levander, Vice President of Innovation, Engineering and Technology comments that fully autonomous cargo ships are likely to be crossing the world's seas in 10 to 15 years.

Numerous partnerships have been established over the years to bring this vision closer to reality:

- Rolls-Royce and Google are collaborating to improve Rolls-Royces Autonomous Identification System. Rolls-Royce will use Google's Cloud Machine Learning Engine to train vessels to recognize objects they might encounter at sea.

- The European Union's Maritime Unmanned Navigation through Intelligence in Networks – MUNIN - operated by Fraunhofer Centre for Maritime Logistics and Services, is exploring the technical, economic, and legal feasibility of operating unmanned merchant vessels autonomously during an open-sea voyage.
- DNV GL, an international ship-certification organization, is exploring the feasibility of using unmanned battery-powered vessels to transport freight along Norway's long coastline.
- China's Maritime Safety Administration is working with partners to find ways for autonomous ships to be used within China's own commercial and military maritime sectors.

Aside from the multiple advantages and operational efficiencies associated with autonomous shipping, it will make global trade entirely dependent on technology. In a case of a major power outage event caused by space weather, global trade might suddenly come to a standstill.

What strategies and design choices are autonomous ship designers pursuing to reduce the inherent vulnerabilities of computer-controlled ships? What policies could governments enact to improve the safety and resilience of autonomous shipping in light of global space weather events?

Rising anti-globalization sentiment

Will emerging anti-globalization sentiments pose a challenge to current economic order in the long term, much to the surprise of elites and experts?

Research conducted by Brookings Institute suggests that recent slumps in trade growth are attributable to cyclical or structural factors and do not indicate a reversal of globalization. Experts say that today's level of economic integration exceeds the heights of globalization's first wave, which occurred between 1870 -1914, and Yet, recent developments such as Brexit and anti-free trade sentiments in Europe and the US reveal growing discontent with globalization and some of its byproducts such as free trade, free markets and immigration.

For example, the Trans-Pacific Partnership (TPP), which will cover 40% of the global economy, was abandoned by the Trump administration and was even challenged in pro-trade nations such as Canada and Germany. Similarly, the US was initially skeptical towards China's major strategic Belt and Road Initiative, although the initiative got the support of president Trump in the end. If anti-globalization sentiment continues to rise, trade and scientific cooperation might be negatively affected even if a complete reversal of globalization is highly unlikely.

If the rise of inequality continues undressed, will a potential overhaul of the current economic system become more likely? Will protectionist and nationalistic sentiments prove detrimental to science and technological and thereby slow down progress on pressing global challenges, including space weather research?

Next generation of satellites providing advance warning of space weather events

A new satellite developed by the European Space Agency will provide an advance warning of space weather events and improve space weather research

The European Space Agency (ESA) is preparing to launch a satellite by 2023 that can drastically improve our forecasts and understanding of extreme space weather events. The satellite will be based in the gravitationally stable point L5 and will provide a side-on view of the sun's surface.

By observing the Sun's surface as it rotates towards Earth, the probe will give a preview of sunspots, some of which produce CMEs, before they directly face Earth. In contrast, other satellites such as SOHO and DISCOVR are located in geostationary point L1 and can raise alarm only once plasma is already hurtling into space towards the Earth, providing just 15-17 hours warning. A satellite based in L5 would see the Sun's rotating surface four to five days before one at L1 would.

Will an advance notice of 5 days be enough for grid operators to prepare for disruption? How helpful will those be?

Are there any potential concerns that could derail the next tranche of funding planned for the L5 probe? Currently funding between €20 to €30 million, out of €450-million (US$478-million) required for the mission has been approved.

Reversal of the Earth's magnetic poles and associated implications

Temporary reversals in the Earth's magnetic poles happen rarely but could have significant implications for life on Earth. When will the next one occur?

The Earth's magnetic field is in a constant flux. This results in both long-term as well as temporary and incomplete reversals such as *excursions*, when the magnetic poles move away from the geographic poles before returning back to their original locations. The last known temporary reversal – the Laschamp event – happened 41,000 years ago. The last full reversal – the Brunhes-Matuyama – 780,000 years ago. The intervals between reversals is irregular, and it is hard to predict when the next one is due. Scientists believe that it might happen within the next 2,000 years.

A potential swap of the Earth's magnetic poles will change and weaken the shielding effect of its magnetic field, allowing radiation to penetrate through the Earth's atmospheric layers and bring about high risks for satellites and ground-based electrical infrastructure.

Scientists are now studying the liquid core of the planet, trying to predict the 'weather of the core' by tracking its movement and linking a potential reversal to storms happing in the core. Satellites and observatories also measure how the magnetic fields is moving, which gives insight into movements of the liquid core.

How devastating could a reversal of the Earth's magnetic poles be, and could it possibly lead to large scale collapse? How could society minimize the impacts of a partial reversal if one occurred in the next 50 years?

New tracking technologies to complement /compete with GPS systems

Researchers and private companies are working on new technologies to improve and supplement GPS systems. Could these technologies potentially replace GPS in the future?

The Global Positioning System (GPS) is indispensable for businesses, the military, and economies in general. It is not, however, error-proof and can be jammed by US rivals in some parts of the world. In light of these vulnerabilities, new technologies are currently being developed that could complement or replace GPS in the future.

- The Defense Advanced Research Projects Agency (DARPA) is working on high-precision clocks, self-calibrating gyroscopes and accelerometers, and high-precision navigation instruments that will be able to track position for long periods without relying on external sources. These technologies are reportedly more reliable, accurate and customizable than GPS. DARPA is also researching sensors that use signals of opportunity such as television, radio, cell towers, satellites, and even lightening, for real-time tracking. ASPN alleviates issues related to fixing locations in buildings, deep foliage, underwater or underground, where GPS access can be limited.
- Another technology developed by DARPA is a timing and inertial management unit (TIMU) – a single chip that contains a six-axis inertial management unit (three gyroscopes and three accelerometers) and integrates a highly-accurate master clock into a single miniature system. The TIMU contains everything needed to aid navigation when GPS is temporarily unavailable. The chip design is accomplished through a new fabrication process and each of the six micro fabricated layers of the TIMU is only 50 microns thick.
- Locata, another technology under development, is intended primarily for indoors and city environments. Locata is a new positioning system using ground-based equipment to project a radio signal over a localized area that is a million times stronger on arrival than GPS. It can work indoors and outdoors and its receivers can be shrunk to fit within a cell phone. The US military signed a contract for a large-scale test of Locata at the White Sands Missile Range in New Mexico.

When will these technologies be reliable enough to be deployed in emergency situations?

Will they supplement or compete with GPS systems in the future?

Growth of the global space economy

Humans are conquering the last frontier with investments – while ready to reap the benefits of a thriving space sector, are we prepared to deal with some of the challenges that the democratization of space poses?

The global space economy, currently valued at $330 billion, is set to reach over $600 billion by 2030. Whereas in the past most space craft and science missions were funded by the public sector, private companies are expected to play a pivotal role in commercializing the space sector in the years to come.

Space X, Virgin Galactic and Amazon's Blue Origin Program are well known contenders in the new space race, but many other companies are aiming to tap on the commercial potential of space. In Europe, an ecosystem of 450 mostly small companies has emerged, generating €900 million ($1.05 billion) per year in revenue. Some countries, such as Luxembourg, actively encourage the growth of space industries with well-funded initiatives.

In addition, a revolution in satellite technology has made space more accessible to thousands of academic researchers, startups and hobbyists. The number of nano-satellites or CubeSats orbiting the Earth reportedly jumped from 12 in 2011 to 569 in 2017, increasing the likelihood of collisions with larger craft due to space debris.

How much will the space sector contribute to the global economy in the future? The higher the significance of the space sector, the higher the risks associated with extreme space weather events that might damage critical infrastructures the sector depends on. Will nano-satellites create more vulnerabilities in current satellite infrastructure rather than increasing the benefits to science and business?

Next generation of radiation-proof electronics

A nano-material developed by the Australian National University promises to make technology and infrastructures resistant to radiation

Satellites as well as astronauts orbiting the Earth are at a constant risk from radiation. Current technologies can mitigate negative impacts by absorbing radiation through thick filters. Yet, these only mitigate harmful effects and aren't completely resistant. Electronics in critical infrastructure remain vulnerable. For example, integrated circuits gradually degrade or even fail when exposed to space radiation. In October 2016, the US space weather satellite DISVOVER went offline five time in a year since it became operational. The outages were reportedly caused by cosmic rays and stopped scientific data from flowing, leaving the engineers to scramble to recover the spacecraft.

A team at the Australian National University has developed a nano-material that might prevent such dangerous events in the future. The material can reflect or transmit light on demand. An ultra-thin film from this material can be adjusted to reflect various dangerous ultraviolet or infrared radiation in different environments thereby significantly increasing the resistance threshold against radiation. The material is reportedly cost effective and allows for confined temperature control.

How probable it is that satellites monitoring space weather go offline when a major such event happens?

Will new materials such as the one developed at the Australian National University make space infrastructure completely resistant and when can they be realistically deployed?

Man-Machine Interface

Recent research brings telepathic communication a step closer to reality

Scientists have been pursuing machine-enabled human enhancement for decades with the ultimate objective of merging human consciousness with machine capabilities. Initially, research on Brain-Computer Interfaces (BCIs) started in 1970s and the first neuroprostethic devices implanted in humans appeared in the mid-1990s. Most of these devices were designed to restore damaged hearing, sight and movement. Further efforts explored how brain implants can relieve damage caused by strokes, Alzheimer’s or concussions.

Researchers are now experimenting with enabling telepathic communication with the help of BCI and Computer-Brain Interfaces (CBI) devices. In 2014 an experiment confirmed the viability of non-invasive brain-to brain communication by transmitting the words ‘hola’ and ‘ciao’ between four humans – one based in India and there other in France. One of the participants was in the BCI branch where the messages originated. The other three were assigned to the CBI branch to receive the messages. Using an internet-linked electroencephalogram (EEG) and robot-assisted image-guided transcranial magnetic stimulation (TMS) the words were encoded into binary and emailed from India to France. At this receiving location, a CBI transmitted the message to the receivers' brains through noninvasive brain stimulation and without the use of tactile or visual cues.

In a more recent experiment, scientists at the University of Washington linked two human brains for a question and answer game in 2015. Further research is needed to establish how more substantial messages can be sent before brain-to-brain communication becomes a reality.

How soon and how likely it is that brain-to-brain communication will become a reality?

Will microchips enabling such a communication be susceptible to space weather impacts, given that most of them use radio-frequency identification and the internet to facilitate brain-to-brain communication?

Next generation of communications and computing systems

Progress in material science will enable the development of quantum systems and much faster terahertz communications

Recent discoveries in the field of material science are likely to enable ultra-high-speed communications and computing, based on light rather than electricity.

Researchers at Harvard University created a time crystal – material that has a repeating atomic structure in time rather than space. While the atoms in a time crystal are continuously in a non-equilibrium state and keep replicating in time the material itself does not change. The discovery will potentially enable much more stable quantum systems which is currently one of the main challenges in the field.

Another team based at the University of Utah discovered a combination of organic and inorganic compound that has the same structure as perovskite but can be layered on silicon wafer that would use the terahertz spectrum. The process is inexpensive and simple.

Terahertz is a band between infrared light and radio waves – the next generation of communications bandwidth covering frequencies from 100 gigahertz to 10,000 gigahertz whereas a modern cell phone operates at 2.4 gigahertz. Using these light frequencies to transmit data will make communications and computing thousand times faster.

The researchers believe that it's another 10 years before terahertz technology for communications and computing is used in commercial products but consider to be a major milestone.

Is the terahertz range more or less susceptible to the effects of space weather events? How probable is it that new materials enabling terahertz communication will be in commercial products within the next 10 years?

Potential limitations to scalability of batteries for renewable energy storage

Growing efficiency and lower price are likely to make batteries for renewable energy much more affordable and widespread unless supply of key materials becomes an issue

Batteries are essential for the transition to clean energy and a distributed power grid. Storage and price were the main obstacles to widespread adoption until recently. However, battery efficiency is growing at 8% annually and prices are expected to drop 50% by 2018 according to Ravi Manghani, a senior energy storage analyst at GTM Research, as cited in Wired Magazine. This is driven by business initiatives and new scientific discoveries.

For example, Tesla's Gigafactory aims to scale battery production and make batteries cheaper. The factory is expected to produce 35 gigawatt-hours of batteries per year, pushing lithium batteries to unprecedented scale quickly.

At the same time, researchers at MIT have developed a prototype for a sulfur-flow battery which costs $100 per kilowatt-hour of energy stored. Both the anode and cathode of this battery are liquid electrolytes; the anode is sulfur dissolved in water and the cathode is an aerated liquid salt solution that takes up and releases oxygen with lithium ions moving between the electrolytes.

The battery is intended for long-term storage because it is scalable to a large size and made of earth-abundant materials.

No absolute limitations to battery manufacturing are currently foreseen, but experts warn that without proper planning there might be bottlenecks in the supply of some materials required for batteries, especially lithium and cobalt. Potential setbacks can be caused not so much by geographic distribution but by the ability to open new mines.

Even though geographic distribution is not a concern at the moment, will a less cooperative international climate limit the development of lithium-ion batteries in the future and therefore halt the transition to clean energy?

5G Communication networks and the advent of the Internet of Things

Will the transition to 5G networks and the Internet of Things make society much more dependent on technology?

Fifth-generation wireless technologies will dramatically increase bandwidth and faster data transmutation rates. Japan, South Korea and Singapore are frontrunners in the deployment of 5G networks. Other advanced economies are expecting to debut 5G networks between 2020 and 2025.

4G networks use the radio spectrum that sits below 3 gigahertz which is running out and getting more expensive. 5G is expected to live in bands above 3 gigahertz and will have to handle 1,000-fold increase in data volumes with low latency in order to enable new applications such as humanoid robots, robotic surgery, connected cars and the Internet of Things.

Currently the main roadblock to 5G networks is the lack of standards defining interoperability and ensuring security, but telecoms and regulators are trying to work out a consensus on these. The main advantage of 5G networks is not only that they will be super-fast thereby giving rise to the Internet of Things, but also much less energy hungry.

How soon will the Internet of Things become prevalent in developed societies? What policies and regulations will need to be implemented to ensure that the Internet of Things benefits everybody – corporations and technology providers as well as consumers? Are governments developing backup plans to guide society and businesses on how to behave in a case of IoT breakdown?

Quantum computing and the next wave of technological and societal transformation

Quantum computers are coming closer to reality as a result of gradual discoveries in the field promising the rise of faster and more powerful machines

Quantum computing encodes information by harnessing the quantum state of matter. Unlike digital machines, quantum computers store information in qubits that can be 0, 1 or a combination of the two simultaneously – a state known as superposition. Because of the ability to represent 0 and 1 at the same time, quantum computers can perform much faster and more powerful computations. Another important feature of qubits is their ability to get intertwined through the phenomenon of entanglement whereby one qubit in an entangled pair instantly reveals the value of its partner, even if they are far apart.

