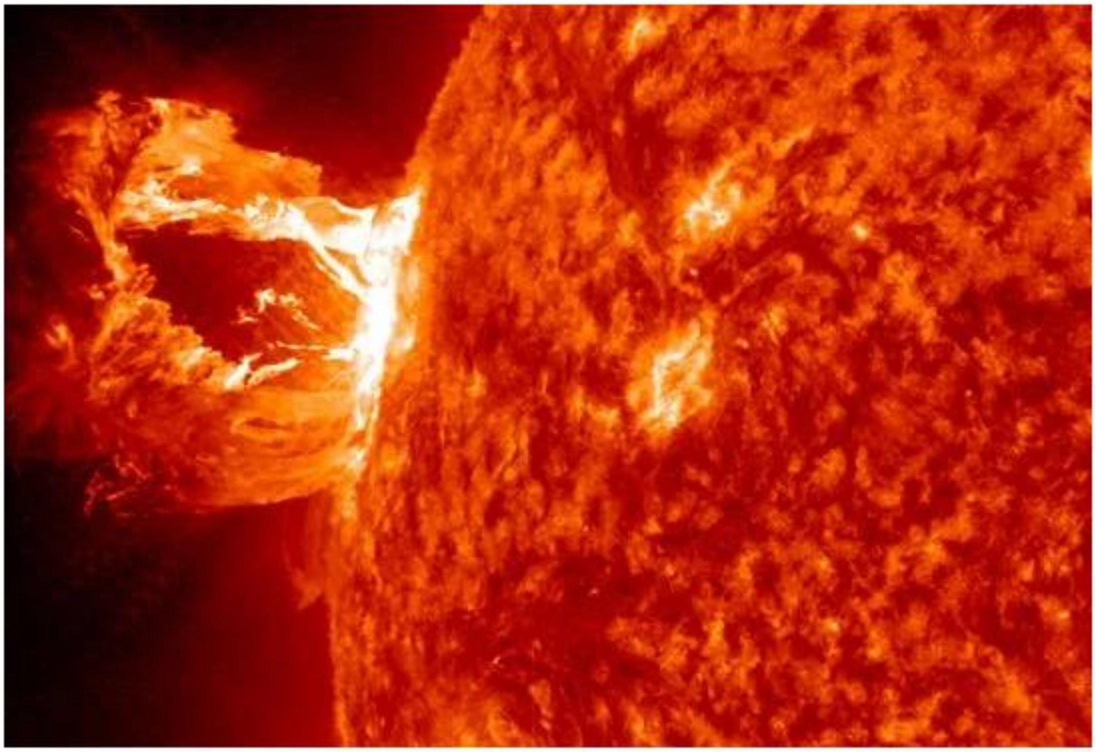

The sun, after reaching the peak period of its 11-year cycle, has unleashed a number of dazzling solar flares in the space of a few days

Safety Management of Geospatial Threats of Space Weather Intrusion

Ronald H. Freeman, PhD
Editor-in-Chief, Journal of Space Operations & Communicator

Abstract. The disquieting effects of solar storms on Earth and to spacecraft it orbits include disruptions to telecommunications from on-orbit satellites to ground stations, power grid "blackouts", and initiating triggers in earthquakes. The need to protect Earth from the most intense forms of space weather - great bursts of electromagnetic energy and particles streaming from the Sun- require costly replacement hardware spares for infrastructural recovery. However, greater the need is for more accurate and timely forecasts to prepare for impending space weather events. Characterization of space weather and their sources informs the technologies and operational strategies for risk management of geospatial threats. This paper investigates the nature of space weather, how it impacts Earth, and the safety management required for risk mitigation of its effects.

1. Introduction

Space weather refers to "conditions on the Sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of spaceborne and ground-based technological systems and can endanger human life or health" [1]. Similar to terrestrial weather, space weather should be something that exists in the space environment even without any influence on technological equipment. In general, comparisons between terrestrial weather and space weather and recognizing their analogies are useful but the essential differences have also to be kept in mind.

Energetic particle populations having a solar or galactic origin and penetrating into the Earth's space environment cause risks to spacecraft equipment and radiation hazards to astronauts on manned missions. Anomalies in the operation of satellites and even permanent damage can occur at low Earth orbits (LEO), at the radiation belts which are regularly crossed by navigation system as well as scientific satellites, and at the geostationary distances (GEO) at which a huge number of different Earth observing, telecommunication and military satellites lie. A different type of a space weather effect on LEO satellites is caused by an increased atmospheric drag. The enhanced X-ray, UV and particle radiations imply that the upper atmosphere is heated and expanded during space weather events. The drag may result in a complete loss of the spacecraft unless proper corrective measures are performed.

Telecommunication between satellites and the ground applies high enough radio frequencies (RF) that permit the signal pass through the ionosphere, while ground-to-ground communication can make use of reflection from the ionosphere. Thus, as ionospheric properties vary during space weather events, RF communication is also affected. Consequently, the signal can be distorted, fade or disappear totally, and the signal can propagate along unusual paths and to unexpected distances. Satellite navigation systems having a large number of different applications that rely on ionospheric plasma vary in a wide range of temporal and spatial scales, which makes the determination of the influence on RF signals difficult [2].

