4.22 Solar Events

4.22.1 Hazard Profile

There are many different types of space weather that can result in what is referred to as a "solar event". These naturally occurring hazards are relatively new to the sphere of hazard mitigation planning, and include concerns raised by geomagnetic storms, coronal mass ejections, solar radiation storms, and solar flares (radio blackouts) that are relevant to local hazard mitigation planning teams.

Solar wind is the constant stream of plasma and charged particles from the sun that escape out into space. A ***geomagnetic storm*** is a major disturbance of Earth's magnetosphere (the magnetic field surrounding the planet) that occurs when there is a very efficient exchange of energy from the solar wind into the space environment surrounding Earth. Geomagnetic storms result from variations in the solar wind that produces major changes in the currents, plasmas, and fields in Earth's magnetosphere. The solar wind conditions that are effective for creating geomagnetic storms are sustained (for several to many hours) periods of high-speed solar wind, and most importantly, a southward directed solar wind magnetic field (opposite the direction of Earth's field) at the dayside of the magnetosphere. This condition is effective for transferring energy from the solar wind into Earth's magnetosphere.[113]

The largest storms that result from these conditions are associated with ***Coronal Mass Ejections*** **(CMEs)**. These events are large expulsions of plasma and magnetic field from the Sun's corona. They can eject billions of tons of coronal material and carry an embedded magnetic field (frozen in flux) that is stronger than the background solar wind interplanetary magnetic field (IMF) strength. CMEs travel outward from the Sun at speeds ranging from slower than 250 kilometers per second (km/s) to as fast as near 3000 km/s. The fastest Earth-directed CMEs can reach our planet in as little as 15-18 hours. Slower CMEs can take several days to arrive. They expand in size as they propagate away from the Sun and larger CMEs can reach a size comprising nearly a quarter of the space between Earth and the Sun by the time it reaches our planet.[114]

Imminent CME arrival is first observed by the Deep Space Climate Observatory (DSCOVR) satellite, located at the L1 orbital area. Sudden increases in density, total interplanetary magnetic field (IMF) strength, and solar wind speed at the DSCOVR spacecraft indicate arrival of the CME-associated interplanetary shock ahead of the magnetic cloud. This can often provide 15 to 60 minutes advanced warning of shock arrival at Earth – and any possible sudden impulse or sudden storm commencement; as registered by Earth-based magnetometers.[2]

During storms, the currents in the ionosphere, as well as the energetic particles that precipitate into the ionosphere add energy in the form of heat that can increase the density and distribution of density in the upper atmosphere, causing extra drag on satellites in low-earth orbit. The local heating also creates strong horizontal variations in the ionospheric density that can modify the path of radio signals and create errors in the positioning information provided by GPS. While the storms create beautiful aurora, they also can

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[113] Geomagnetic Storms: https://www.swpc.noaa.gov/phenomena/geomagnetic-storms

[114] Coronal Mass Ejections: https://www.swpc.noaa.gov/phenomena/coronal-mass-ejections

disrupt navigation systems such as the Global Navigation Satellite System (GNSS) and create harmful geomagnetic induced currents (GICs) in the power grid and pipelines.[1]

Solar flares are large eruptions of electromagnetic radiation from the Sun lasting from minutes to hours. The sudden outburst of electromagnetic energy travels at the speed of light, therefore any effect upon the sunlit side of Earth's exposed outer atmosphere occurs at the same time the event is observed. The increased level of X-ray and extreme ultraviolet (EUV) radiation results in ionization in the lower layers of the ionosphere on the sunlit side of Earth. Under normal conditions, high frequency (HF) radio waves are able to support communication over long distances by refraction via the upper layers of the ionosphere. When a strong enough solar flare occurs, ionization is produced in the lower, more dense layers of the ionosphere, which causes HF radio signals to become degraded or completely absorbed. This results in a radio blackout – the absence of HF communication, primarily impacting the 3 to 30 MHz band. Solar flares usually take place in active regions, which are areas on the Sun marked by the presence of strong magnetic fields; typically associated with sunspot groups. As these magnetic fields evolve, they can reach a point of instability and release energy in a variety of forms. These include electromagnetic radiation, which are observed as solar flares.[115]