Scaling qubit processors, making qubits live long enough for effective communication and performing calculations at low temperatures have been the main challenges preventing commercialization of quantum computers so far. Recent academic and commercial research has made progress on all fronts:

- IBM plans to make a 20-qubit processor available by the end of 2017 and is testing a prototype quantum processor with 50 qubits. This is the required threshold to demonstrate that quantum computers can perform tasks that are unattainable for digital machines.
- Researchers at the University of Deft in the Netherlands are making progress in making qubits achieve both superposition and entanglement for long enough without being easily upset by vibrations or fluctuating electric fields.
- Scientists at the University of Finland reported to have built the first standalone cooling device that can be integrated into a variety of quantum electronic devices. The next step is to apply the device to cooling qubits in reality to allow a quantum computer to run algorithms in low temperatures.

Scientists believe that the day when quantum computers will surpass classical machines and reach quantum supremacy is rapidly approaching. China and the United States are already in a quantum computing arms race that might potentially change long-held dynamics in commerce, intelligence, military affairs and strategic balance of power.

Will quantum computing lead to a new dominant system for communication, replacing classical communication made of digital bits? Will digital machines and related infrastructures become obsolete in the next 50 years? How resistant will quantum technologies be to the effects of space weather events?

Automation and AI transforming the corporate life

Will AIs make better managers and decision makers than humans?

Automation is not a novel development in manufacturing plants and blue-collar jobs. Routine tasks in car assembly lines or dangerous ones in extreme environments have been the domain of robots for a long time. As research on machine learning, big data and artificial intelligence (AI) continue to progress, even more professions and specific tasks will become at least partially automated.

Industries prime for automation include healthcare where intelligent systems will first enable doctors to make better and individualized diagnoses before potentially replacing medical staff at hospitals. In finance, Deutsche Bank's CEO recently revealed his expectations that robots will replace 'large chunks' of the bank's workface, to match competitiveness of rivals who have only half as many employees. Transportation is another sector where automation is expected to have a big impact with self-driving cars eliminating the need for human driver and drones replacing couriers.

However, machines will not be confined to routine tasks only and are likely to make their way straight into corporate boardrooms. Tieto is a company headquartered in Finland and the first Nordic corporation to appoint an AI to its leadership team. The AI is called Alicia T and her role involves the support of data-driven decision-making and incubation of novel data-driven ideas with the help of machine intelligence and advanced data analytics. Alicia is expected to participate in discussions which will be enabled by a conversational interface system and will also have voting rights.

How likely it is that AI will be solely responsible for corporate governance and operations in the future?

How will corporations handle extreme situations resulting from space weather events if both workers and decision-makers inadvertently find themselves on vacation as a result of unexpected power black outs?

Rising volatility, unpredictable conflicts and impacts on sensitive infrastructure

In a volatile and unpredictable world, unexpected violent outbursts might pose danger to critical infrastructure

The international environment is becoming more volatile and less predictable. The influence of the US and Europe is weakening whereas Russia, China and Turkey are becoming increasingly assertive and North Korea increasingly defiant. These trends have accompanied the populist revolt against globalization and, according to Eurasia Group, the G-Zero world with no global leader – picked up on multiple fronts in 2016.

As challenges such as climate change, resource and food scarcity and refugee crises are likely to exacerbate over the years, the chances of unexpected violent conflicts are likely to rise. Professor Joan Johnson-Freese at the U.S. Naval War College in Rhode Island comments that “When there are situations, as currently, where trust is low between Asian countries, between China and the U.S., and increasingly between Russia and other countries, dual-use space technology can create security dilemmas."

Critical infrastructure such as satellites in geosynchronous orbit might be a potential target in such situations. For example, in 2007 China demonstrated an ability to destroy a satellite with a weapon from Earth. More recently, in 2013, China launched a rocket on a ballistic trajectory near to geosynchronous Earth orbit which raised suspicions in the United States.

Brian Weeden, technical advisor for the Secure World Foundation in Broomfield, Colo. admits that the U.S. military is grappling with now is the potential for other countries to reach out and touch those satellites that are critical for military intelligence and surveillance.

How are governments evaluating and preparing for increased risks to critical military and commercial satellite infrastructure? How likely is a big international conflict in the next 10 years that might lead to critical infrastructure being attached or shut down?

Construction of underwater cities

Rising sea levels prompt designers, architects, engineers and businessmen to envision urbanization of the oceans

Ongoing ocean and atmospheric warming is expected to lead to continuous rise of sea levels over the coming centuries. This poses a danger to densely populated coastal areas around the world where most of the Earth's population is based. Estimations suggest that more than a billion people, predominantly in Asia, live in low-lying coastal regions. As climate change might force inhabitants out of coastal areas and make it impossible to grow food on the ground, visionaries are considering how to make oceans hospitable to human life.

A project by Tokyo-based Shimizu Corporation provides a glimpse into the future – the firm's architects want to build underwater cities called Ocean Spirals. These will be self-sufficient and habitable settlements consisting of two elements – a 500-metre-diameter spherical city with a tower accommodating homes and a spiral structure that connects this sphere with a base station on the ocean floor. The spiral will provide the city with resources such as renewable energy, fresh water and food. For example, turbines on the ocean floor will draw power from the waves and currents and energy will be generated using thermal energy conversion to be used in the spherical city on top of the spiral. [13]

The city could be inhabited by 5,000 people. Although no concrete construction plans are yet approved, if the project was to proceed, the first Ocean Spiral would sit 16,400 feet below sea level off the coast of Tokyo.

Will underwater cities require completely new types of communication and transportation infrastructure? If underwater cities such as the Ocean Spirals are going to be self-sufficient, will this make life more self-contained? Will current levels of globalization and interconnectedness continue to exist if life is to move under water? Will infrastructure connecting various underwater cities be developed, similar to one existing over ground?

The race to utilize the Arctic

The Arctic might see a substantial buildup of infrastructure as populations escaping inhabitable areas affected by climate change migrate up north

Global warming is causing the melting of the Arctic ice cap. Sea ice is disappearing faster than expected and nations such as the U.S., Canada, Russia, China and the Nordic European countries

[13] Thermal energy conversion – a process that takes advantage of the temperature difference between cooler deep seawater and warmer shallow seawater to drive a generator to produce electricity

are vying for economic influence in the Arctic region, expecting access to undiscovered oil, natural gas and warming waters becoming richer in fish.

The prospects of opening the Northwest and Northeast Passages[14] to shipping by 2050 are likely to increase ship traffic in the Arctic Ocean. In addition, the withdrawal of ice leaving sovereign shores exposed to foreign attacks is expected to prompt countries to build infrastructure for defense as well as commercial purposes.

Similarly, permafrost in Siberia, Northern Canada, Alaska and Greenland is melting rapidly. Siberia might become the go to place to live due to climate change by 2080 with people flocking to large areas that are likely to become much more hospitable due to warmer weather and more farming opportunities. In the Alaskan Tundra, farmers are already taking advantage of the warmer climate substantially increasing produce such as crops and vegetables.

As currently densely populated areas might become inhabitable in the future, systemic migration to the north might lead to the buildup of infrastructure to support cities, farming and shipping.

How intense will migration to regions close to the Arctic is likely to be? (This will help estimate how much new infrastructure will be required). Will the race to utilize the Arctic result in greater vulnerabilities since the poles are most susceptible to disruption caused by space weather events?

[14] The Northwest and Northeast Passages connects China to Europe. Due to thawing ice, travel time through the passages can be reduced from 15,000 miles to 8,000 miles, saving ships time and fuel.

Scenarios of Societal Development

Objectives

Following the Trend and Emerging Issues Analysis process described above, we conducted a qualitative scenario analysis in order to better identify a range of possible futures relevant to forecasting society's future vulnerability to space weather events. In doing so, we were able to explore more of the logical possibilities that could cause divergence from straight-line extrapolations of present trends. This scenario work, in turn, provided direct input into the making of the Space Weather Impact Model system and its Scenario Builder interface.

Scenarios are, at most, forecasts—they are not predictions of what will specifically happen. Rather, scenarios attempt—in various ways—to frame the logical boundaries of the future and to help those of us without the gift of prophesy to better explore the unexpected or 'divergent' turns the future might take. In doing so, there is often a tension between keeping the scenarios 'realistic' to a broad audience while allowing them to challenge key assumptions about how change might logically unfold. Unfortunately, what tends to be most intuitively 'realistic' to many readers is a future in which fairly little changes from the way things are in the present.

The scenarios developed for this project were therefore meant to map out more of the diverging space that defines our possible futures. In doing so, they describe futures that are in some respects familiar and in other respects markedly different. They also, by necessity, represent relatively simply explorations of those futures. While scenario forecasting analysis can involve multiple rounds of research and analysis, involving scores of participants over several months, not all scenario work requires such intensity to yield useful foresight. For this project, the objective was to help the research team sketch out the broad outlines of multiple futures in order to usefully inform the modeling process.

Methodology

There are a variety of methods for generating scenario forecasts within the field of futures studies. For this project we selected morphological analysis for several reasons. First, it is a well-established foresight method with decades of use "in the field" and with many references and citations in the literature. Second, as a foresight method, it is reasonably well-known among those conducting science and technology forecasting for governmental and intergovernmental agencies in North America and Europe. Third, it more readily produces a greater number and greater diversity of scenarios than other popular methods, such as the critical uncertainties method that only produces four scenarios (immediately recognizable by its familiar 2x2 matrix). Fourth, it provides a great deal of structure to the process of generating forecasts, structure that makes it easier for audiences to understand the logic underlying forecasts.

Because the scenarios were designed to explore societal vulnerability to space weather events, we began with a vulnerability framework common to the Climate Change literature, that of *exposure, sensitivity, and adaptive capacity*. We used these characteristics to construct a morphological matrix that ultimately contained five parameters: extent of the built environment, nature of critical infrastructure systems, short-term mitigation and recovery capacity, long-term adaptive capacity, and policy priorities. The vulnerability characteristic of adaptive capacity was split into two parameters for the matrix in order to separate short-term resilience from the long-term adaptive capabilities of society. Policy priorities was added to allow the scenarios to better explore the impact of divergent public and private priorities in the future.

The alternative values for each parameter were developed based on extensive literature review and with inputs from the trend analysis and from the emerging issues analysis. The values in the table that resulted represent alternative possible outcomes for each of the five parameters. Because the purpose of the scenarios was to broaden the view of the future rather than narrow it, an effort was made to identify a diversity of possible end states for each parameter, with the guiding criteria that the values should have some logical and clear connection to currently observed trends, emerging issues, and dynamics. The final morphological table is shown in Table 3.

Table 3: Final Morphological Table

Extent of the Built Environment	Nature of Critical Systems	Short-Term Mitigation and Recovery	Long-Term Adaptive Capacities	Policy Priorities
Rapid, haphazard urban development	Lack of significant technical breakthroughs	Poorly prepared, few mitigation measures	Weak adaptive capacity	Economic growth
New terrestrial expansion	Decentralized and distributed systems	Somewhat prepared, moderate mitigation efforts	Strong but inconsistent capacity	Sustainable growth
Radical directions in human habitation	Machine revolution	Well prepared, high levels of mitigation	Informed but under resourced	Societal resilience
Space economy and spacefaring	Technological transformation	Divergent levels of preparedness and mitigation	Strong, systemic capacity	Geopolitical competition
Unwinding global integration	Shift to mega infrastructure projects			Strong inward (domestic) turn
	Deterioration and decreasing investment in maintenance			
	Privatized critical infrastructure			

To winnow down the number of possible scenarios form the above morphological table, we conducted a modified cross-consistency assessment. This consisted of comparing a subset of the values in the table with each of the other values, looking for logical incompatibilities. We selected the first two parameters (columns) in the morphological table (the Extent of the Built Environment and the Nature of Critical Systems) and compared the values in each with every other value in the table to discover any inconsistent pairings. For example, Space Economy and Spacefaring from the first column was found to be incompatible with the Policy Priority of Strong Inward Turn in the last column.

In addition to the modified cross-consistency assessment, the project team conducted an assessment looking for natural attractor pairs. These were obvious or logical pairings between two variables from different columns. Here it was common to find pairings where one value would logically enable or reinforce the emergence of the second value. One example was the natural attractor pair of Rapid, Haphazard Urban Development with Deterioration and Decreasing Maintenance. As with the cross-consistency assessment, and to maintain the process's own consistency, we used the first two columns in the table as the basis for the assessment, focusing on comparing those values with all the other values in the table.

Together, the information resulting from these two assessments was used to identify logical and compelling combinations of values across the morphological parameters. Five combinations (herein referred to as scenarios) were developed. Given the purpose of the scenarios for exploring a broad range of possible futures, effort was made to ensure that the scenarios were more divergent rather than less so. With the scenarios outlined, we then "fleshed" them out, using the exercise to determine how these scenarios would logically emerge and to consider how some specific new developments would play into them. For that, the final scenarios also incorporated additional trends and emerging issues, some of which are identified in the scenario tables that follow the scenario narratives.

The five space weather vulnerability scenarios:

- Tearing Ahead
- Resilient Redesign
- Starry Future
- Separate Paths
- Halting Transformations

Space Weather Vulnerability Scenarios

Each of the following five scenarios explores a logical possible future derived from a unique combination of possible end states in the morphological table. The scenarios first briefly explore the major reasons for change in each future, describe key social and economic changes, and finally explore aspects of vulnerability to space weather events. The tables for each scenario can be found in Appendix A5.

Tearing Ahead

A greater emphasis on short term growth and a failure of politics and policies to enforce smart, sustainable growth leads to a more crowded and haphazard world.

This is a future defined by rising labor dislocation (from widespread automation), growing inequality, and greater economic insecurity. In this environment, officials consistently issue promises for economic growth and governments show an almost maniacal, single-minded pursuit of near-term economic gains – quick wins that play well with audiences. Domestically, bigger, denser cities are seen as the answer, and policies shift to encourage more rapid urban development. Globally, repeated economic shocks and rising volatility contribute to the anxiety of the world's "precariat." Here, the long-run trends of urbanization and littoralization continue unabated, producing sprawling, difficult-to-govern megacities and "megaslums."

These are high consumption societies: governments focused on high employment and GDP growth, companies focused on expanding markets, and individuals encouraged to consume to drive economies. The accelerated diffusion of a digitally connected life – pervasive Internet of Things (IoT), rich data on individuals, and AI-driven anticipatory purchasing – make consumption effortless. Production, supply chains, and consumption all become deeply dependent on the machine-managed flow of information and material. Everywhere around the world, individuals and communities rely on these digitally-enabled flows of goods and services.

With so much policy making focused on issues such as boosting employment and achieving short-run economic gains, funding and attention for many types of longer-term concerns, such as contingency planning, suffer. In the US, a decades-old trend of underinvestment in basic infrastructure maintenance continues, even as billions of dollars of new infrastructure to support urban growth is built – at the lowest cost and as rapidly as available labor allows. Domestically, there is little support for systems or standards that would improve resilience to environmental shocks or reduce long-term vulnerability. From basic science and research to engineering improved systems for monitoring and forecasting, there are few advancements.