Terrestrial Weather	Space Weather
Neutral gas physics	plasma physics
“Playground”: atmosphere	“playground”: interplanetary space, magnetosphere, ionosphere, and atmosphere
Efficient satellite monitoring	few satellites
Extensive global ground network	set of local ground networks with different instruments
Regional-scale modeling	global modeling
Public and professional customers	professional customers
Economic impacts clear	direct and indirect economic impacts under discussion

Table. Comparison Between Terrestrial Weather and Space Weather [*Pirjola et al.*, 2003]

In an increasingly technological world, space weather is a serious matter where almost everyone relies on cell phones and on GPS controls, not just with in-car map system, but also per airplane navigation, and operations dependent on the extremely accurate clocks that govern financial transactions. Historically, the 1859 Carrington Event was a geomagnetic storm triggered by an eruption of charged particles that streamed toward Earth. It was in the early days of telegraphs that particles from the sun were powerful enough to send a charge through telegraph lines that shocked operators and lit telegraph paper on fire [3]. “What Carrington saw was a white-light solar flare—a magnetic explosion on the sun," explained David Hathaway, solar physics team lead at NASA's Marshall Space Flight Center in Huntsville, Alabama. In 1989, when telegraphers disconnected the batteries powering the lines, aurora-induced electric currents in the wires still allowed messages to be transmitted [4].

Plasma (i.e. one of the four fundamental states of matter) a gas of ions and free electrons and an accompanying magnet field, are released in the form of a corona mass ejections (CMEs). They originate from active regions on the Sun's surface, such as groupings of sunspots associated with frequent flares [5]. Satellite data helps scientists predict these solar eruptions, but there are still plenty of questions about how the sun works for which answers would improve forecasts of space weather. Earth’s magnetic field protects Earth against the sun’s firehose of energy, but sometimes the sun overpowers the planet’s defenses. When that happens, solar radiation heats the upper atmosphere and charges it with electricity, which is what causes auroras at the northern and southern poles. CMEs arrive a day later and subsequently changes Earth’s magnetic field. National power grids start to fail when currents in the ground are produced along with the giant current created in the ionosphere. In the worst-case scenario, CMEs damage equipment, requiring replacements in order to restore power back to the grid [6].

There is a legitimate need to protect Earth from the most intense forms of space weather - great bursts of electromagnetic energy and particles sometimes stream from the sun. Solar activity currently ramps up toward what is known as solar maximum, something that occurs approximately every 11 years. Such solar cycles have occurred over millennia. The explosive heat of a solar flare may not make it all the way to Earth surface, but electromagnetic radiation and energetic particles certainly do. Solar flares temporarily alter the upper atmosphere disrupting signal transmission from a GPS satellite to cause dislocalization off by many yards. Solar flares cause disruptions of radar, cell phone communications, and GPS receivers.