Solar Radiation Storms occur when a large-scale magnetic eruption, often causing a coronal mass ejection and associated solar flare, accelerates charged particles in the solar atmosphere to very high velocities. The most important particles are protons which can get accelerated to large fractions of the speed of light. At these velocities, the protons can traverse the 150 million km from the sun to the Earth in just 10's of minutes or less. When they reach Earth, the fast moving protons penetrate the magnetosphere that shields Earth from lower energy charged particles. Once inside the magnetosphere, the particles are guided down the magnetic field lines and penetrate into the atmosphere near the North and South Pole. A Solar Radiation Storm can persist for time periods ranging from hours to days.[116]

Solar Radiation Storms cause several impacts near Earth. When energetic protons collide with satellites or humans in space, they can penetrate deep into the object that they collide with and cause damage to electronic circuits or biological DNA. During the more extreme Solar Radiation Storms, passengers and crew in high flying aircraft at high latitudes may be exposed to radiation risk. Also, when the energetic protons collide with the atmosphere, they ionize the atoms and molecules thus creating free electrons. These electrons create a layer near the bottom of the ionosphere that can absorb High Frequency (HF) radio waves making radio communication difficult or impossible.[4]

4.22.1.1 Geographic Location/Extent

Geomagnetic disturbances in the atmosphere occur all the time, but infrequently are they strong enough to be classified as a storm, and even more infrequently strong enough to cause problems. Geomagnetic storms and their resulting auroras are more common near the poles due to increased magnetism, but space weather events can occur locally all over the globe. Satellites can also easily be affected by the various forms of space weather, and while not local to the United States or the CVPDC, damaging effects on one or several of these would be widespread.

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[115] Solar Flares: https://www.swpc.noaa.gov/phenomena/solar-flares-radio-blackouts

[116] Solar Radiation Storm: https://www.swpc.noaa.gov/phenomena/solar-radiation-storm

4.22.1.2 Magnitude/ Severity

4.22.1.2.1 Planetary K-index

Currently, regional-level space weather warnings and alerts are provided by the Space Weather Prediction Center (SWPC) at the National Oceanic and Atmospheric Administration. The Planetary K-index (Kp), are used to characterize the magnitude of geomagnetic storms. Kp is an excellent indicator of disturbances in the Earth's magnetic field and is used by SWPC to decide whether geomagnetic alerts and warnings need to be issued for users who are affected by these disturbances. It quantifies disturbances in the horizontal component of earth's magnetic field with an integer in the range 0-9 with 1 being calm and 5 or more indicating a geomagnetic storm. It is derived from the maximum fluctuations of horizontal components observed on a magnetometer during a three-hour interval.[117] The planetary 3-hour-range index Kp is the mean standardized K-index from 13 geomagnetic observatories between 44 degrees and 60 degrees northern or southern geomagnetic latitude. The label 'K' comes from the German word 'Kennziffer' meaning 'characteristic digit'. The K-index was introduced by Julius Bartels in 1938. SWPC has used the K-index since the forecast center began operations. An estimated current Kp index chart can be found on the SWPC's website, and a recent example can be seen below (Figure 4-184).[118]