Resilient Redesign

Climate change and human demands collide, prompting a widespread search for innovative ways to house, feed, and support increasingly vulnerable communities and populations.

A few key trends define a future of necessary innovation and adaptation. The rapidly rising impacts of climate change, urban growth, and human consumption exert an exponential toll on societies. In addition to endemic growth, climate change and conflict drive a fast-growing number of human diasporas, mass migrations that contribute further destabilizing dynamics in destination countries. This in turns drives a value and policy shift to resilience and adaption. Many governments, unable and unwilling to solve these rapidly mounting challenges, turn to privatization to generate the solutions and provide the governance needed to meet these needs. While technology and innovative design certainly are front and center in this transformation, a more fundamental value shift towards adapting to change and working to live within certain boundaries is the most important change.

In the context of continued crises and mounting challenges, the private and nonprofit sectors strike off in myriad different, innovative directions to address social and economic challenges. Do it yourself (DIY) collectives financed by crowdfunding, wealthy philanthropic activity, and lots of public-private-nonprofit partnerships emerge to create new housing solutions and to overhaul existing energy, food, and transportation systems. In coastal regions there are experiments with a variety of solutions, including ambitious projects to build more artificial islands, converting aging shipping fleets into permanent migrant flotillas, and designing oceanic cities above and below the water. On land, there is a fast-growing "radical urbanization" sector, experimenting with many technologies to completely overhaul urban food production, energy production, and housing design to create denser, more populous, and more resilient urban landscapes. All of these innovations are designed to operate in less hospitable climes.

While privatization and self-directed innovation produce a lot of positive change, one consequence of privatization and the many unique collaborations is a wide diversity of governance approaches and a range of outcomes. While some locales are extremely well-thought out and well prepared for environmental shocks and shifts, others have the right intentions and yet suffer in the execution or the speed of development. Some places end up with highly distributed and largely self-contained systems while others are more centralized yet feature a much higher level of disaster preparedness and redundant systems. In some regions there are high levels of coordination among these evolving communities with increasingly private governance, while in others there is not. Given the diversity of communities and unique approaches within each, overall there is a slight tendency to focus on local resilience before addressing regional cooperation and interdependencies.

Starry Future

A global competition over technological innovation and great power competition propel the widespread digitization and automation of society and launch a new international space race.

This is a future that witnesses a rapidly evolving global competition for technological innovation across a number of key technologies, fields such as artificial intelligence, robotics, and quantum computing. At the same time, the shifting geopolitical landscape drives a renewed "space race" as rising powers seek to establish and cement their places in space. With private industry playing a key role, there are a range of important innovations in commercial space flight. Based on these, there is a booming market for satellite-based communications and imagery, rapidly growing science sector, and a rapidly expanding tourism sector. Even as these markets find their footing, new and more ambitious plans are announced for a permanent presence on the Moon and on Mars, and longer-term programs for machine-based resource extraction in the solar system.

While humanity's rapidly expanding foothold in outer space is the most notable geographic development, around the world societies have been steadily rewired with machine augmentation. A prime beneficiary of the global tech race, AI has rapidly evolved in its applications and comes to play important roles across education, economics, healthcare, and even governance. Just as machines (AI and robotics) play a key enabling role in the commercial space sector, on Earth there is widespread automation of transportation, manufacture, and the management of ever-more-complicated supply chains. Machines, both of the soft and hard varieties, are commonplace aids in daily life, with a variety of assistive AIs teaming with individuals, teams, and other machines to carry out tasks, anticipate needs, predict outcomes, and manage (i.e. control) a widening array of mobile and immobile connected devices.

Economic growth is a primary policy goal of many countries (fueling much international competition). Yet, many painful lessons about the myriad vulnerabilities society is exposed to through basic cyberthreats, widespread reliance on systems of autonomous systems, and extensive and rapidly expanding space infrastructure eventually drive governments to legislate increasingly strong standards for secure and resilient systems. Pervasive automation across systems, coupled with advances in analytics and modeling, combined with the new need to protect space infrastructure and assets, enable a new level of system-wide responsiveness. Critical systems have much better anticipatory and self-regulatory capabilities, minimizing systems cascades in the event of emergencies. Meanwhile, human oversight includes a much greater appreciation for global interdependencies and space-borne risks, with a much-expanded focus on preparedness, cooperative planning, and long-term reduction of vulnerability.

Separate Paths

The evolution of a more fragmented world order leads to less integrated global systems and more divergent developmental paths among nations.

A future shaped by the trends of rising nationalism and a deep-rooted backlash against a Western-led globalization. As rising actors seek to form new spheres of political and economic influence, the world experiences the creation of competing regional policy regimes and increasingly tangled and fraught relationships. Small but recurring military flare-ups keep international tensions high and cooperation low, with competition extending across economic, political, and military realms. As global integration and shared norms unravel, competition over technological leads increase and governments become increasingly concerned with securing critical systems against foreign influence or disruption.

The global competition for technological leadership leads to important innovations in systems such as new precision timing and navigation systems, developed to avoid reliance on GPS and other US-dominated systems. The race to lessen reliance on foreign energy creates important developments in technologies such as microgrids and new energy storage technologies, advances that enable more distributed energy production and use. With international tension so high and with competition so fierce, corporate and scientific espionage hits all-time highs, along with cyber exploits to obtain or derail technical innovation. Governments and companies prioritize securing many digitally connected systems against a variety of vulnerabilities – even enabling systems to autonomously isolate themselves when threatened.

In such an environment there are significant differences between countries and regions in terms of governance, long-term planning, and specific policy priorities. Overall, there are much lower levels of international cooperation, sharing of data, or collective standard setting across the board. Relatively modest scientific progress is made in areas that have little direct impact on political, military, and economic priorities. The competitive and threat-filled environment drives a rise in proprietary, even secretive, system design and governance. There is little interoperability, with some countries and companies are much less vulnerable and more resilient than others. Within the US, states have prioritized issues like infrastructure upkeep and improvement very differently, depending in part on how they have fared as global integration has begun to unravel.

Halting Transformation

Spurred by the mounting pressures of climate change, population growth, and economic development, countries begin an uneven but determined push for more innovative and sustainable models of growth.

After years of increasing extreme weather, the world suffers an unusually powerful series of extreme weather events, which trigger multiple cascade failures in coastal areas, overwhelming governments and collapsing local economies. In the immediate aftermath of the string of disasters, a groundbreaking new study concerning global vulnerabilities to disasters is issued. Featuring new models and compelling new data, the report warns that future disasters will be worse and shows how future cascade failures will spread worldwide. Galvanized by the recent disasters and focused by the recent study, there are widespread calls for new technologies and new systems that can better provide for growing needs in increasingly stressed and turbulent environments. A series of high level conferences, international panels, and world summits ultimately leads to a major policy shift in many capitals.

Dramatically increased policy support and sustained funding greatly accelerate the development of radical new technologies to help address the world's growing challenges. Society undergoes a two-pronged technological transformation that rewires basic systems. Quantum computing, one of the key advancements, comes of age and goes mainstream, augmented by technologies such as biocomputing and DNA-based storage systems. Biology, in fact, rises to the fore as one of the key areas of advancement, with bio-based industrialization becoming prevalent. This is an era in which genetic engineering and synthetic biology explode when coupled with new computing technologies. On a more macro level, urban design and architecture are pushed to innovate new housing, urban energy, urban food production, and transportation models. On a parallel philosophical and ethic tract, infrastructure and business model design ethos embraces closed loop thinking and "circular economy" models.

While there is a broadly shared commitment to finding innovative new ways to provide more for more people, and while there is definitive collective movement towards long-term sustainable growth, there are considerable differences between countries in their ability to withstand *short-term* shocks. These are largely due to the different rates at which countries can redevelopment and retrofit, rather than any lack of commitment. Governmental support for local and private sector preparedness and resilience dramatically increases, though here too absolute numbers vary according to region. Due to these strong, shared commitments to change, there is a high degree of international cooperation, joint research, and coordination in disaster planning, mitigation, and response, which extends to space weather.

The Space Weather Impact Model

Introduction to the Model

The Space Weather Impact Model (SWIM) is a long-range foresight tool designed to aid in the analysis of space weather events and their potential economic and societal consequences under different scenarios of societal and technological development. The SWIM system is a collection of interlinked system dynamics modules that together work to capture the short-term impact pathways of space weather events as well as long-term societal and technological changes. The model draws on the latest space weather, critical infrastructure, and modeling literature (as detailed above) for its structure and is initialized using a database of economic, demographic, infrastructure, and governance data drawn from a wide array of sources (see Appendix A2). The model includes a standalone app that allows users to explore how the implementation of different technologies and changing rates (and even direction) of societal changes can impact society's vulnerability to, and therefore damage from, space weather events. This section provides an overview of the SWIM's design philosophy, its structure and construction, and its interface and use. The following section presents an analysis of model results, including base case, scenarios, and model benchmarking.

Model Design Philosophy

SWIM's design draws from a constellation of modeling approaches, including system dynamics modeling (SD), critical infrastructure interdependency modeling, disaster impact/interoperability modeling, econometric modeling, and scenario analysis. The contributions from each are highlighted here.

- **System Dynamics (SD) Modeling**
  - Human society and the technological infrastructure that underpins it are complex, dynamic systems, as is the Sun-Earth system that gives rise to space weather. Thus, the SD approach to modeling, with its ability to capture complex, nonlinear interactions and behaviors through its use of dynamic stocks and flows and feedback loops was identified as the best framework for replicating the various components of the systems being modeling.
- **Critical Infrastructure Interdependency Modeling**
  - The interdependencies between critical infrastructure networks form a complex system-of-systems where impacts to one infrastructure can reverberate through the rest. The literature contains many different approaches to modeling these networks, including SD (described above). The SWIM approach draws in

particular on the SD three 'block' model developed by Canzani (2016) and extended by (Luglio 2017). Canzani uses a series of interconnected SD blocks to capture the nonlinear dynamics underlying CIs as simply as possible, where: Block 1 models the disruptive event (in terms of a pulse function representing timing, magnitude, and duration); Block 2 models each critical infrastructure in terms of its operational status; and Block 3 models the interdependencies between the CIs. In the Canzani block model, the dynamics of each critical infrastructure is partly a function of the CI's internal operations in the face of a disruptive event (determined by the percent of the CI network in working operation, offline, or under repair/restoration at a given time) and partly a function of the state of operations of each other connected infrastructure, thus capturing both direct disruptions to service provision and indirect disruptions due to dependencies. SWIM builds on Canzani (2016) and Luglio (2017)'s approach by adding a Vulnerability Index to each CI that acts as a modifier to the standard impact from the disruptive event, increasing or decreasing the likelihood of network elements becoming stressed and failing based on the infrastructure's particular characteristics–SWIM also introduces the notion of stressed infrastructure elements, where infrastructure services are still provided but at reduced rates rather than the standard binary of working/not working.

- **Disaster Impact Modeling**
  - A standard approach used to calculate the economic impact of natural disasters, the disaster impact modeling method (also referred to as inoperability modeling) traditionally uses a modified Leontief economic input-output model to capture the ripple effects of sectoral disruption through the rest of the economy (Leontief 1986). In a Leontief model, an economy (from local to global) is broken down into sectors or individual industries where each sector's inputs and outputs are organized into flows to each other sector. Thus, if one sector's outputs are disrupted, each sector relying on that sector for inputs is also disrupted, to a varying degree. SWIM adopts this method in order to calculate the amount of economic activity disrupted (expressed in terms of GDP) by a given space weather event through its disruption to the infrastructure sectors' intermediate outputs to the rest of the economy, where the level of disruption comes from the critical infrastructure module.
- **Econometric Modeling**
  - Econometric modeling uses statistical analysis to identify quantitative relationships between independent variables (drivers) in order to forecast future values of a dependent variable (outcomes). It is a common tool in quantitative foresight modeling and analysis. The SWIM approach uses statistical relationships identified in the literature to parameterize the drivers of infrastructure demand and supply in order to calculate the change in demand and supply for each infrastructure type over time. It also uses standard statistical extrapolation techniques provide initial forecasts of exogenous variables that are later modified by other model elements or direct user inputs.
- **Scenario Analysis**

- Scenario analysis is a standard foresight methodology for 1) identifying potential factors that could alter current development trajectories in different ways and thereby give rise to alternate futures, and 2) to map out these alternative futures, usually in terms of what's possible, probable, and preferable. Scenario analysis can include qualitative and quantitative methods. The SWIM project includes both qualitative scenario analysis, in the form of the five alternate futures based on emerging issues analysis (described in detail above), and quantitative scenario analysis, through the inclusion in the model of user-modifiable variables representing potential technological and societal changes—variables that impact infrastructure vulnerability levels and the rates of change among the various drivers of infrastructure demand and supply. The SWIM app is designed to allow users to use the model to carry out their own quantitative scenario analysis.

Model Structure and Construction

The Space Weather Impact Model attempts to capture the full range of dynamics involved when it comes to the potential impact of space weather events, from direct, 1st order impacts to indirect 2nd and 3rd order impacts. Figure 2, below, provides a basic outline of the model's structure. User-entered space weather events (geomagnetic, radiation, radio blackout) directly impact certain infrastructure networks, which, following the impact pathways established in the literature, go on to indirectly impacts those systems dependent on their services (other infrastructures as well as various economic and social systems), and, in turn, to impact future infrastructure supply, demand and vulnerability. In the diagram, black arrows represent 'long-term' model dynamics, yellow arrows short-term dynamics, and green arrows the various 'handles' by which users can create model interventions (scenarios).