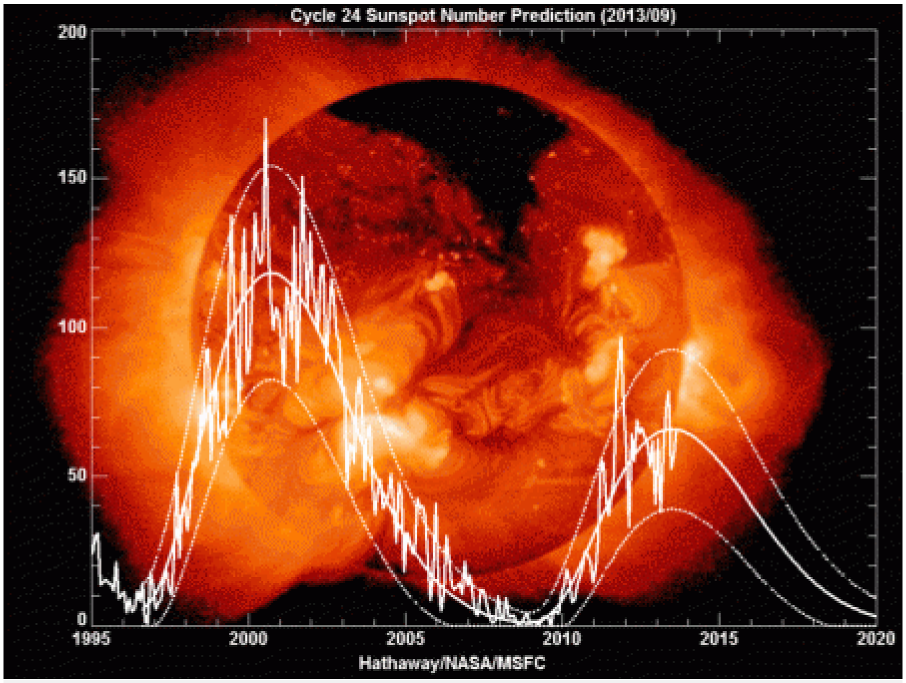
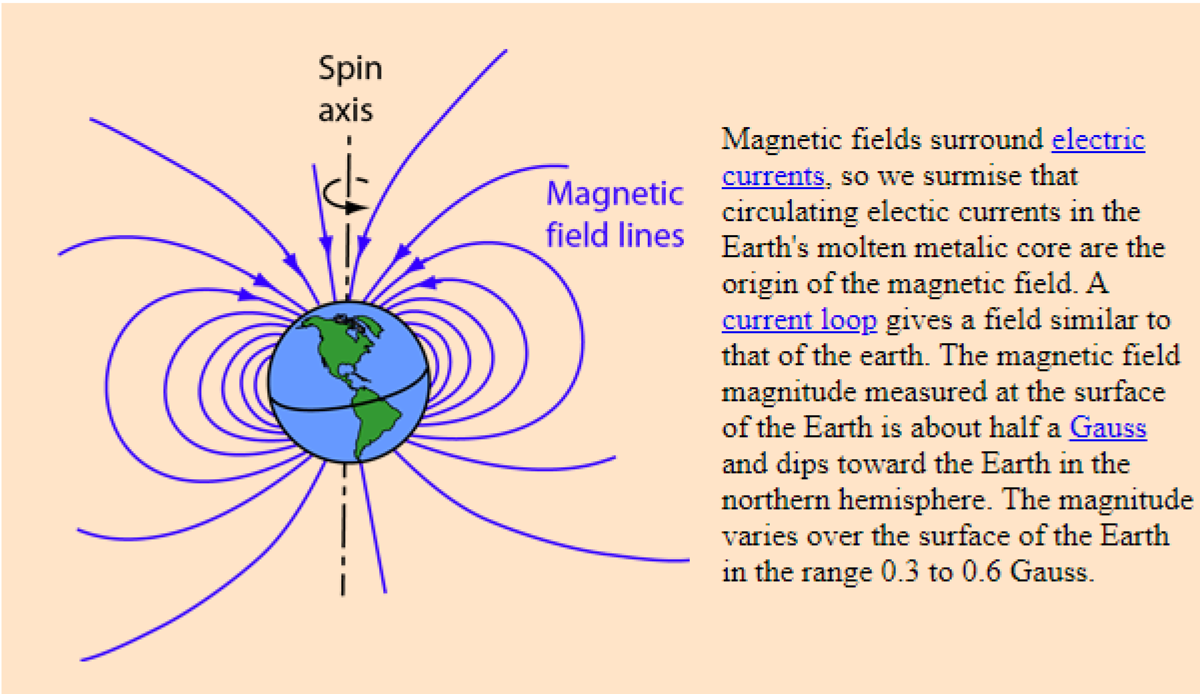


Diagram showing the sunspot number prediction for Sunspot Cycle 24. The peak appears around the summer of 2013.

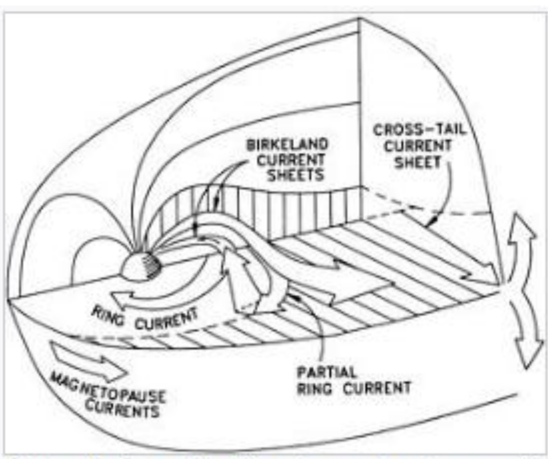
Solar flares are sudden releases of energy, witnessed over the surface of the sun, with magnitudes that can scale up to a sixth of the total energy output from the star, each second. They are often followed by enormous coronal mass ejections. These solar flares often occur around sunspots, where magnetic fields penetrate the light-emitting photosphere, linking the corona to the solar interior. The solar flares are rapidly generated following the release of magnetic energy stored within the corona. Indeed, according to the Space Weather Prediction Center (SWPC), a number of the solar storms that preceded the X1.7 solar flare resulted from a new sunspot cluster, called Region 1882 [7].

On 2014March 29, a sunspot called AR2017 erupted in a massive solar flare. This was not a new occurrence, as there had been three prior very large solar flares reported, one of which disrupted both communications and the Global Positioning System function [8]. Even more disruptive, CMEs from solar explosions propel bursts of particles and electromagnetic fluctuations into Earth's atmosphere, colliding with crucial electronics onboard satellites to interrupt system functions [9]. With additional CME observations a better idea of their shapes and trajectories would suggest the value of having cameras on board spacecraft in future space weather monitoring missions [10].

The magnetic field of the Earth acts as a magnetic bottle for some types of particles in the Earth's environment. Particles can be trapped so that they bounce back and forth between the north and south magnetic poles along field lines. They travel by spiraling around these field lines at a frequency called the 'gyro frequency'. The particles approach the polar regions where the field strength is high, and as their cyclotron frequency increases, they spiral along tighter and smaller orbits around a particular field line. After they are reflected at these polar 'mirror points' they fan out along the field lines towards the equatorial plane as their cyclotron frequency decreases and their orbit radius increases.