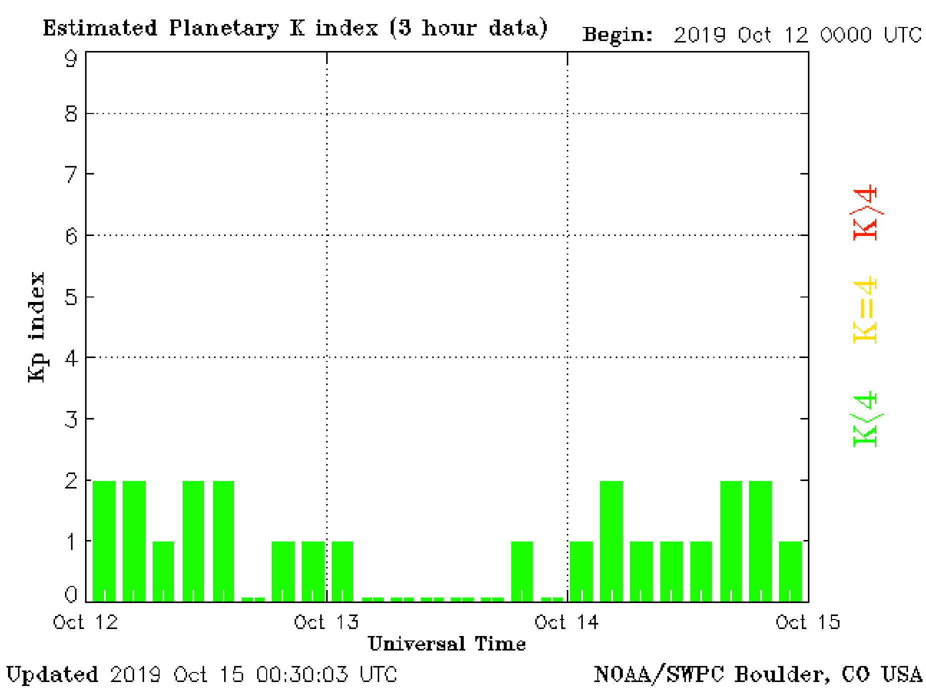

Figure 4-184 Estimated 3-hour Planetary Kp-index (Kp) on Oct 12, 2019

4.22.1.2.2 NOAA G-scale

The Kp scale is a reasonable way to summarize the global level of geomagnetic activity, but it has not always been easy for those affected by the space environment to understand its significance. The NOAA

[117] https://www.swpc.noaa.gov/sites/default/files/images/u2/TheK-index.pdf
[118] https://www.swpc.noaa.gov/products/planetary-k-index

G-scale was designed to correspond, in a straightforward way, to the significance of effects of geomagnetic storms (Table 4-172). The relationship between the NOAA G-scale and Kp is also shown in Table 4-172.

Storm watches are issued when the highest predicted NOAA estimated Kp-indices for a day are K = 5, 6, 7, or >= 8 and are reported in terms of the NOAA G scale. K-index Warnings are issued when NOAA estimated Kp-indices of 4, 5, 6, and 7 or greater are expected. K-index Alerts are issued when the NOAA estimated Kp-indices reach 4, 5, 6, 7, 8, or 9.

Solar Radiation Storms are categorized using the NOAA Space Weather Scale on a scale from S1 - S5. The scale is based on measurements of energetic protons taken by the Geostationary Operational Environmental Satellite system GOES satellite in geosynchronous orbit (Table 4-173).

SWPC currently forecasts the probability of S1 (Minor Radiation Storm) occurrence as part of our 3-day forecast and forecast discussion products and issues a warning for an expected S1 or higher event; as well as a warning for when the 100 MeV (megaelectronvolt) proton level is expected to reach 1 pfu (proton flux unit). Additionally, SWPC issues alerts for when each NOAA Space Weather Scale Radiation Storm level is reached (S1-S5) and/or when the 100 MeV protons reach 1 pfu.[4]

Solar flare intensities cover a large range and are classified in terms of peak emission in the 0.1 – 0.8 nm spectral band (soft x-rays) of the NOAA/GOES XRS. The X-ray flux levels start with the "A" level (nominally starting at 10^{-8} W/m^2). The next level, ten times higher, is the "B" level (≥ 10^{-7} W/m^2); followed by "C" flares (10^{-6} W/m^2), "M" flares (10^{-5} W/m^2), and finally "X" flares (10^{-4} W/m^2).

Radio blackouts are classified using a five-level NOAA Space Weather Scale, directly related to the flare's max peak in soft X-rays reached or expected (Table 4-174). NOAA's Space Weather Prediction Center (SWPC) currently forecasts the probability of C, M, and X-class flares and relates it to the probability of an R1-R2, and R3 or greater events as part of our 3-day forecast and forecast discussion products. SWPC also issues an alert when an M5 (R2) flare occurs.[3]

Table 4-172 NOAA Space Weather Scale for Geomagnetic Storms

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
G 5	Extreme	Power systems: Widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. Spacecraft operations: May experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. Other systems: Pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).	Kp = 9	4 per cycle (4 days per cycle)
G 4	Severe	Power systems: Possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. Spacecraft operations: May experience surface charging and tracking problems, corrections may be needed for orientation problems. Other systems: Induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).	Kp = 8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	Power systems: Voltage corrections may be required, false alarms triggered on some protection devices. Spacecraft operations: Surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. Other systems: Intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).	Kp = 7	200 per cycle (130 days per cycle)

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
G 2	Moderate	Power systems: High-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. Spacecraft operations: Corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. Other systems: HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).	Kp = 6	600 per cycle (360 days per cycle)
G 1	Minor	Power systems: Weak power grid fluctuations can occur. Spacecraft operations: Minor impact on satellite operations possible. Other systems: Migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).	Kp = 5	1700 per cycle (900 days per cycle)