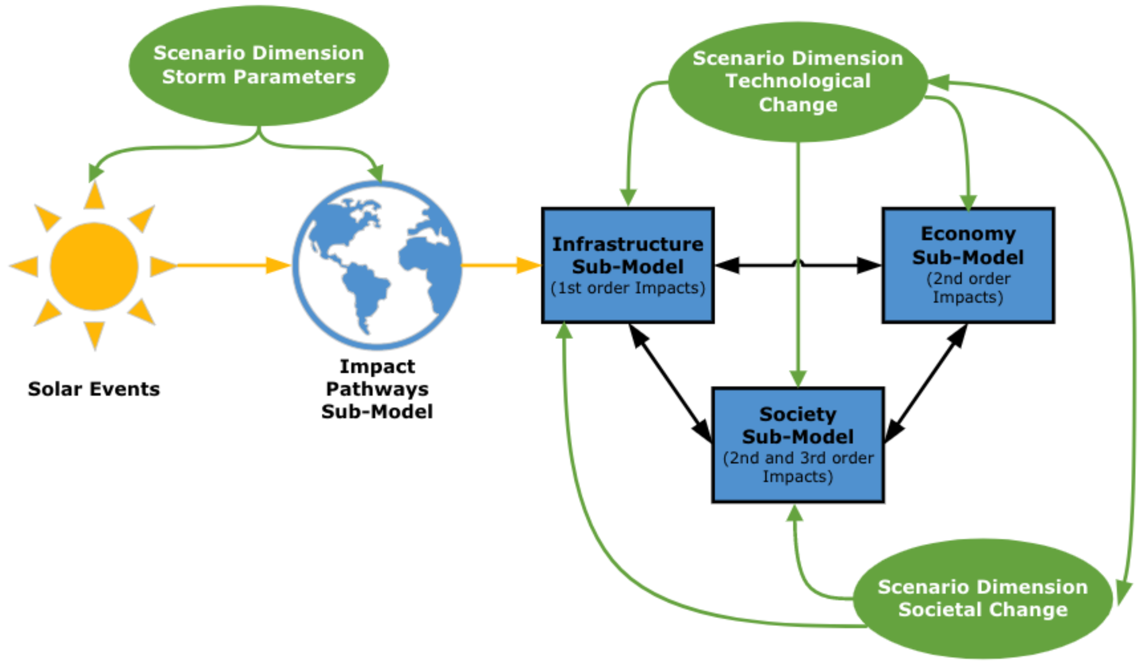

Figure 2: SWIM Basic Structural Diagram
Source: Authors' conception, SWIM version 1.1

Model Overview

This section provides an overview of the eight interlinked system dynamics modules that make up the SWIM system: the Space Weather Module, the Critical Infrastructure Module, the Economic Disruption Module, the Economic Forecast Module, the Demographics Forecast Module, the Governance Forecast Module, the Infrastructure Forecast Module, and the Technological Change Module. Figure 3 shows how/where these modules fit into the model's overall structure and the basic interactions between each.

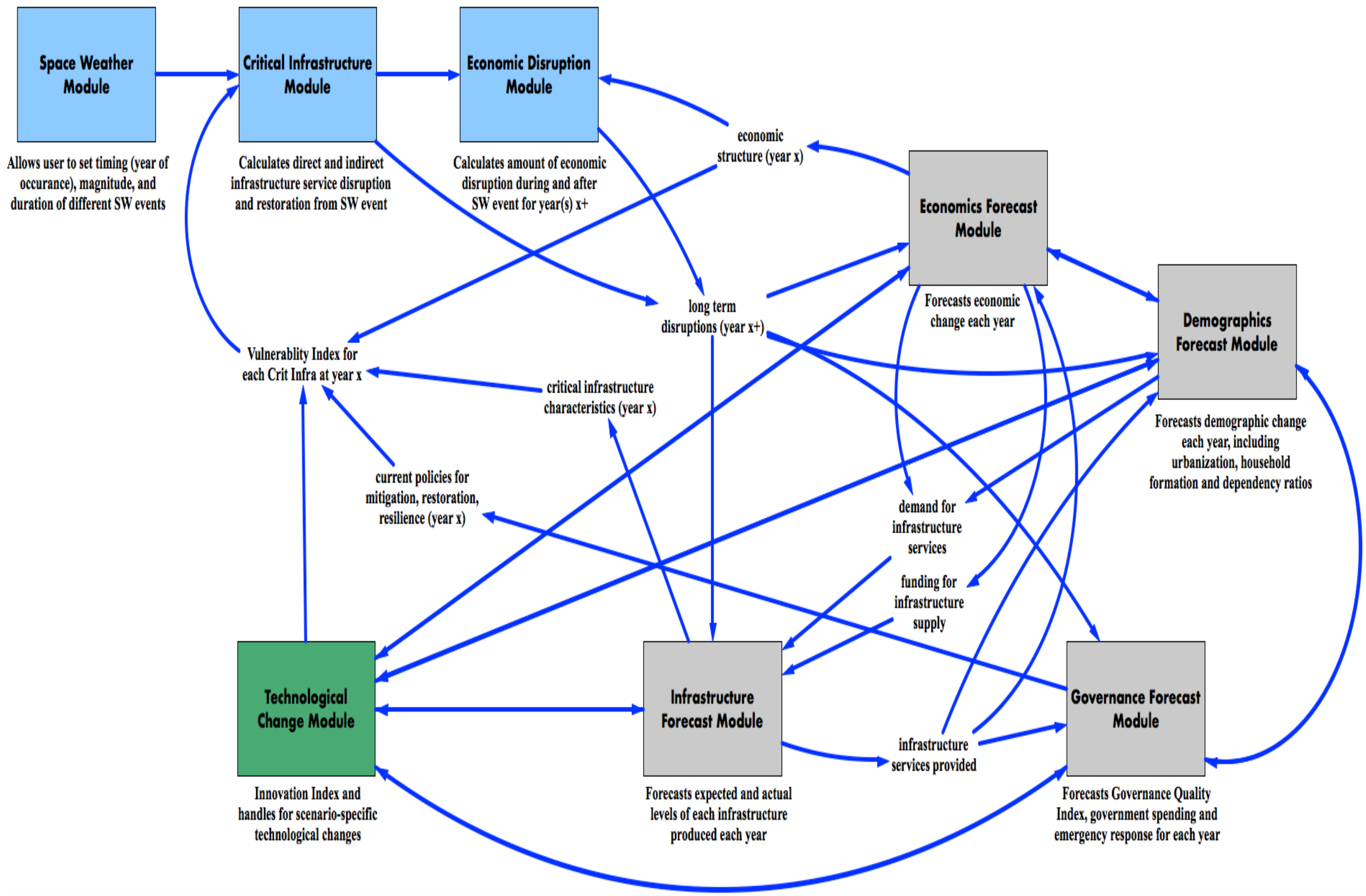

Figure 3: SWIM High-Level Diagram
Source: Authors, SWIM version 1.1

Model Elements

Space Weather Module

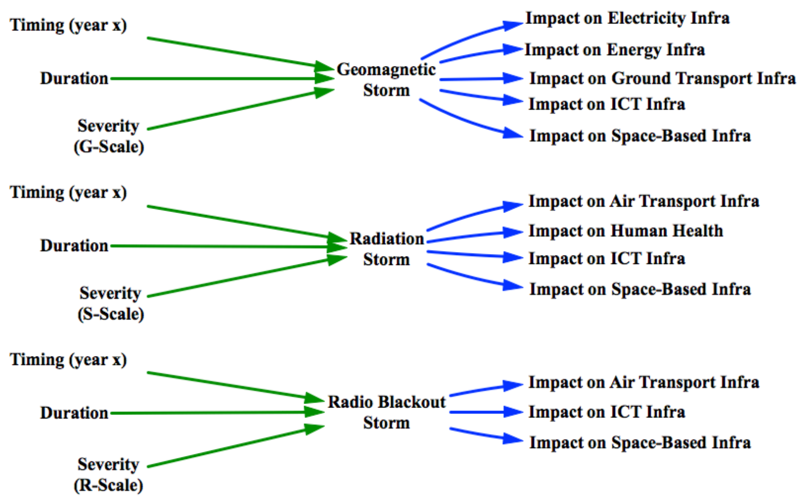

Figure 4: SWIM Space Weather Module
Source: Authors, SWIM version 1.1

The Space Weather Module contains the dynamics for modeling the three primary types of space weather events: geomagnetic storms, radiation storms, and radio blackout storms. Each storm type has a user-determined year of occurrence (between today and 2100), duration, and severity level (using the NOAA scale). Users can also determine whether all three storm types occur at once or in succession or not at all. Each storm type impacts specific infrastructures, following the impact pathways identified in the literature, where:

- **Geomagnetic storms impact:**
  - Electrical infrastructure
  - Ground transportation infrastructure
  - ICT infrastructure
  - Energy Infrastructure
  - Space-based infrastructure
- **Radiation storms impact:**
  - Air transportation
  - Human health
  - ICT infrastructure
  - Space-based infrastructure
- **Radio blackout storms impact:**
  - Air transportation
  - ICT infrastructure
  - Space-based infrastructure

Critical Infrastructure Module

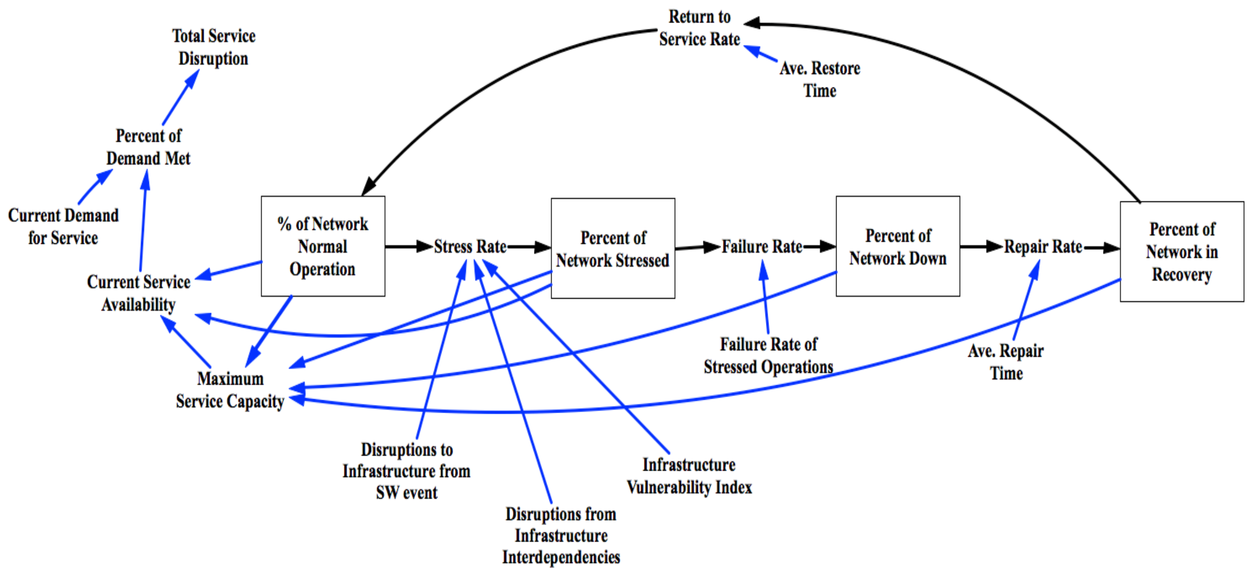

Figure 5: SWIM Critical Infrastructure Module Simplified Diagram
Source: Authors, SWIM version 1.1

The Critical Infrastructure Module calculates the level of service disruption inflicted on each critical infrastructure network based on inputs from the Space Weather Module (storm type, timing, duration, severity), the Vulnerability Index for each infrastructure, and dependencies between individual CIs. Thus, when a space weather event occurs, impacts of various magnitudes spread across the entire network of critical infrastructures. The Critical Infrastructure Module divides each infrastructure network into four categories based on current operation status (normal operation, stressed, down, and in recovery). Disruptions cause infrastructure elements within the network to flow between each status, as, over time, elements become stressed, fail, and are then repaired. From this, the module calculates how much 'service' each critical infrastructure is able to provide before, during, and after each disruption. The level of network disruption then feeds forward to the Economic Disruption Module.

The Vulnerability Index used by the Critical Infrastructure Module is calculated independently for each CI, using the 'vulnerability framework' from the literature on Climate Change impact assessment modeling (IPCC). The model therefore calculates *exposure, sensitivity,* and *adaptive capacity* scores for each CI, each based on multiple variables—some endogenous and some exogenous/user-determined for scenario analysis. Figure 6 (below) provides a generic version of the Infrastructure Vulnerability Index's construction (see Appendix A6 for details on the individual indices for each CI).

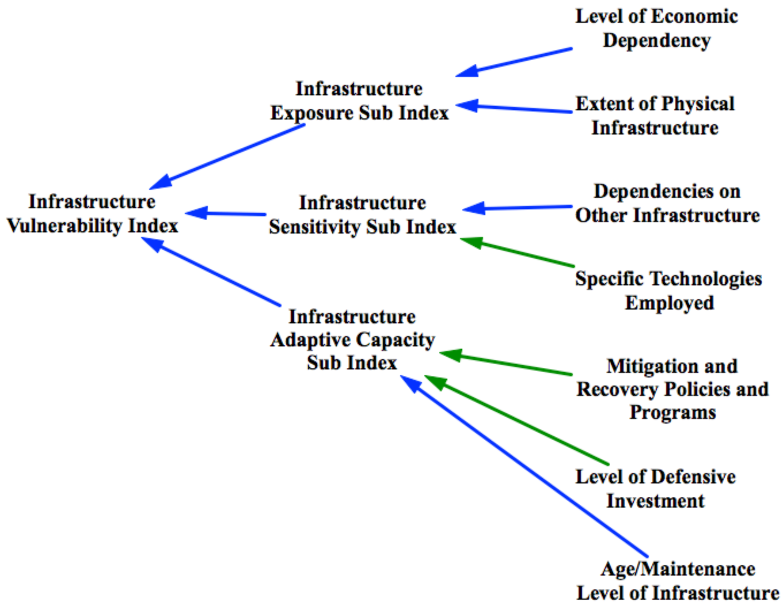

Figure 6: SWIM Infrastructure Vulnerability Index Simplified Diagram
Source: Authors' Conception, SWIM version 1.1

Economic Disruption Module

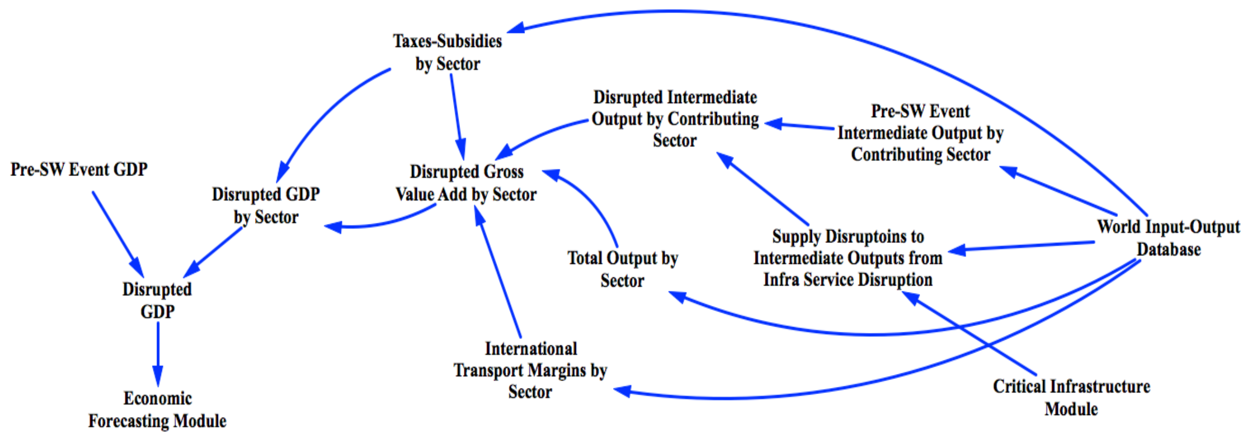

Figure 7: SWIM Economic Disruption Module Simplified Diagram
Source: Authors, SWIM version 1.1

At the heart of the Economic Disruption Module is an Input-Output table derived from the World Input-Output Database (WOID).[15] The SWIM version of this IO table includes the inputs and

[15] Accessible at http://www.wiod.org/home [April 20th 2018]. The WOID includes separate data for 43 countries and provides model estimates for the rest of the world in order to reach global coverage. The sectors are classified using the International Standard Industrial Classification revision 4 (Timmer et al 2015).

outputs for 24 sectors and subsectors (consolidated from the original 56 sectors) both globally and for the US. The table provides the normal (pre-event) level of intermediate outputs (inputs) by contributing sector and the normal total output and final consumption for each sector and consumer type. The Economic Disruption Module then uses the table to calculate pre-event GDP for each sector and for the economy as a whole. When a space weather event occurs (via user input), the module pulls in the services disruptions generated by the Critical Infrastructure Module (and the current year total GDP from the Economics Forecast Module) and then applies those disruptions to the intermediate outputs produced by each impacted sector. Intermediate and total outputs are then recalculated for each sector and a new, 'disrupted' GDP is calculated. The difference between pre- and post-event GDP is used to represent the total amount of economic activity disrupted by the storm. This disruption, in turn, feeds into the Economics Forecast Module to impact the rate of economic growth going forward.