These flows of particles form the equatorial 'Ring Current'. Ground stations detect the build-up of the ring current because the current produces its own magnetic field which modifies the Earth's equatorial magnetic field particularly its horizontal surface component. The strength of the Ring Current field is measured by hourly averages of the so-called 'Disturbance Storm-Time (Dst) index which is given in units of nano-Teslas or nT. The Earth's normal field at the surface has a total strength of about 50,000 nT, and the Ring Current field can produce easily-measured Dst's near 200 nT for strong magnetic storms [11].



Schematic view of the different current systems which shape the Earth's magnetosphere.

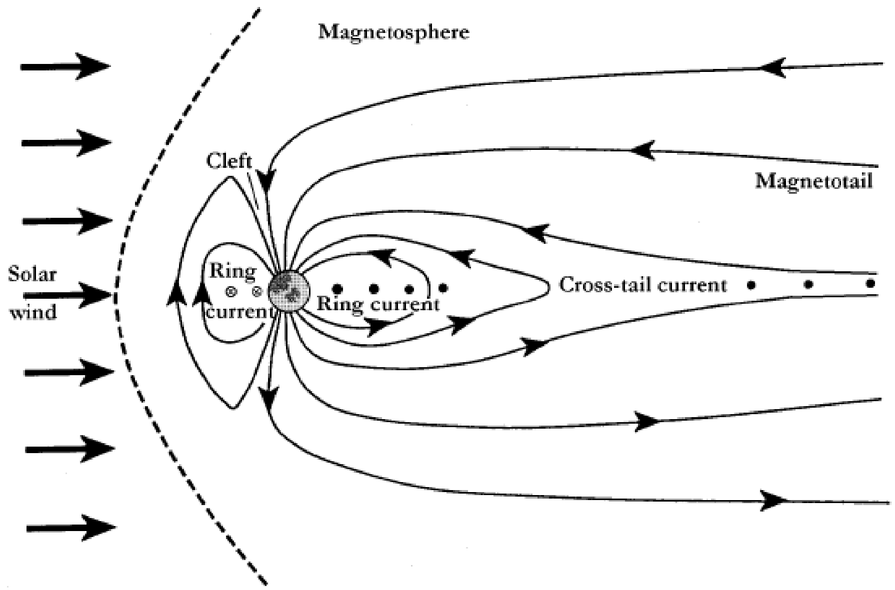
Earth's ring current is responsible for shielding the lower latitudes of the Earth from magnetospheric electric fields. It therefore has a large effect on the electrodynamics of geomagnetic storms. The negative deflection of the Earth's magnetic field due to the ring current is measured by the Dst index. The ring current energy is mainly carried around by the ions, most of which are protons. However, one also sees alpha particles in the ring current, a type of ion that is plentiful in the solar wind. In addition, a certain percentage are O^+ oxygen ions, similar to those in the ionosphere of Earth, though much more energetic. This ion mixture suggests that ring current particles probably come from more than one source. During a geomagnetic storm, the number of particles in the ring current will increase. As a result, there is a decrease in the effects of geomagnetic field [12].

Space storms are the prime complex processes of space weather. They interconnect, in a uniquely global manner, the Sun, the interplanetary space, the terrestrial magnetosphere and atmosphere, and occasionally the surface of the Earth. Energy from the Sun drives a continuous interaction of these distinct but coupled regions. The essential element of space storms in the near-Earth space environment is the ring current, which is an electric current flowing toroidally around the Earth, centered at the equatorial plane and at altitudes of ~10,000 to 60,000 km. The trinity of ring current "life" includes its sources, its buildup processes, and its decay mechanisms. The ring current is formed by the injection into the inner magnetosphere of ions originating in the solar wind and the terrestrial ionosphere. The injection process involves electric fields, associated with enhanced magnetospheric convection and/or magnetospheric sub-storms. The main carriers of the storm-time ring current are positive ions, with energies from ~1 keV to a few hundred keV; they are trapped by the geomagnetic field and undergo an azimuthal drift around the Earth. The usually dominant ion species is H+, while the abundance of O+ ions – originating in the terrestrial ionosphere, increases with storm intensity. During the main phase of great storms, O+ ions dominate the ring current. Intensity enhancements of the ring current decrease the horizontal component of the magnetic field in the vicinity of the Earth. Ground magnetograms recording this decrease are used for the construction of the *Dst* index, which is the main measure of space storm intensity and therefore attracts special attention. A large part of ongoing disputes on storm dynamics actually relates to characteristics of *Dst* variations rather than ring current dynamics. Space-atmosphere coupling during storms is an important part of space weather: space disturbances are communicated to the atmosphere, and the atmosphere can in turn drastically influence storm dynamics through the massive outflow of oxygen ions [12].