(Kp of 0 to 4 is below storm, which we label as G0. Source: NOAA's Space Weather Prediction Center) [119]

Table 4-173 NOAA Space Weather Scale for Solar Radiation Storms

Scale	Description	Effect	Physical measure (Flux level of >= 10 MeV particles)	Average Frequency (1 cycle = 11 years)
S 5	Extreme	Biological: Unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. Satellite operations: Satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate	10^5	Fewer than 1 per cycle

[119] https://www.swpc.noaa.gov/noaa-scales-explanation

Scale	Description	Effect	Physical measure (Flux level of >= 10 MeV particles)	Average Frequency (1 cycle = 11 years)
		sources; permanent damage to solar panels possible. Other systems: Complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.		
S 4	Severe	Biological: Unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. Satellite operations: May experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. Other systems: Blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S 3	Strong	Biological: Radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. Satellite operations: Single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. Other systems: Degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	Moderate	Biological: Passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk. Satellite operations: Infrequent single-event upsets possible. Other systems: Small effects on HF propagation through the polar regions and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S 1	Minor	Biological: None. Satellite operations: None. Other systems: Minor impacts on HF radio in the polar regions.	10	50 per cycle

Table 4-174 NOAA Space Weather Scale for Radio Blackouts

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
R 5	Extreme	HF Radio: Complete HF (high frequency) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and in route aviators in this sector. Navigation: Low-frequency navigation signals used by maritime and general aviation systems experience outages on the sunlit side of the Earth for many hours, causing loss in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.	X20 (2×10^{-3})	Less than 1 per cycle
R 4	Severe	HF Radio: HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time. Navigation: Outages of low-frequency navigation signals cause increased error in positioning for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth.	X10 (10^{-3})	8 per cycle (8 days per cycle)
R 3	Strong	HF Radio: Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth. Navigation: Low-frequency navigation signals degraded for about an hour.	X1 (10^{-4})	175 per cycle (140 days per cycle)
R 2	Moderate	HF Radio: Limited blackout of HF radio communication on sunlit side, loss of radio contact for tens of minutes. Navigation: Degradation of low-frequency navigation signals for tens of minutes.	M5 (5×10^{-5})	350 per cycle (300 days per cycle)
R 1	Minor	HF Radio: Weak or minor degradation of HF radio communication on sunlit side, occasional loss of radio contact. Navigation: Low-frequency navigation signals degraded for brief intervals.	M1 (10^{-5})	2000 per cycle (950 days per cycle)

4.22.1.3 Previous Occurrences

The largest measured CME event hit earth in 1859 causing massive magnetic fluctuations in the Earth's magnetosphere and sent electrified gas and subatomic particles toward the earth with the energy of 10 billion atomic bombs. Known as the Carrington Event, named after the scientist who first saw the solar flare, telegraph communication around the world failed as wires shorted out and caught fire. Colorful auroras also illuminated skies all over the world and were seen as far south as Cuba and Hawaii. [120, 121]

In 1921, another strong geomagnetic storm (caused by a CME) produced the lowest-latitude (13.83°S) observation of an aurora in Apia, Samoa. This event also caused significant disruption of telegraph services in the United States and as well as reportedly more severe fires.[122] Extensive interconnectivity of electrical systems and general electrical dependencies across infrastructures were low at the time, so the effects were restricted to certain sectors. One example occurred following an aurora caused fire at the 57th street control tower of the New York Central Railroad, which knocked out the entire signal and switching system below 125th street.[123]

More recently, in 1989, the greatest damage caused by CME was observed on the Earth. A solar storm event wiped out electrical power to the entire province of Quebec, Canada, and affected 6 million people. Astronomers witnessed this powerful explosion on the sun which sent a billion-ton cloud of gas toward the earth at a million miles an hour. Almost immediately, the resulting solar flare caused short-wave radio interference. Two days later the geomagnetic storm reached earth and again caused widely seen aurora in southern areas. The magnetic disturbance also created electrical currents in the ground beneath much of North America, which in less than two minutes, caused the entire Quebec power grid to lose power. Across the United States, this event resulted in over 200 power grid problems, but luckily at the time (2:44 am), the U.S. had power to spare. [124, 125]

In December 2005, X-rays from a solar flare disrupted satellite-to-ground communication and the GPS system for about 10 minutes and as a result threatened satellite-guided air, sea, and land travel. In April 2017, a moderate G2 (Kp=6) event occurred and caused a simultaneous power grid failure in San Francisco, New York, and Los Angeles. [126]

4.22.1.4 Relationship to other hazards

Figure 4-185 shows the interrelationship (causation, concurrence, etc.) between this hazard and other hazards discussed in this plan update.