Infrastructure Forecast Module

The Infrastructure Forecast Module consists of two parts: the first forecasts demand for each infrastructure, while the second forecasts the amount of infrastructure built to meet demand for those infrastructures as well as the current level of infrastructure stocks and physical state (well-maintained, aging). Each year, new infrastructure is built so long as demand is higher than current supply and while there is sufficient funding, and each year existing infrastructure ages and is maintained/replaced—again, so long as funds are sufficient. Each infrastructure has an initial supply, funding level, and new construction and maintenance unit costs taken from the literature. Infrastructure stock levels are then used by the Critical Infrastructure Module as part of calculating the Vulnerability Index measure. Demand for each infrastructure is based on changes in the drivers of demand for that infrastructure. In Figure 8, below, changes in Urbanization, Governance, GDPPC, Urban Households, and technology-driven efficiencies, all influence the level of demand for a generic infrastructure.

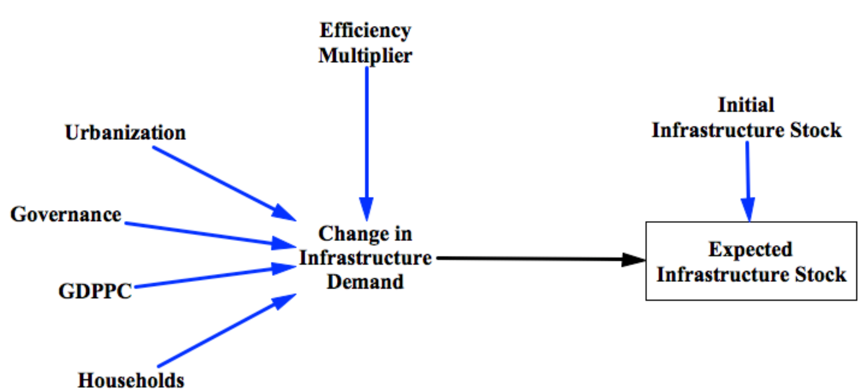

Figure 8: SWIM Infrastructure Demand Simplified Diagram
Source: Authors, SWIM version 1.1

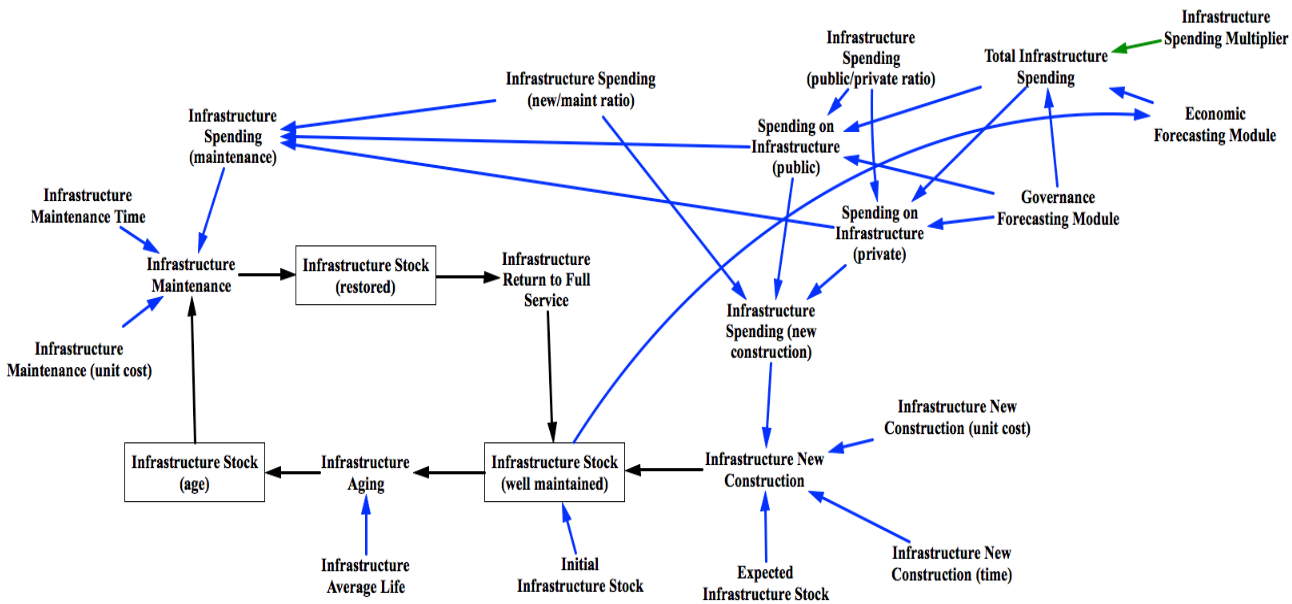

Figure 9: SWIM Infrastructure Supply Simplified Diagram
Source: Authors, SWIM version 1.1

The supply side of the Infrastructure Forecast Module determines how the actual stock of each infrastructure changes in each model year. When demand for new infrastructure (the expected level of infrastructure) exceeds the current stock, the supply side builds more infrastructure based on unit costs and available funds. Funding for infrastructure is divided between public and private sources and between supporting new construction and maintaining existing infrastructure stocks. Each infrastructure stock ages over time, requiring maintenance to return to good order. The percent of stock in need of maintenance (aged) is used in vulnerability calculations. By default, total infrastructure spending is kept constant at 3.5% of global GDP (average global spending for the last decade) (Oxford Economics 2017)—but this assumption can be changed by the user.

Technological Change Module

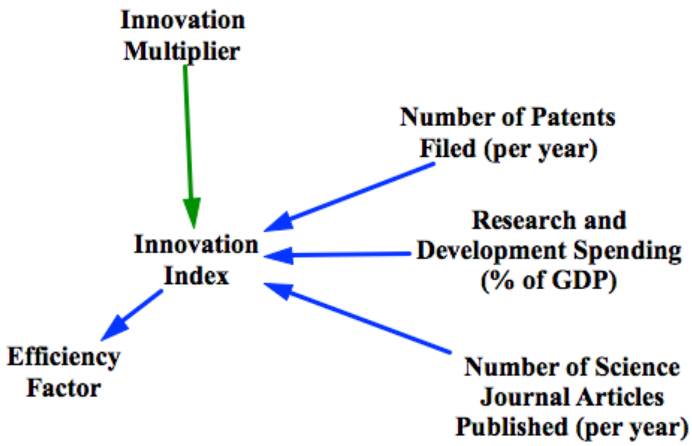

Figure 10: SWIM Technological Change Module Simplified Diagram
Source: Authors, SWIM version 1.1

SWIM uses an Innovation Index to represent the rate of technological change over time. The Innovation Index consists of three indicators commonly used to measure technological change: the number of patents filed each year, the number of science and technology journal articles published each year, and the annual amount spent on research and development as a percent of GDP. The Innovation Index is a driver of demand for certain infrastructure services (representing new products/markets) and is used by the Vulnerability Index (impacts *sensitivity* by representing the rate of development/deployment of next gen technologies) and is used to drive the Efficiency Multiplier, which decreases demand for certain infrastructures (representing process and production efficiencies). The indicators used to calculate the Innovation Index are currently forecast exogenously, but the User can alter the overall rate of Innovation through the Innovation Multiplier.

Demographics Forecast Module

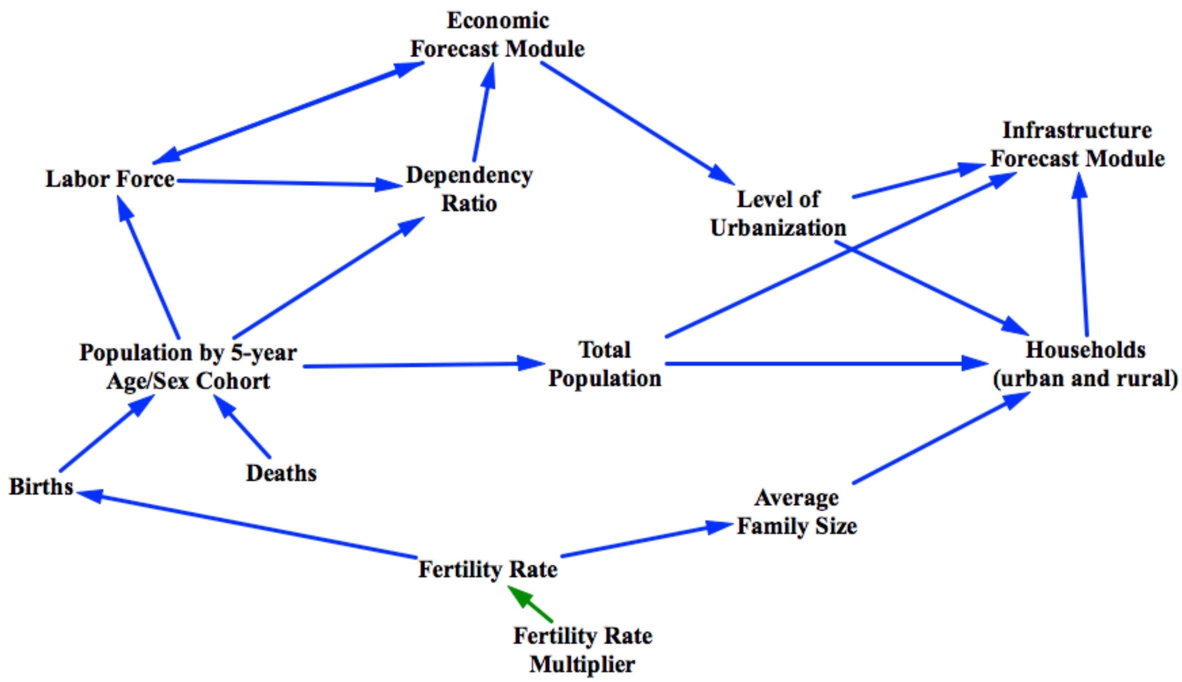

Figure 11: SWIM Demographics Forecast Module Simplified Diagram
Source: Authors, SWIM version 1.1

The Demographics Forecast Module is divided into two parts: population and urbanization and families/households. The population submodule uses a standard 5-year population cohort model initialized with data from the United Nations World Population Prospects 2017 Revision (UNWPP) to produce a dynamic population forecast. Age-specific fertility and mortality rates change over time based on the UNWPP's Medium Variant scenario. Changes in the fertility rate are also used to drive changes in family size over time. Population, family size, and the urbanization rate are used in the second part of the Demographics Module to calculate the number of urban and rural households in each year. Outputs from the Demographics Forecast Module (including urbanization, households, total population, the dependency ratio and potential labor force size) are used to drive infrastructure demand and economic growth.

Economics Forecast Module

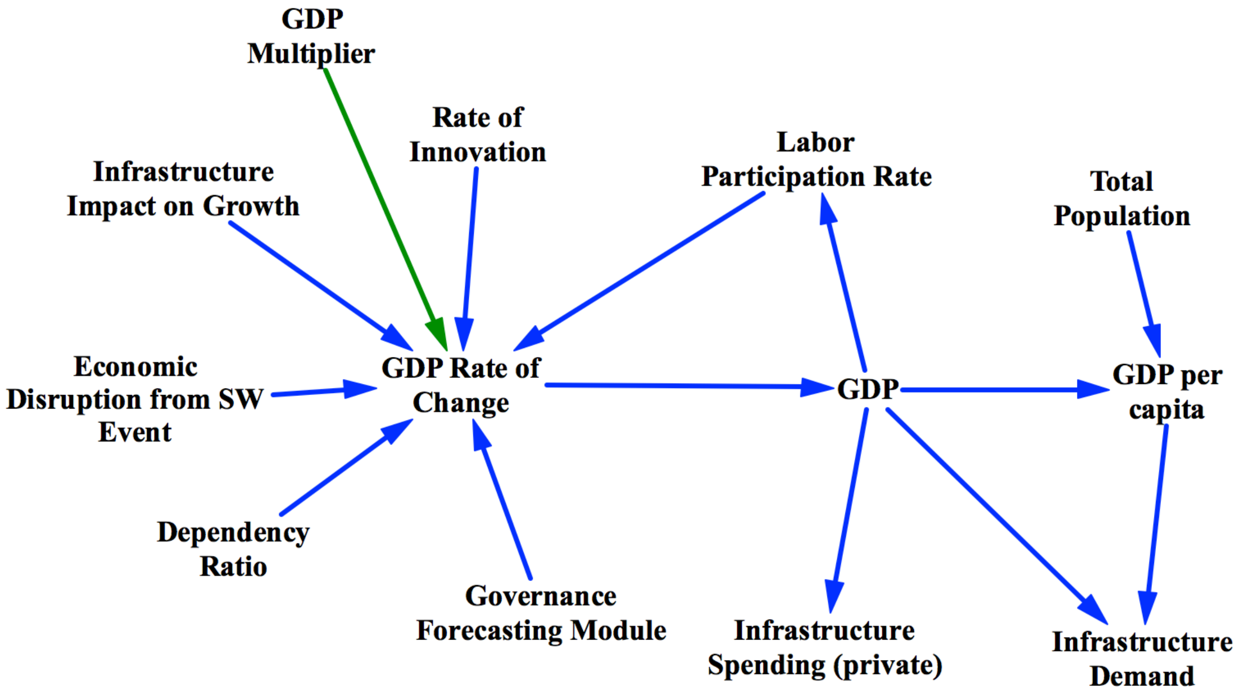

Figure 12: SWIM Economics Forecast Module Simplified Diagram
Source: Authors, SWIM version 1.1

The Economics Forecast Module provides measures of economic development (GDP and GDP per capita) used in the calculation of infrastructure supply and demand, and the labor participation rate. The module begins with an exogenous extrapolative forecast of GDP (based on data from the WDI) and modifies the forecast based on endogenous changes in infrastructure supply, the dependency ratio, labor participation, the innovation rate, changes in governance quality, and, of course, the level of economic disruption caused by space weather events. The rate of GDP change can also be directly modified by user input.