2. Geospatial Threats of Space Weather Intrusion

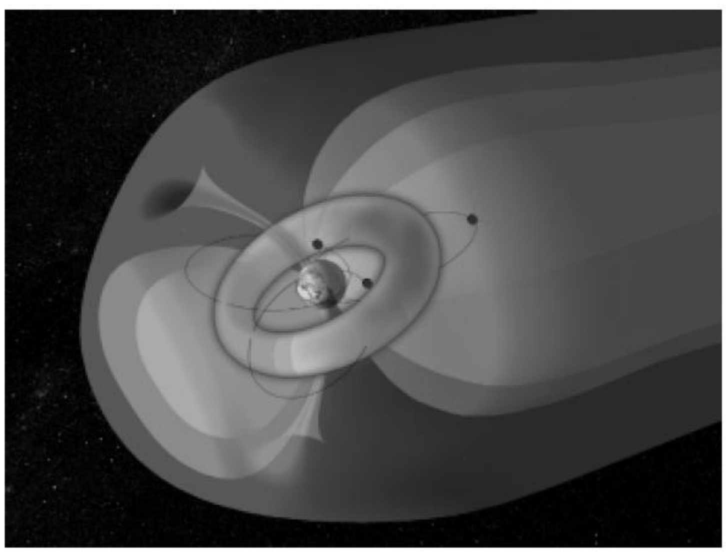
Space storms, the key phenomenon of space weather, have a number of effects in near-Earth space environment: Acceleration of charged particles in space, intensification of electric currents in space and on the ground, impressive aurora displays, and global magnetic disturbances on the Earth surface – all define storm features and origins of the denomination "magnetic storms". A network of observatories were established in the late 19th century by the British Empire (Canada, Africa and Australia) showing that magnetic storms were essentially identical in morphology all over the world: a steep decrease of the horizontal component of the geomagnetic field over many hours, followed by a gradual recovery which lasted several days. The change in the magnetic field was small, about 50-300 nT out of a total intensity of 30,000- 60,000 nT, but its world-wide appearance suggested that a large-scale disturbance in space was the physical reason: a huge "ring current" in space circling the Earth emerged as a good candidate. Chapman and Ferraro (1930, 1931) proposed a transient stream of outflowing solar ions and electrons responsible for terrestrial magnetic storms. O nce the solar stream had reached the Earth, charged particles would leak into the magnetosphere and drift around the Earth, creating a current whose field would oppose the main geomagnetic field [12]. However, the fact that radiation belt particles contribute little to the ground effects of space storms was recognized rather early (Akasofu et al., 1961) – actually before any direct observations of the ring current itself. After four decades of space exploration, quite a few things are known about weather in space. Space storms are often preceded by a well-defined mark, which is the arrival of an interplanetary shock. The interplanetary condition for a storm to develop is a prolonged, southward-directed IMF (interplanetary magnetic field) and that the solar antecedents of intense storms are coronal mass ejections rather than solar flares (Gosling, 1993; Bothmer and Schwenn, 1995; Gonzalez and Tsurutani, 1997). The main effect of space storms on the terrestrial magnetosphere is the injection of energetic ions and electrons from the near-Earth magnetotail into the inner magnetosphere, causing the westward-flowing ring current to grow significantly.

The "traditional" graphical representation of a space storm, or more correctly of its effects on the Earth, is the time profile of the *Dst* index. The westward-flowing ring current decreases the horizontal component of the geomagnetic field. Low-latitude ground magnetometers that record this decrease, provide the data for the construction of the *Dst* index, which is a geomagnetic index commonly used as a measure of magnetic storm intensity. The disturbance storm time (Dst, Kyoto Dst) index is a measure in the context of space weather. It gives information about the strength of the ring current around Earth caused by solar protons and electrons.



A schematic picture of the terrestrial magnetosphere (Daglis et al., 1999).

The ring current around Earth produces a magnetic field that is directly opposite Earth's magnetic field, i.e. if the difference between solar electrons and protons gets higher, then Earth's magnetic field becomes weaker. A negative Dst value means that Earth's magnetic field is weakened. This is particularly the case during solar storms. Solar storms consist of three major components: solar flares, solar proton events (SPEs) and coronal mass ejections (CMEs). CMEs can interact with Earth's magnetic field to produce a geomagnetic storm. Not all solar storms produce all three elements but the largest solar storms tend to.



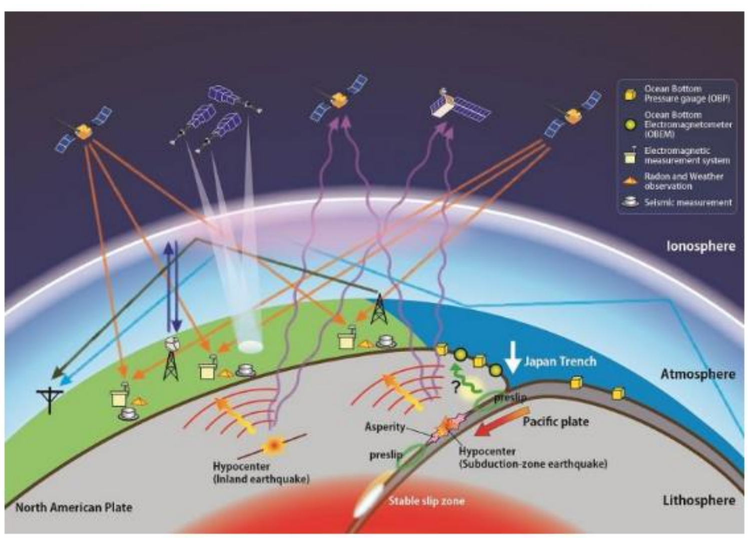
Ideally symmetric ring current visualised as a toroid encircling the earth (courtesy of H. Koskinen, Finnish Meteorological Institute).