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[120] 150 Years Ago: The Worst Solar Storm Ever: https://www.space.com/7224-150-years-worst-solar-storm.html

[121] A Perfect Solar Superstorm: The 1859 Carrington Event: https://www.history.com/news/a-perfect-solar-superstorm-the-1859-carrington-event

[122] The 1859 space weather event revisited: limits of extreme activity: https://www.swsc-journal.org/articles/swsc/pdf/2013/01/swsc130015.pdf

[123] New York Railroad Storm: http://www.solarstorms.org/SS1921.html

[124] The Day the Sun Brought Darkness: https://www.nasa.gov/topics/earth/features/sun_darkness.html

[125] Here's What Would Happen if a Solar Storm Wiped Out Technology as We Know It: https://www.sciencealert.com/here-s-what-would-happen-if-solar-storm-wiped-out-technology-geomagnetic-carrington-event-coronal-mass-ejection

[126] Yesterday's Broad Power Outage Likely Caused By Geomagnetic Storm: https://www.zerohedge.com/news/2017-04-22/yesterdays-broad-power-outage-likely-caused-geomagnetic-storm

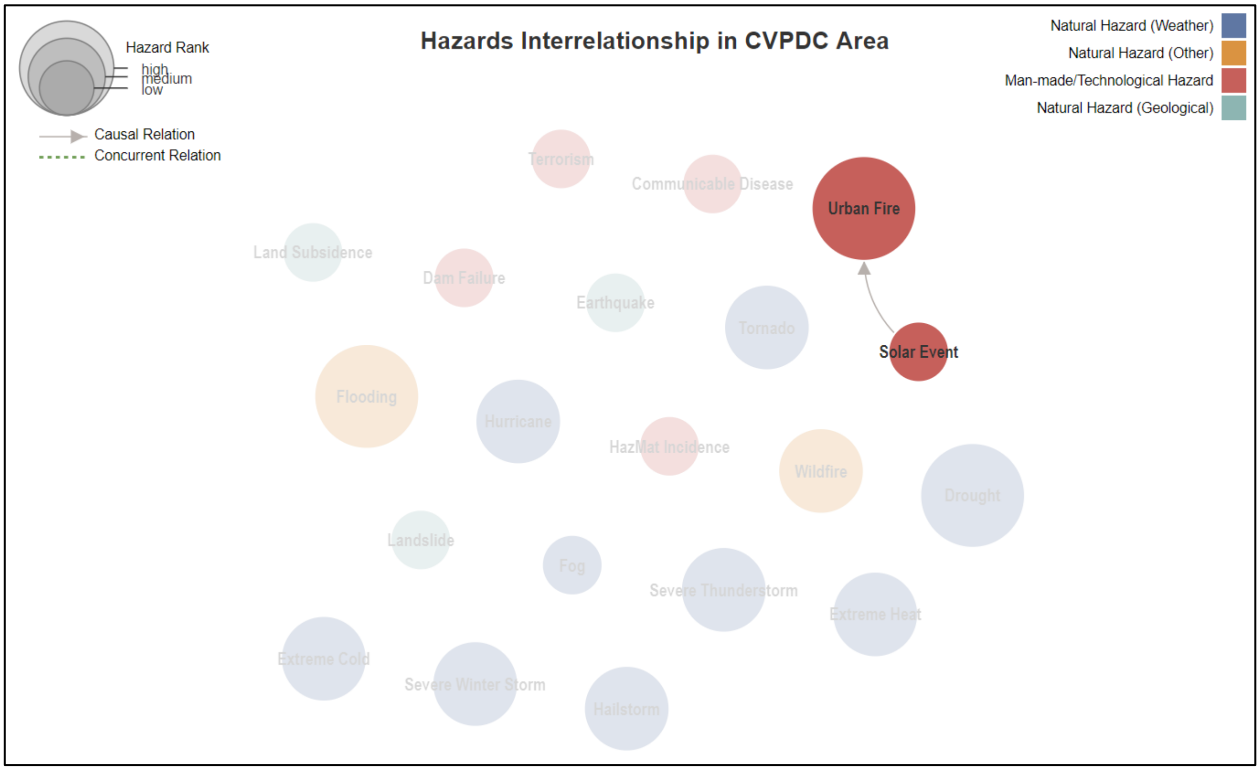

Figure 4-185 Hazards interrelationship

4.22.2 Impact and Vulnerability

Modern electric and communication systems are much different now than in 1859. Everything from electricity, water, and heat to 911 calls, cell networks, banking, and the internet, is even more deeply interconnected. Estimates suggest a modern Carrington Event could cost humanity between $1 and $20 trillion dollars and could take up to a decade for the worldwide recovery effort. The focus on space related catastrophes used to be on asteroids, however now, due to modern technology and greater interconnectedness, other scenarios must be considered.

4.22.2.1 Electric grid

The geo-magnetically induced currents (GICs) created from solar storms can cause widespread electric grid outages in two ways: First, they can cause permanent damage of critical grid components, such as high-voltage power transformers. This is of particular concern as high voltage transformers are not easily replaceable. Second, the GICs can cause voltage instability in the grid and cause the system voltage to collapse, resulting in a widespread but temporary outage. [127]

[127] DHS Science and Technology Directorate: Solar Storm Mitigation: https://www.dhs.gov/sites/default/files/publications/Solar%20Storm%20Mitigation-508_0.pdf

4.22.2.2 Navigation system

The use of Global Navigation Satellite Systems (GNSS), including the Global Positioning System (GPS), has grown dramatically in the last decade. GPS receivers are now in nearly every cell phone and in many automobiles, trucks, and any equipment that moves and needs precision location measurements.