Governance Forecast Module

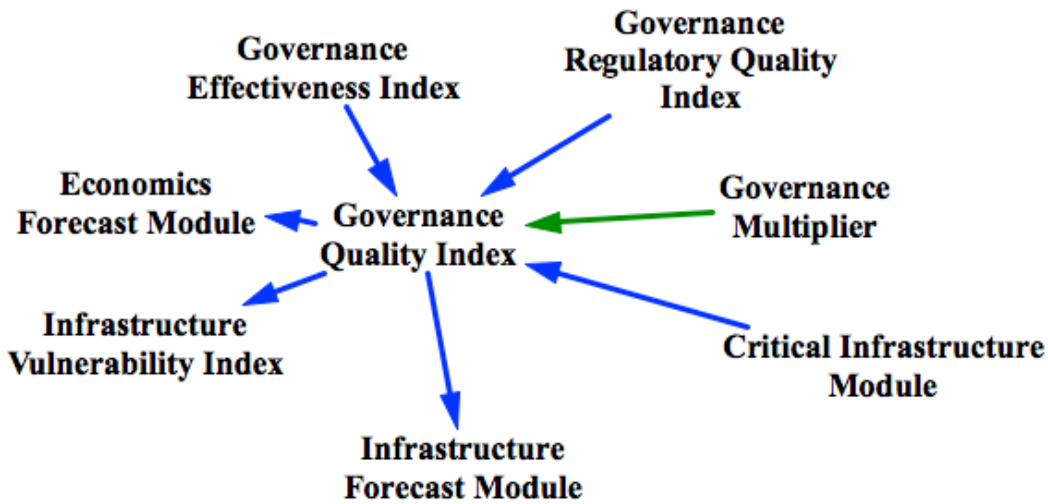

Figure 13: SWIM Governance Forecast Module Simplified Diagram
Source: Authors, SWIM version 1.1

The Governance Forecast Module provides a measure designed to get at the quality of governance and government institutions in terms of both the regulatory environment and of the effectiveness of policies and institutions to manage society. The SWIM uses a composite measure of governance quality which is forecast exogenously from two data series, the Governance Effectiveness Index and Regulatory Quality Index from the World Bank's Worldwide Governance Indicators Database. The Governance Quality Index is used as an input to several modules, including the Economics Forecast Module, where changes in governance quality are reflected in overall economic growth, the Infrastructure Vulnerability Index, where changes in governance influence infrastructure adaptive capacity scores through its impact on mitigation and defensive investments, and the Infrastructure Forecast Module, where governance quality helps drive demand for certain infrastructures like the water supply and public transport. Because the ability to govern depends, in part, on the status of critical infrastructures, disruptions to service supplies can have a negative effect on governance quality. The rate of change in governance quality can also be directly modified by user input.

The SWIM Model Software

The Space Weather Impact Model was created using the Vensim DSS system dynamics modeling platform developed by Ventana Systems, Inc. (Julian Smart et al. 2010). The model's current database was created using Microsoft's Excel. The standalone SWIM App (described and pictured below) is a Venapp and was also created using the Vensim DSS application. Users can access both the standalone version and the full version of the model via a public Dropbox; for the standalone, no additional software is required. To use the full model, users will need to first download either the free Vensim Model Reader or Vensim PLE version which can be found here. The Reader and PLE versions are compatible with both Windows (XP through 10) and Macintosh OSX (10.9+).

Using the Standalone App

The SWIM standalone app is a compiled version of the model that includes an easy to use interface consisting of a number of 'screens.' Upon launching the app, you will see the Title Screen. You may need to maximize the window to ensure scaling is correct. Clicking Continue will tell the app to load the full model and latest model run and will take you to the Scenario Builder screen.

Scenario Builder

The Scenario Builder screen allows users to develop custom scenarios using the SWIM system. Users can select the timing, duration, and severity of the three types of space weather and then can make a number of technological and societal interventions in order to explore how critical infrastructure vulnerability and therefore space weather's economic and societal impacts might change over time.

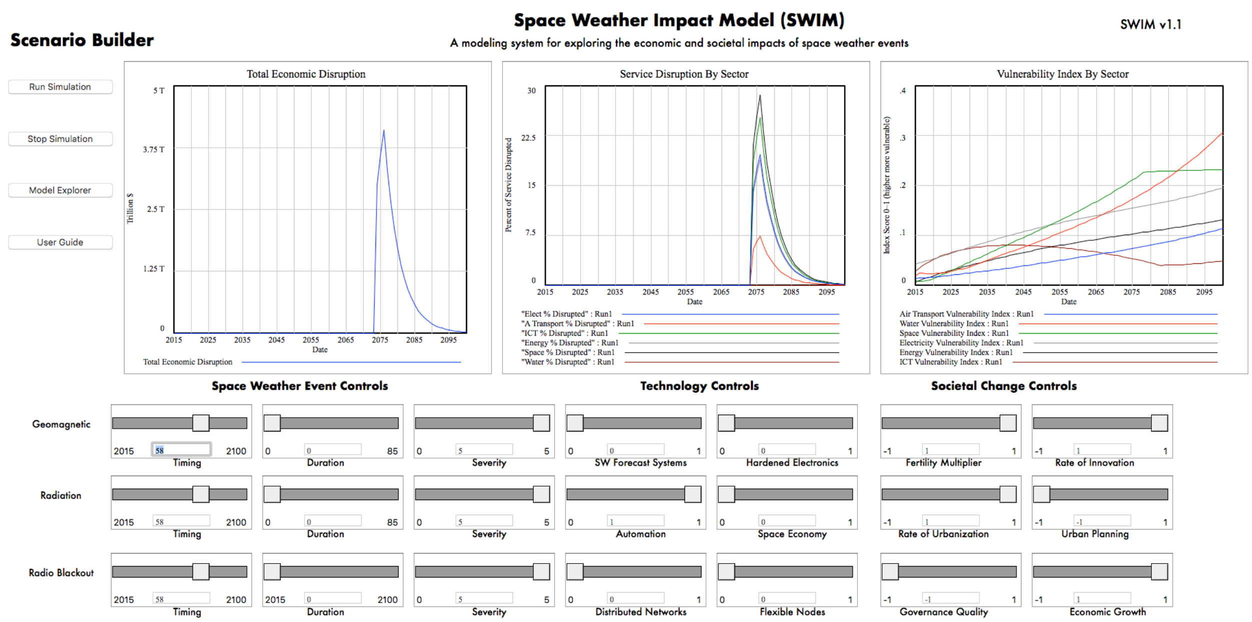

Figure 14: SWIM Scenario Builder Interface

Source: Authors, SWIM version 1.1; Vensim DSS 7.2 by Ventana Systems, Inc.

Model Explorer

The Model Explorer is a series of screens that take the user on a walking tour of the model's structure and modules, with diagrams and explanatory text.

User Guide

The User Guide provides instructions on how to use the app.

SWIM Analysis and Results

Our tour of the SWIM's design and construction complete, we now turn to exploring the results produced by the full model. We begin this exploration by examining the model's Base Case results; the Base Case is a 'no surprises' scenario where current trends largely continue and where no significant disruptions (like a severe space weather event) occur. This allows us to evaluate the model's general behavior before introducing a major impactor or various scenario-based interventions (new technologies, policies, and other societal changes) designed to modify society's vulnerability to space weather. We will then turn to benchmarking the model, comparing the SWIM Base Case with existing quantitative forecasts in order to judge the validity of the model results. Finally, we will use the model to reproduce the five qualitative Societal Development scenarios (described above) in order to explore how different societal choices may impact overall vulnerability to space weather events. Results are presented for the world as a whole and for the United States.[16] All results were produced using SWIM version 1.1.

The Base Case

The Economy

Under the SWIM Base Case, global GDP grows from $77 trillion in 2015 (in constant 2010 dollars) to 194 trillion by 2100, a 252% increase. In per capita terms, the increase is 'only' 170%, from $10,200 per capita in 2015 to $17,300 in 2100. While the global economy grows throughout the time horizon, growth is more rapid in the first half of the century compared to the second half, largely due to demographic changes—slowing population growth and population aging leading to a smaller workforce. Most of the growth in the latter half of the century is driven by increasing infrastructure stocks and a steady increase in innovation.

Demographics and Urbanization

The SWIM Base Case forecast of global population is based on the United Nations Population Division's World Population Prospects 2017 Revision, and thus closely matches its numbers. As with the UN forecast, the SWIM shows the global population growth rate slowing over the rest of the century and possibly even 'topping out' or declining by the 2080s. Despite the slowing growth rate, there remains significant momentum and so global population under the Base Case still grows from roughly 7.4 billion in 2015 to 11.2 billion in 2100, a 51% increase. Meeting the needs of today's 7.4 billion while ensuring resources will remain for tomorrow's roughly 4 billion is a daunting prospect and will likely require significant technological advances in energy and food production, and natural resources management.

The global population is, increasingly, an urban one. In 2015, about 54 percent of the world lived in urban areas. The SWIM Base Case's urbanization forecast is an extension of the forecast made by the UN World Urbanization Prospects 2014 Revision. Under the Base Case, nearly 83 percent of the world will be living in urban areas by 2100, highlighting again the technical and resource challenges ahead, but also the policy and governance hurdles of managing a significantly larger and more urban society.

The global population is also likely to be significantly older by 2100. Under current demographic trends, the dependency ratio—the ratio of persons aged 0–14 and 65+ to the number of

[16] The model has the capability to model any country or country grouping; the current process for doing so is to replace the datafiles used by the model with versions appropriate to the country/grouping. Later revisions should expand this capability and make it easier for users to switch countries.

'working-age' persons (15–64) is set to grow from 54 percent to 74 percent by 2100, even as the proportion of young people begins to decline. Population aging is often seen as a potential major 'headwind' for the global economy. The uncertainty here is whether continued advances in automation and medical technologies are able to keep productivity increasing as the workforce ages and even shrinks.

Governance

The quality of governing systems and institutions is an important driving factor for both economic growth and human wellbeing. The SWIM model combines two measures of governance quality drawn from the World Banks' Worldwide Governance Indicators database and exogenously forecast by the International Futures (IFs) global forecasting model: Governance Effectiveness and Governance Regulatory Quality.[17] Without any disruptive challenges, governance systems around the world see steady improvement over the century, though quality will continue to vary greatly from country to country. In the SWIM system, governance is another system impacted by the disruption of critical infrastructure, as we will see in the scenario analysis below.

Infrastructure and Technology

The SWIM system captures the advance of technology through an index of standard measures of innovation: scientific articles published, patents filed, and funding for research and development. Under the Base Case, the Innovation Index increases almost fourfold, from .23 in 2015 to .86 in 2100, suggesting that even in a case of linear growth (technology tends to be exponential), the amount of technological change over this century is likely to be quite high (and also likely to be highly disruptive and hard to quantify).

As world population grows and the push to urbanize continues, the demand for infrastructure services is set to grow markedly. Under the Base Case, infrastructure as a 'stock'—the combination of energy, ICT, electrical, transportation, water and space-based infrastructure stocks—increases by 200% between 2015 and 2100, with ICT and space-based infrastructure seeing the largest gains in terms of percent change over time. Interestingly, and perhaps realistically, energy and electrical infrastructure see the smallest percent increases as economic development and technological developments push greater efficiency in both sectors.

Benchmarking the Model

The SWIM's Base Case demographic and urbanization forecasts match with the UN Population Division's medium variant scenario, both SWIM and UNPD forecast a global population of 11.18 billion by 2100 and both forecast an urbanization level of 66% by 2050 (the end year of the World Urbanization Prospects forecast). The model's governance forecasts are drawn from existing forecasts from the International Futures model. In terms of the SWIM's economic forecast, the SWIM Base Case appears to be rather conservative, producing a global GDP roughly 65% of the

[17] An open-source modeling system produced by the Frederick S. Pardee Center for International Futures at the University of Denver https://pardee.du.edu/

OECD's 2060 Baseline long-term forecast from 2014,[18] and 60% that forecast by IFs in 2100. Use of the model's GDP multiplier scenario intervention handle, however, closes this gap significantly. The SWIM's economic module remains largely extrapolative and lacks the dynamic feedbacks and more detailed structure needed to produce more exponential style economic growth. Again, use of the GDP multiple provides an exponential type growth pattern. The infrastructure supply and demand models represent the most dynamic aspect of the model, involving multiple economic and demographic drivers. Here, the patterns for service demand and provision follow similar trendlines to other models, but the lack of saturation effects makes for larger infrastructure stocks by 2100—an assumption the SWIM makes is that while individual infrastructure technologies might saturate more quickly, demand for broader services might not. The addition of saturating behaviors to individual infrastructures is an area for future refinement.

Scenarios

The SWIM scenario results provide a quantitative look at how different potential paths of societal development could alter vulnerability to space weather events. The first scenario 'The Storm' looks at the impact of a severe space weather event on the SWIM Base Case forecast, while the other scenarios emulate the five identified through our scenario analysis.

The Storms

The Storms scenario is a test of the model's Base Case behavior under the impact of a severe space weather event. Three time periods are selected (2015, 2050, and 2100) in order to see how vulnerability varies over time. The test storm is an extreme geomagnetic storm (scale 5G), with varying duration (a few hours to days).

The 2015 Storm

- Short duration: peak economic disruption $1.8 trillion, loss of infrastructure services: 17% disruption to electrical, energy, ICT, ground transport, and space-based.
- Long duration: $4.8 trillion, loss of infrastructure services: 46% disruption to electrical, energy, ICT, ground transport, and space-based.

The 2050 Storm

- Short duration: peak economic disruption $2.6 trillion, loss of infrastructure services: 19% disruption to electrical, energy, ICT, ground transport, and space-based.
- Long duration: peak economic disruption $7.1 trillion, loss of infrastructure services: 50–52% disruption to electrical, energy, ICT, ground transport, and space-based.

The 2100 Storm

- Short duration: peak economic disruption $3.4 trillion, loss of infrastructure services, 21% disruption to electrical, energy, ICT, ground transport, and space-based.

[18] https://data.oecd.org/gdp/gdp-long-term-forecast.htm

- Long duration: peak economic disruption $9.2 trillion, loss of infrastructure services, 58% disruption to electrical, energy, ICT, ground transport, and space-based.

Conclusion: a clear pattern of increasing cost and disruption with time—more years of economic growth allowing for greater accumulation of infrastructure stock and a clear pattern of increased costs and disruption with longer duration storms, significantly more so. Both behaviors appear realistic based on the current literature and global costs seem reasonable based on current estimates.

The following scenarios all utilize a geomagnetic storm with a 2050 occurrence, long duration and G5 Severity.

Tearing Ahead

A greater emphasis on short term growth and a failure of politics and policies to enforce smart, sustainable growth leads to a more crowded and haphazard world.