The general morphology of a storm-*Dst* shows a relatively sharp and large decrease of *Dst* indicating the "main phase" of the storm, and the subsequent slow increase of *Dst* marks the storm recovery. Some storms, especially the largest ones, begin with a sudden impulse (positive excursion of *Dst*), marking the arrival of an interplanetary shock. The *Dst* index is widely used to monitor and predict magnetic storm activity and therefore attracts special attention.

The prevailing perception is that there are other magnetospheric currents (crosstail current, substorm current wedge, magnetopause current, Birkeland field-aligned currents), which also fluctuate during space storms and influence the ground magnetic field and, consequently, the *Dst* index.

CME-induced Earthquakes

Sun-Earth connections are complex and involve solar wind, ionosphere and ground. Ritz [13] and Serrano et al [14] have investigated the relationship between the solar activity and earthquakes. The appearance of many magnetic storms in years of maximum solar activity implicates the cause for an increased number of earthquakes. Magnetic storms would result in anomalies of geomagnetic field and in eddy current in the faults, producing earthquakes with near west east strike. Initiation of an earthquake occurs easily since the eddy currents heat the rocks in the faults and therefore decrease the shear resistance and the static friction limit of the rock [15]. During the minima of sunspots, earthquake events are detected more often around specific geological features such as slip strike faults or subduction zone. In 2004 a multinational consortium led by the French government launched a new earthquake detection satellite called DEMETER (Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions) [16].



Conceptual diagram of an integrated satellite and terrestrial framework for multiparameter observations of pre-earthquake signals in Japan. The ground component includes seismic, electro-magnetic observations, radon, weather, VLF–VHF radio frequencies, and ocean-bottom electro-magnetic sensors. Satellite component includes GPS/total electron content, synthetic-aperture radar, Swarm, microwave, and thermal infrared satellites. Credit: Katsumi Hattori, presented in Ouzounov et al, 2018, Chapter 20

DEMETER's purpose was to study disturbances in the ionosphere related to natural geophysical events such as earthquakes, volcanic eruptions or tsunamis. Infrared radiation detected by satellites indicated a warning sign of earthquakes to come. Sensors in NASA's Terra Earth Observing System satellite registered what NASA called a "thermal anomaly" on 21 January 2001 in Gujarat, India, just five days before a 7.7-magnitude quake occurred; the anomaly was gone a few days after the quake. Earthquake forecasters can also watch for changes in the ionosphere by monitoring very- low-frequency (3 to 30 kilohertz) and high-frequency (3 - 30 megahertz) radio transmissions. Analysis of Ionosphere perturbations related seismic activity using the VLF radio signals monitored on the days of arrival of high-speed solar wind with the DEMETER satellite. It showed well-pronounced maximum in the number of earthquakes seen on the day of arrival of high-speed solar wind and one day after it [17].

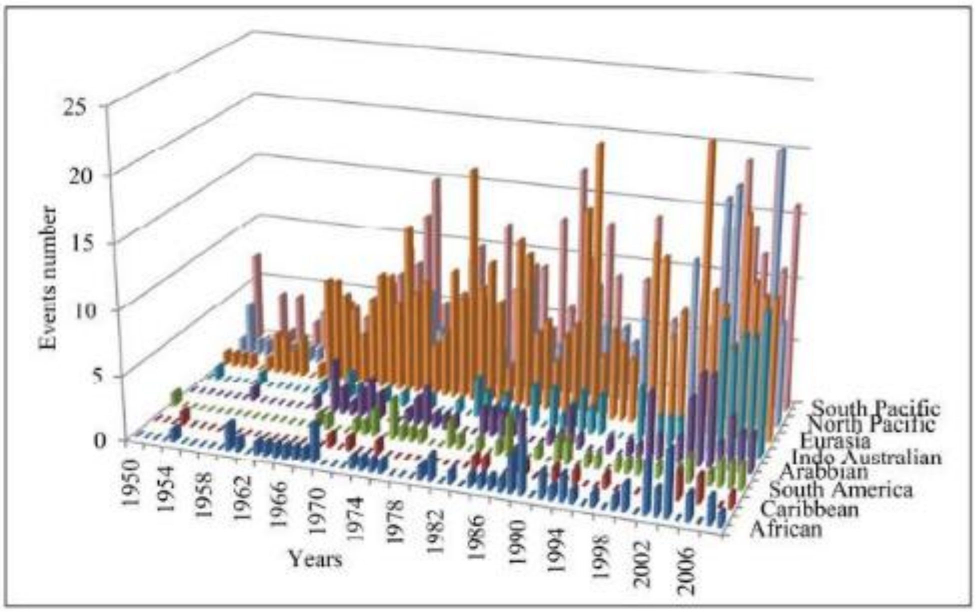


Figure. The last part of the 20th century (1950-2009): earthquakes events in Hemi-spheres, South and North

During each of the 5 solar maxima (1958, 1968, 1979, 1991, 2000) there was a clear maximum of earthquake events for some tectonic plates. During the last solar maximum (2000), earth-quake activity increased on the Arabian, Eurasia and North Pacific plates. Other plates (Caribbean, Africa and South America) had fewer events. After 2005, in most plates, earthquake events decreased, even with better data acquisition. This coincided with decreased solar activity.