Space weather events can impact GPS functioning in a variety of ways. GPS radio signals travel from the satellite to the receiver on the ground, passing through the Earth's ionosphere. In the absence of space weather, GPS systems compensate for the "average" or "quiet" ionosphere, using a model to calculate its effect on the accuracy of the positioning information. But when the ionosphere is disturbed by a space weather event, the models are no longer accurate, and the receivers are unable to calculate an accurate position based on the satellites overhead. [128]

4.22.2.3 Oil, Gas, and Other Pipeline

Solar storms can affect pipe-to-soil voltages, leading to currents that disturb flow meter signals, which can result in false pipeline flow rate data. The induced currents can also increase pipeline corrosion rates. Insulating flanges, meant to interrupt current flow, creates an additional point where electric potential can result in current flow to ground, increasing the risk for corrosion.

4.22.2.4 Control system

Solar storm interference may impact rail supervisory control and data acquisition (SCADA) system dispatch operations and communication networks that employ wireless technologies, especially those dependent on GPS timing signals.

4.22.2.5 Solar event impact to Smart City

Smart City is a concept of utilizing technologies and connected data sensors to enhance a city's infrastructure and operations. This includes monitoring and managing of public assets, transportation systems, citizens, power plants, water supplies, information systems, civil bodies, and other community services. All of these technological systems are becoming more interconnected, and all require a constant supply of electric power. This fact makes them incredibly vulnerable to a single CME event and should therefore be importantly considered as the desire for "smarter" cities rapidly increases.[129]

4.22.3 Risk Assessment

In January 2008, the American National Academy of Sciences (NAS) prepared a report entitled: "Severe Space Weather Events - Understanding Societal and Economic Impacts: A Workshop Report" (2008). The paper contained a calculation of the economic effect of an estimated CME event in 2012. They used historical data on the major CME event in 1921 to run their hypothetical scenario. If a similar impact hit the Earth, the total economic cost would be:

- Future severe geomagnetic storm scenario: $1 trillion to $2 trillion in the first year,
- Depending on damage, full recovery could take 4 to 10 years.