Scenario interventions: increased rate of urbanization (+1), poor urban planning (-1), rapid economic growth (+1), reduced spending on infra maintenance, reliance on automation (+1)

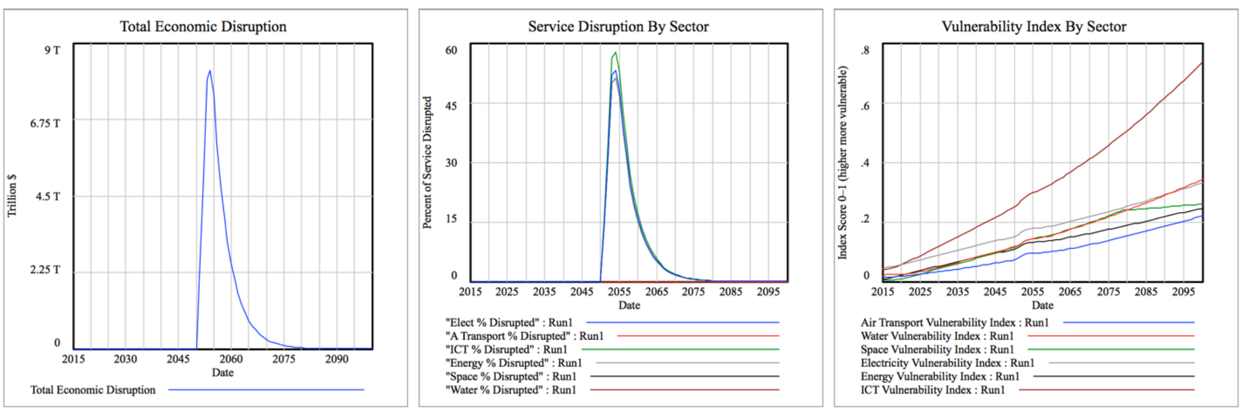

Figure 15: SWIM scenario results, Tearing Ahead
Source: SWIM Standalone App v1.1
Note: graph y-axis is currently auto-scaled

Damage and disruptions: peak economic disruption $8.2 trillion ($1.2 trillion above Base Case), loss of infrastructure services 52–58%

Economy: GDP $156 trillion

Resilient Redesign

Climate change and human demands collide, prompting a widespread search for innovative ways to house, feed, and support increasingly vulnerable communities and populations

Scenario interventions: improved space weather forecasting and warning systems (+1), hardened electronics (+1), distributed networks (+1), flexible nodes (+1), improved governance (+1), improved urban planning (+1), reduced economic growth (-.15), increased innovation (+.5)

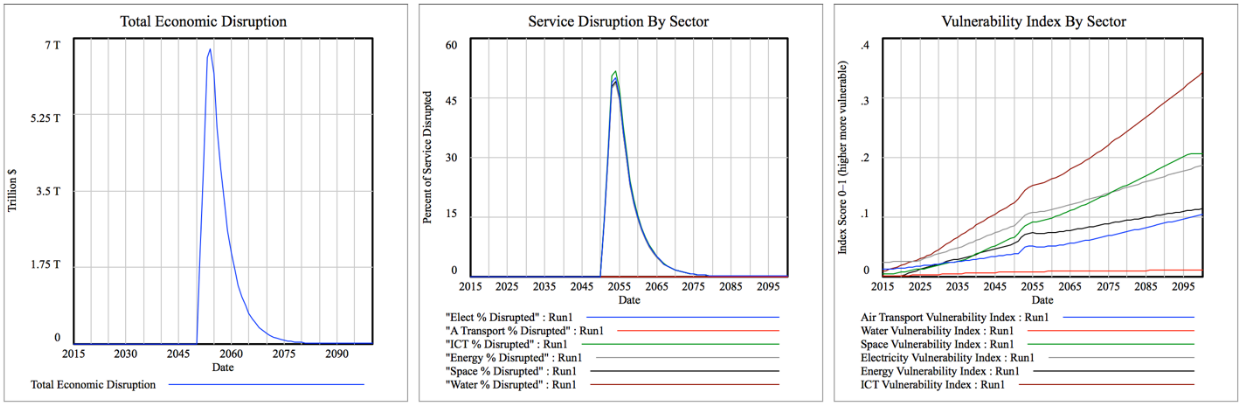

Figure 16: SWIM scenario results, Resilient Redesign
Source: SWIM Standalone App v1.1
Note: graph y-axis is currently auto-scaled

Damage and disruptions: peak economic disruption \$6.7 trillion (\$400 billion below Base Case), loss of infrastructure services 45–50%

Economy: GDP \$122 Trillion

Starry Future

A global competition over technological innovation and great power competition propel the widespread digitization and automation of society and launch a new international space race.

Scenario interventions: improved space weather forecasting and warning systems (+1), hardened electronics (+1), distributed networks (+1), flexible nodes (+1), improved governance (+1), Reliance on Automation (+.5), Space Economy (+1), increased economic growth (+.5)

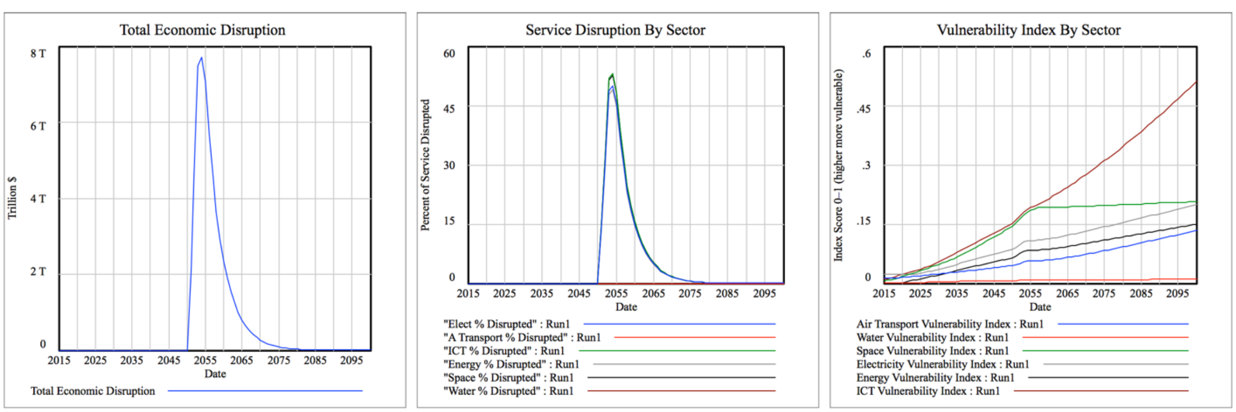

Figure 17: SWIM scenario results, Starry Future
Source: SWIM Standalone App v1.1
Note: graph y-axis is currently auto-scaled

Damage and disruptions: peak economic disruption $7.6 trillion ($500 billion above Base Case), loss of infrastructure services 50–52%

Economy: GDP $140 trillion

Separate Paths

The evolution of a more fragmented world order leads to less integrated global systems and more divergent developmental paths among nations.

Scenario interventions: reduced economic growth (-.5), reduced governance (-1), distributed networks (+1), reliance on automation (+1)

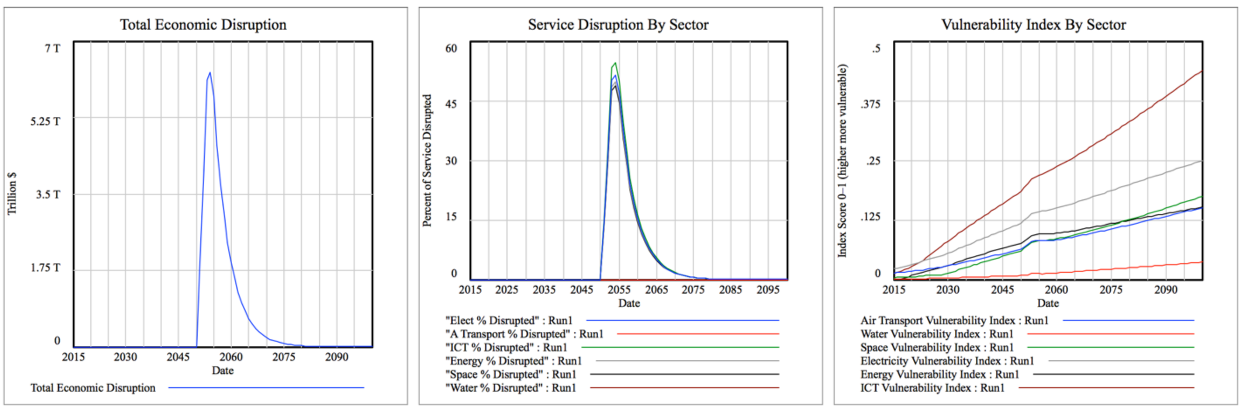

Figure 18: SWIM scenario results, Separate Paths
Source: SWIM Standalone App v1.1

Damage and disruptions: peak economic disruption $6.2 trillion ($900 billion below Base Case), loss of infrastructure services 54–58%

Economy: GDP $94 trillion

Halting Transformations

Spurred by the mounting pressures of climate change, population growth, and economic development, countries begin an uneven but determined push for more innovative and sustainable models of growth.

Scenario interventions: improved space weather forecasting and warning systems (+1), hardened electronics (+1), distributed networks (+1), flexible nodes (+1), improved governance (+1), decreased economic growth (-.2), improved urban planning (+1), decreased urbanization (-1), increased innovation (+1)

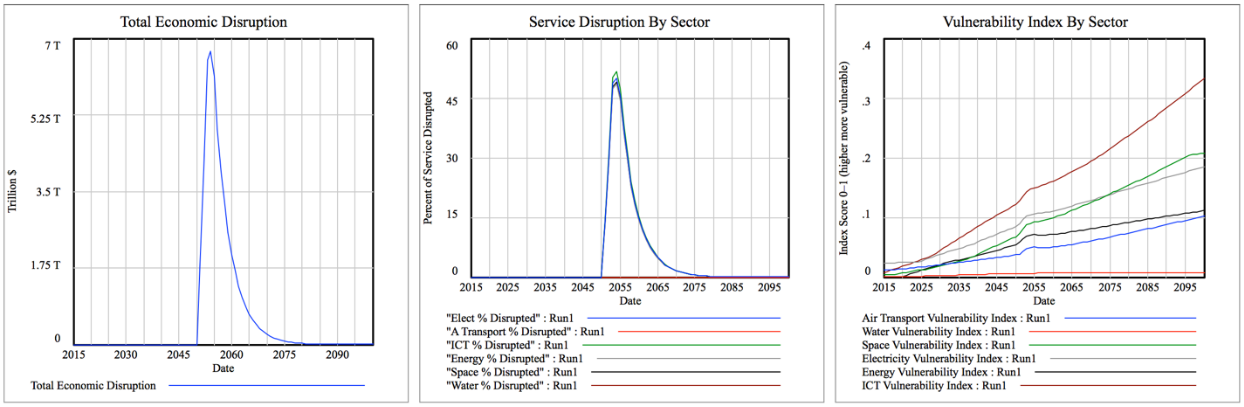

Figure 19: SWIM scenario results, Halting Transformations
Source: SWIM Standalone App v1.1

Damage and disruptions: peak economic disruption $6.5 trillion ($600 billion below Base Case), loss of infrastructure services 50–52%

Economy: GDP $109 trillion

The Worst Case

Storm Characteristics: occurrence at 2050, extreme geomagnetic, extreme radiation, extreme radio blackout, long duration

Scenario Interventions: increased rate of urbanization (+1), poor urban planning (-1), rapid economic growth (+1), reduced spending on infra maintenance, reliance on automation (+1)

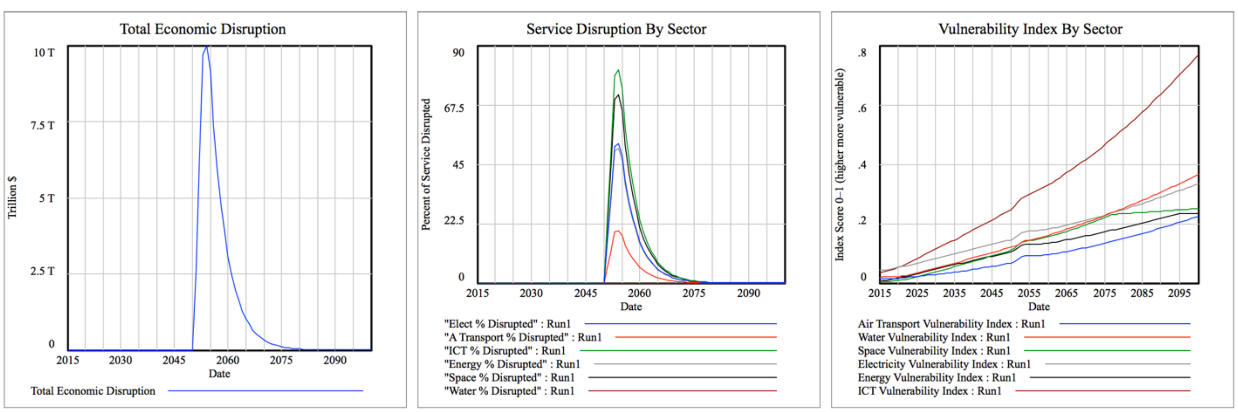

Figure 20: SWIM scenario results, Halting Transformations
Source: SWIM Standalone App v1.1

Damage and disruptions: peak economic disruption $9.8 trillion ($2.7 trillion above Base Case), loss of infrastructure services 85% ICT, 70% space-based, 50% electricity, 50% energy, 50% ground transport, 25% air transport

Economy: $151 trillion

Conclusions

This project set out to apply a rigorous foresight approach to the analysis of space weather and its impacts, a topic of increasing importance as society becomes more dependent on highly interconnected and highly digitized critical infrastructure systems. In order to do so, we 1) undertook an emerging issues analysis to identify some of the developing technologies and other emerging issues with the potential to shape society's vulnerabilities and responses to space weather events; 2) conducted a qualitative scenario analysis to establish a set of alternate future pathways of societal development; 3) constructed a quantitative model to begin to get at the potential costs and disruptions associated with space weather events.

We found severe space weather events pose a significant risk to modern society through the disruption of the critical infrastructure systems upon which we depend, particularly electricity, ICT, transportation, and space-based infrastructures. Severe space weather events not only have the potential to inflict economic damage on an unprecedented scale, with the SWIM system's forecasts joining existing estimates of storm-related costs running in the trillions of dollars, but also, in the case of long-term service disruptions, can undermine governance systems (including emergency response, security and health systems) at all levels of society. Depending on severity and the area directly affected, recovery could take months to years and require coordinated, international efforts. The 2017 hurricane season and its ongoing fallout in Puerto Rico and beyond is a primary example of what an extended recovery could look like.