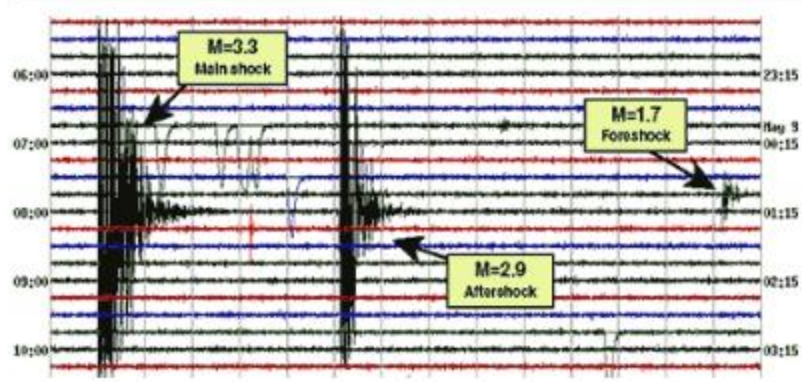
The increase of earthquakes depended on the place they occurred/ It depends on most of heterogeneity in the crust and also the geological variables such as if the tectonic plate is transform, convergent, divergent. The depth of an earthquake is an important parameter and it seems to influence the correlation between plates and events. The highest correlation (Sun-Earth) is observed for shallow earthquake events. In the period (1900-2010) there has been generally higher solar activity with many sunspots and CME's.

The main sources of high-speed solar wind are solar coronal holes and coronal mass ejections (CME's). Satellite and ground-based instruments regularly monitor them both and able to forecast periods of enhanced seismic risk. To be geo-effective, the solar wind from a coronal hole or from a CME has to first arrive at the Earth. The geo-effectiveness of solar wind from a coronal hole or from a CME depends on its position relative to the Earth. For CMEs, an additional factor is their size and speed. Faster and wider CMEs are more geo-effective [18]. Solar wind speed which causes more dynamic pressure on Earth's magnetosphere is the physical mechanism which increases the number of earthquakes. Variations in solar wind during a CME event can exert pressure, deforming and shrinking the magnetosphere by 4Re (Earth radius). The pressure will affect the Earth surface in different ways depending of the tectonic of each region; some areas are more susceptible to release energy in a form of earthquake or other analogous phenomena (such as volcanoes). Earthquakes and volcanism occur primarily in those zones where one plate is rubbing against the "fault lines". Earth directed CMEs were very frequent during 2000- 2002.

There was a continuous impact of huge amount of energy, changing the Kp indices (planetary indices) and free electrons in the upper part of the atmosphere. These changes in Sun-Earth environment induced by the Sun have changed the geosphere and atmosphere from time to time. A similar explanation for earthquakes happening during the minima relies in the Solar Wind decreasing speed. If the solar speed is lower, the magnetosphere relaxes and expands again; earthquakes would follow a different trajectory this time. Earthquakes happen more in geological feature such as strike slip fault or trenches (subduction zones). Finally, earthquakes do not follow cycles as solar cycles because it happens in a sequence determined by the plate and the geological feature of each of them. It is difficult to find out a direct connection Solar Maxima and ground since earthquakes perhaps happen in clusters or related to each other. It makes events less cyclic and interconnected depending of the Earth structure of each region under surveillance [19].

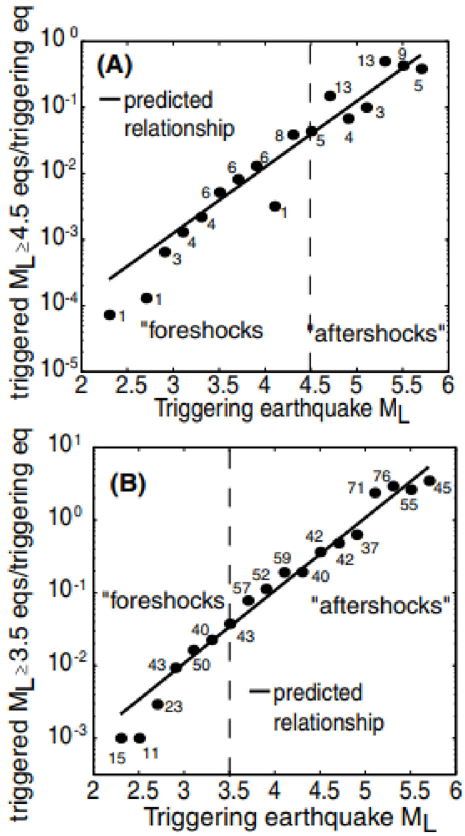
Solar storm-induced Earthquakes

Additionally, when solar storms are directed towards Earth, they cause large disturbances in near-Earth space. For example, they disrupt communications or damage space craft electronics. Understanding in detail what happens when solar storms reach Earth is crucial to mitigate their effects. Using measurements from the Cluster spacecraft, investigated was how solar storms modified the properties of the very first region of near-Earth space encountered when journeying towards Earth. This region, called the foreshock, extends ahead of the protective bubble formed by the Earth's magnetic field. The foreshock is home to intense electromagnetic waves, and disturbances in this region perturb the Earth's magnetic bubble. Foreshock processes can have global effects on the Earth's magnetosphere, causing enhanced wave activity in the downstream magnetosheath (Dimmock et al., 2016) and down to the Earth's surface (Bier et al., 2014), or triggering fast magnetosheath jets, which can cause impulsive penetration of plasma into the magnetosphere and trigger magnetic reconnection (Plaschke et al.). The study revealed that solar storms modify the foreshock, resulting in a more complex wave activity [20].