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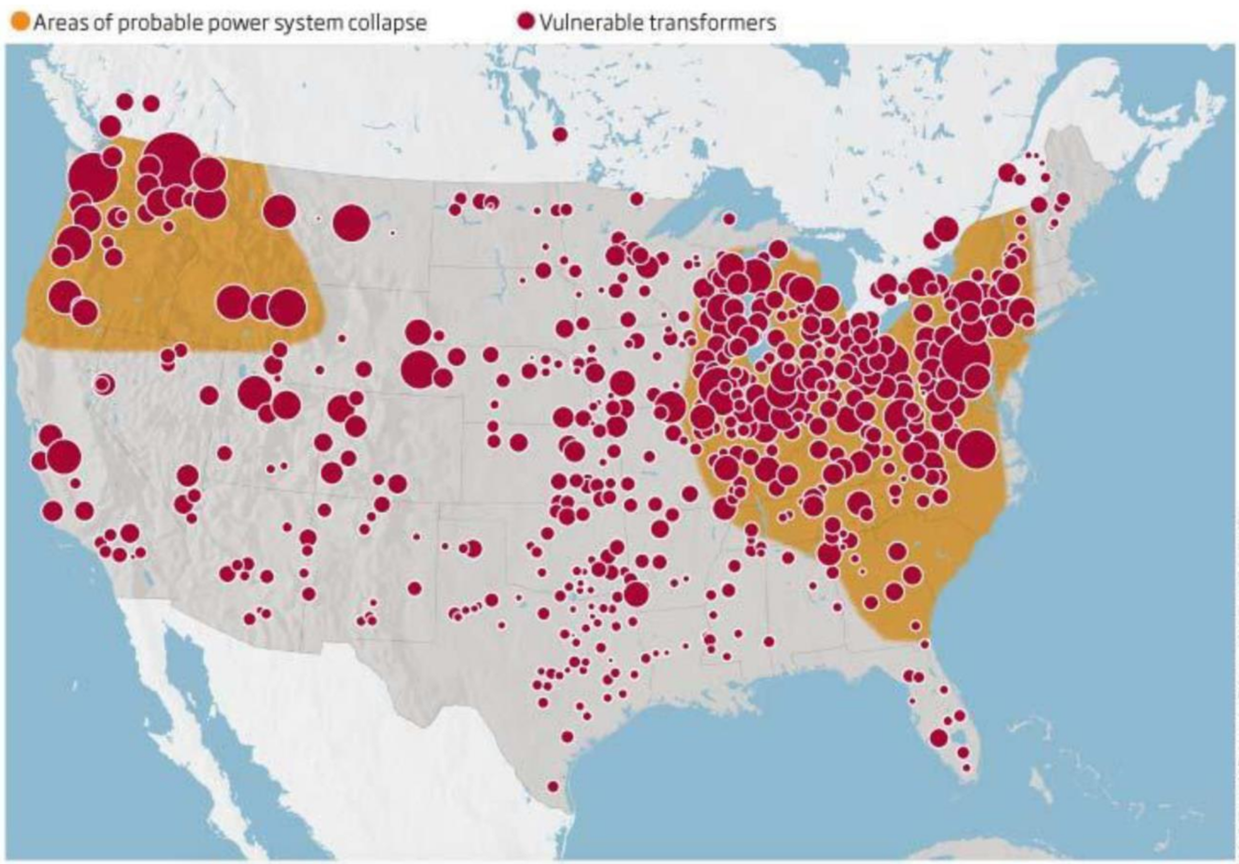
[128] Space Weather and GPS Systems: https://www.swpc.noaa.gov/impacts/space-weather-and-gps-systems

[129] Protection of the Smart City against CME: https://www.sciencedirect.com/science/article/pii/S2352146516306433

In the report, the expected result was shown for the American electrical network system. In NAS' opinion, a severe space weather event in the US could induce ground currents that would knock out 300 key transformers within about 90 seconds, cutting off the power for more than 130 million people (Figure 4-186). The CVPDC is within the areas of probable power system collapse.



(Blackout Warning. A severe geomagnetic storm would damage transformers in the grid, leading to blackouts across wide areas of the U.S.)

Figure 4-186 Expected blackout regions after simulated CME with an impact level of 1921 (Brooks M. 2009)

4.22.4 Probability of Future Occurrences

While the occurrence of the next major CME event remains impossible to predict, especially for an area as small as the CVPDC, it remains important to mention because the effects can be so widespread. The forecasting of solar storms remains largely unpredictable, but the storms do originate from dark sunspots (areas of increased magnetic activity) which can be seen. Astronomers track sunspot activity on the sun using "solar cycles". The current cycle (Solar Cycle 24) is forecasted to end between 2019 and 2020 which indicates a low point in solar sunspot activity. The peak of the next cycle is predicted to occur between 2023 and 2026. An active or weak cycle however, only refers to the total number of storms, not how powerful they are, and therefore the threat of another major CME event is always there.[130]

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[130] Solar Cycle 25 Preliminary Forecast. https://www.swpc.noaa.gov/news/solar-cycle-25-preliminary-forecast

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