Future Directions

The foresight, modeling, and analysis conducted over the course of this project represent a qualitative and quantitative foundation for enhancing our understanding of the economic and societal impacts of space weather events. Based on this foundation and on the experience gleaned from this endeavor, a number of potential next steps and future directions present themselves:

- Further enhancements to the Space Weather Impact Model
    - The SWIM system in its current iteration has a number of limitations that, while beyond scope of the present project, represent important means to improving its forecasting capabilities. These include:
        - A more detailed economic model that better represents a dynamic economy
        - More detailed storm dynamics, including a spatial component to allow for different geographical areas of affect
        - Adding additional critical infrastructure systems (governance, defense, finance, etc.)
        - Treatment of additional countries
        - Additional interface enhancements

- Using technology roadmapping to identify development pathways toward more resilient infrastructures
- Further uniting of the myriad literatures around the impacts of space weather events (critical Infrastructures, disaster impact modeling, the science of space weather, etc.)

Appendices

A1: Abbreviations

CMEs — Coronal Mass Ejections

GICs — Ground-induced currents

HF and **UHF** — High frequency and ultra-high frequency radio

ICT — Information Communication Technologies

ICS — Industrial Control Systems

SCADA — Supervisory Control and Data Acquisition

SD — System dynamics

WDI — World Development Indicators (from the World Bank)

A2: Data sources

Population Data — UN World Population Prospects 2017 Revision

Urbanization — UN World Urbanization Prospects 2014 Revision

Economic Data – World Bank World Development Indicators, Timmer et al. (2015) for World Input-Output Database

Infrastructure Data — World Bank World Development Indicators for measures of infrastructure supply, Rothman, Irfan, Malin et al. (2014) for new construction and maintenance unit costs

Governance Data — World Bank Worldwide Governance Indicators, International Futures system by the Frederick S. Pardee Center for International Futures

A3: Definitions

***Dst* Index**

Measures the amount of change in the Earth's magnetic field, particularly its equatorial region, in response to interaction with space weather (mostly coronal mass ejections). The Index value represents the globally averaged level of change (Baker et al. 2013).

Cascade Impacts

A series of nonlinear impacts stemming from an initial disruption that propagates through a system or systems via systemic interdependencies (Conrad et al. 2006); Cascade impacts have a tendency to start small and slow with initial impact, but then quickly snowball as impacts propagate (Eusgeld et al. 2011).

Complex Systems

Nonlinear systems with a large number of dimensions, strong interaction effects, hidden variables, and feedback loops which tend to produce emergent behaviors (Eusgeld et al. 2011).

Coronal Mass Ejections (CMEs)

Coronal mass ejections are large clouds of solar material (gas and plasma) with associated magnetic fields thrown out of the Sun. CMEs can cause powerful magnetic storms on Earth.

Critical Infrastructure

The "array of physical assets, processes, and organizations" which provide the goods and services upon which "the Nation's health, wealth, and security rely…" This includes physical infrastructure like the electrical grid and governance infrastructures like defense and emergency response (Pederson et al. 2006).

Extreme Space Weather

Usually refers to a solar storm on the magnitude of the "Carrington Event" or, more recently, the July 2012 Coronal Mass Ejection.

High-Speed Solar Wind Streams

Streams of solar wind plasma—stronger than normal—escaping from coronal 'holes.' They can last for hours to days and can cause geomagnetic and ionospheric storms

Infrastructure System

"A network of independent, mostly privately-owned manmade systems and processes that function collaboratively and synergistically to produce and distribute a continuous flow of essential goods and services."—PCCIP 1997

Radio Blackout

A 'natural jamming' effect caused by X-ray and UV emissions from solar flares that can last up to an hour (MacAlester and Murtagh 2014).

Risk

Risk is the product of an event's likelihood and the consequences of its occurrence

Resilience

The ability of a system to anticipate a shock, resist the shock (resistant capacity), to absorb damage caused by the shock (absorptive capacity), and to recover normal operations once a shock has passed (restorative capacity) (Canzani 2016; Ouyang 2014).

Robust Systems

Systems that can tolerate faults and whose overall performance changes little during a shock (Iuliani 2016).

Scintillation

The interference to radio and microwave signals passing through or reflecting from the Earth's ionosphere caused by naturally occurring ionized particles is known as scintillation. This effect can be greatly enhanced during space weather events that disturb the ionosphere. Increased scintillation can degrade or prevent signals to and from satellites and sky wave radio systems (MacAlester and Murtagh 2014).

Solar Cycle

The Sun goes through a regular cycle of increasing and decreasing sunspot activity (sunspots are magnetically active regions on the solar surface) that last about 11 years between solar minimums and solar maximums. In general, more sunspots is associated with more overall solar activity, but strong solar storms have been known to occur during periods of low sunspot activity.

Solar Wind

A constant flow of charged particles escaping from the sun, can cause minimal degradation to signals but is a constant feature

Solar Flares

A powerful solar outburst of visible, X-ray and radio wave emissions that can last from seconds to several hours, and which can sometimes also produce clouds of energetic particles. Flares can produce radio blackouts and interfere with communication and navigation systems.

Space Weather

"Space Weather includes any and all conditions and events on the Sun, in the solar wind, in near-Earth space, and in our upper atmosphere that can affect space-born and ground-based technological systems, and through these, human life and endeavor."–NASA

Vulnerability (general systems)

The degree to which a system is susceptible to and unable to cope with an adverse impact—IPCC 2007

Vulnerability (infrastructure)

"A flaw or weakness in the design, implementation, operation, and/or management of an infrastructure system, or its elements, that renders it susceptible to destruction or incapacitation when exposed to a hazard or threat" –Eusgeld et al. 2011.

A4: Environmental Scanning Database

--all URLS accessed on 5/4/18

Spike in energy demand driven by bitcoin and similar technologies

https://spectrum.ieee.org/energy/policy/the-ridiculous-amount-of-energy-it-takes-to-run-bitcoin

https://www.politico.com/magazine/story/2018/03/09/bitcoin-mining-energy-prices-smalltown-feature-217230?cid=apn

https://cointelegraph.com/news/china-to-use-blockchain-technology-in-tax-collection-and-electronic-invoice-issuance

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A5: Scenario Tables

Scenario A: Tearing Ahead

Extent of the Built Environment	Nature of Critical Systems	Short-Term Mitigation and Recovery	Long-Term Adaptive Capacities	Policy Priorities
Rapid, haphazard urban development	Lack of significant technical breakthroughs	Poorly prepared, few mitigation measures	Weak adaptive capacity	Economic growth
New terrestrial expansion	Decentralized and distributed systems	Somewhat prepared, moderate mitigation efforts	Strong but inconsistent capacity	Sustainable growth
Radical directions in human habitation	Machine revolution	Well prepared, high levels of mitigation	Informed but under resourced	Societal resilience
Space economy and spacefaring	Technological transformation	Divergent levels of preparedness and mitigation	Strong, systemic capacity	Geopolitical competition
Unwinding global integration	Shift to mega infrastructure projects			Strong inward (domestic) turn
	Deterioration and decreasing investment in maintenance			
	Privatized critical infrastructure			

Additional Elements Influencing the Scenario

Emerging Issues	
5G Communication Networks and the Advent of the Internet of Things	
Trends	**Miscellaneous**
Growing wealth inequality Increasing automation in the economy Urbanization	Global economic shocks and volatility

Scenario B: Resilient Redesign

Extent of the Built Environment	Nature of Critical Systems	Short-Term Mitigation and Recovery	Long-Term Adaptive Capacities	Policy Priorities
Rapid, haphazard urban development	Lack of significant technical breakthroughs	Poorly prepared, few mitigation measures	Weak adaptive capacity	Economic growth
New terrestrial expansion	Decentralized and distributed systems	Somewhat prepared, moderate mitigation efforts	Strong but inconsistent capacity	Sustainable growth
Radical directions in human habitation	Machine revolution	Well prepared, high levels of mitigation	Informed but under resourced	Societal resilience
Space economy and spacefaring	Technological transformation	Divergent levels of preparedness and mitigation	Strong, systemic capacity	Geopolitical competition
Unwinding global integration	Shift to mega infrastructure projects			Strong inward (domestic) turn
	Deterioration and decreasing investment in maintenance			
	Privatized critical infrastructure			

Additional Elements Influencing the Scenario

Emerging Issues
Drones and Aircraft Replacing Satellite Fleets
Technological Advances in Farming (NWO)
Climate Change-Driven Innovation (EI4CS 2017)

Trends
Increasing frequency of extreme weather events (terrestrial)
Growing financial costs of extreme weather
Growing number of migrants and refugees

Miscellaneous
Motivating effects of disasters/ESW events on policy

Scenario C: Starry Future

Extent of the Built Environment	Nature of Critical Systems	Short-Term Mitigation and Recovery	Long-Term Adaptive Capacities	Policy Priorities
Rapid, haphazard urban development	Lack of significant technical breakthroughs	Poorly prepared, few mitigation measures	Weak adaptive capacity	Economic growth
New terrestrial expansion	Decentralized and distributed systems	Somewhat prepared, moderate mitigation efforts	Strong but inconsistent capacity	Sustainable growth
Radical directions in human habitation	Machine revolution	Well prepared, high levels of mitigation	Informed but under resourced	Societal resilience
Space economy and spacefaring	Technological transformation	Divergent levels of preparedness and mitigation	Strong, systemic capacity	Geopolitical competition
Unwinding global integration	Shift to mega infrastructure projects			Strong inward (domestic) turn
	Deterioration and decreasing investment in maintenance			
	Privatized critical infrastructure			

Additional Elements Influencing the Scenario

Emerging Issues

Rising Volatility, Unpredictable Conflicts, and Impacts on Sensitive Infrastructure
Automation and AI Transforming the Corporate World
Next Generation of Satellites Providing Better Advance Warning of ESW

Trends	**Miscellaneous**
Growing commercial space industry Rapidly evolving digital fabrication technologies Advances in artificial intelligence Growing incidence and cost of cyber threats	

Scenario D: Separate Paths

Extent of the Built Environment	Nature of Critical Systems	Short-Term Mitigation and Recovery	Long-Term Adaptive Capacities	Policy Priorities
Rapid, haphazard urban development	Lack of significant technical breakthroughs	Poorly prepared, few mitigation measures	Weak adaptive capacity	Economic growth
New terrestrial expansion	Decentralized and distributed systems	Somewhat prepared, moderate mitigation efforts	Strong but inconsistent capacity	Sustainable growth
Radical directions in human habitation	Machine revolution	Well prepared, high levels of mitigation	Informed but under resourced	Societal resilience
Space economy and spacefaring	Technological transformation	Divergent levels of preparedness and mitigation	Strong, systemic capacity	Geopolitical competition
Unwinding global integration	Shift to mega infrastructure projects			Strong inward (domestic) turn
	Deterioration and decreasing investment in maintenance			
	Privatized critical infrastructure			

Additional Elements Influencing the Scenario

Emerging Issues

New Tracking Technologies to Complement/Compete with GPS Systems

Trends	**Miscellaneous**
Rising nationalism and protectionism Growing international competition for technological innovation	Competitive (arms race) dynamics

Scenario E: Halting Transformation

Extent of the Built Environment	Nature of Critical Systems	Short-Term Mitigation and Recovery	Long-Term Adaptive Capacities	Policy Priorities
Rapid, haphazard urban development	Lack of significant technical breakthroughs	Poorly prepared, few mitigation measures	Weak adaptive capacity	Economic growth
New terrestrial expansion	Decentralized and distributed systems	Somewhat prepared, moderate mitigation efforts	Strong but inconsistent capacity	Sustainable growth
Radical directions in human habitation	Machine revolution	Well prepared, high levels of mitigation	Informed but under resourced	Societal resilience
Space economy and spacefaring	Technological transformation	Divergent levels of preparedness and mitigation	Strong, systemic capacity	Geopolitical competition
Unwinding global integration	Shift to mega infrastructure projects			Strong inward (domestic) turn
	Deterioration and decreasing investment in maintenance			
	Privatized critical infrastructure			

Additional Elements Influencing the Scenario

Emerging Issues
Radiation-Proof Electronics
Quantum computing
Bio-based economy
“Circular economy”

Trends	**Miscellaneous**
Rising sea levels Shifting ecosystems Urbanization Growing number of migrants and refugees	Motivating effects of disaster events on policy Shaping role of keystone research reports

A6: Space Weather Severity Scales and Extended List of SW Events

Table 1A5: Extended List of SW Events

Date/Name	Type	Severity (strength of storm)	Impacts
September 1859/The "Carrington Event"	Solar flare and CME-caused geomagnetic storm, energetic solar particle storm	Super Storm, estimated *Dst* ~-850 to ~-1760nT	Caused telegraph systems across the US and Europe to fail
May 14th–15th, 1921	Geomagnetic storm	Extreme, estimated to be of comparable strength as Carrington event	Auroras seen near equator, caused fires at several telegraph stations in Sweden, disrupted US telegraph network
February, 1958	Geomagnetic storm		Disturbances in powerlines in Canada and Sweden and undersea Atlantic cables
May 1967	Solar flare and coronal mass ejection, radio blackouts, radiation storms, geomagnetic storms	Severe	Significant disruptions to communications, especially military communications and radar
August 4th, 1972			Widespread power and telephone outages in US and Canada
March 1989	Geomagnetic storm	Largest storm of the space age, *Dst of ~-589* (Oughton et al. 2017) *to* -640 nT	Failure of Quebec power grid, damage to transformers in England. 6 million people without power for 9 hours

March, 2002	Radio Blackout	Minor	Disrupted UFH military communications in Afghanistan, led to downing of a helicopter and 3 casualties
October/November 2003 "Halloween Storm"	Solar flare, coronal mass ejection	One of the largest solar flares on record, *Dst* of ~-353 (Oughton et al. 2017) to -472 nT	Astronauts took shelter on ISS, polar airline flights diverted, GPS performance degraded, HF radio disrupted, satellite loss, power outages in Europe and Africa
January 2005	Radio Blackout	Minor	Degraded HF radio communications of transpolar airline travel, resulted in rerouting of flights
July 2012	Coronal Mass Ejection	Super Storm *Dst* ~480 min nT to -1182 max	Missed Earth but could have produced severe impacts
Sources: Coker 2017; Eastwood 2017; Oughton et al. 2017; Schrijver 2015;			

A7: Supporting Documents and Files

All SWIM Project files are available for download here.[19]

SWIM Model Files—These files are all contained in a single .zip file: SWIM Model Installer v1.1.zip The .zip includes:

- SWIM Readme v1.1
- SWIM Global Model v1.1 folder (all files in the folder must be kept together)
  - SWIM Global Model full v1.1.vmf –the full model file editable by Vensim DSSDP and readable by Vensim Reader
  - SWIM Global Model v1.1 Standalone App
- SWIM US Model v1.1 folder (all files in the folder must be kept together)
  - SWIM US Model full v1.1.vmf –the full model file editable by Vensim DSSDP and readable by Vensim Reader
  - SWIM US Model v1.1 Standalone App

SWIM Model Database.xlsx—all historical data and existing forecasts used to initialize the model

SWIM Emerging Issues Database v1.pdf—the full list of 'scanning hits' used in the project's emerging issues and scenario analyses

[19] https://www.dropbox.com/sh/g93vggy6g9meini/AAC7qpbtUuq0NaShxJKbVG2ga?dl=0

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