Small foreshocks on a seismic record.

In contrast to *aftershocks*, or smaller earthquakes following a larger one (i.e. mainshock), foreshocks are the ante-counterpart to the mainshock. Whereas aftershocks are triggered by stress changes induced by the mainshock's rupture, foreshocks are triggered by the nucleation phase of the upcoming mainshock. One researcher models an earthquake showing how foreshocks trigger slip on small fault patches surrounding the hypocenters of future earthquakes [21]. Foreshock activity has been detected for about 40% of all moderate to large earthquakes, and about 70% for events of M>7.0. They occur from a matter of minutes to days or even longer before the main shock. Foreshocks are any M 5.6 earthquakes that are smaller than and occur up to 2 days before and within 2.5 fault lengths of other M 5.6 earthquakes [22].



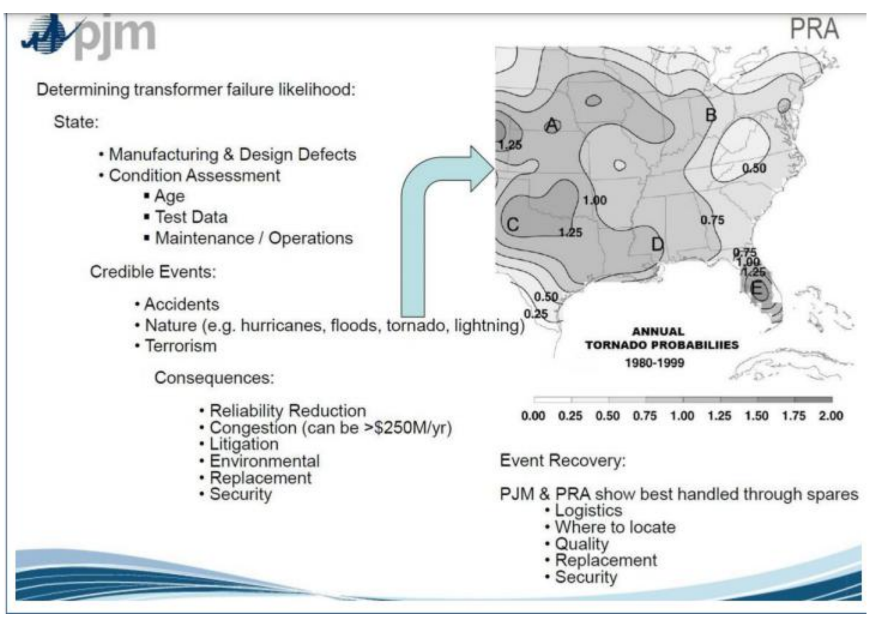
CME-Induced Power Grid Failures

Geomagnetic disturbances (GMDs) occur when Earth is subjected to changes in the energized particle streams emitted by the Sun. The solar events that cause major GMD events are coronal mass ejections (CMEs), which are eruptions of charged particle plasma from the Sun's corona that can bombard the Earth within as little as 14 hours. Near the Earth's surface, these changes induce currents, known as geomagnetically induced currents (GICs), in long electrical conductor systems such as electric power transmission and distribution lines, communication lines, rail lines, and pipelines. GMDs can have significant negative impacts on the electric grid, including electrical and electronic equipment and systems (e.g., high-frequency radio communications, global navigation satellite systems, long-haul telecommunications/internet exchange carrier lines). In November 2014, the National Science and Technology Council within the Executive Branch formed the interagency Space Weather Operations, Research, and Mitigation Task Force (SWORM) to enhance national preparedness for space weather impacts. SWORM developed a National Space Weather Strategy and accompanying National Space Weather Action Plan which laid out specific actions that the task force could take to enhance the nation's resilience against severe space weather events. Goal 4 of the National Space Weather Action Plan called for the U.S to "Improve Assessment, Modeling, and Prediction of Impacts on Critical Infrastructure" and more specifically for the U.S. Department of Energy (DOE) to "develop plans to provide monitoring and data collection systems [23]."

Various agencies have emphasized, and recent events have demonstrated, the critical nature of power transformers in the face of possible high-impact, low-frequency (HILF) events. HILF events include intentional malicious events (e.g., physical attacks, cyber attacks, coordinated attacks, electromagnetic pulse (EMP) weapons, and others), natural disasters (e.g., hurricanes, earthquakes, severe geomagnetic disturbances, etc.), and non-intentional or accidental events such as nuclear power plant accidents. An emergency spare transformer program is a key part of preparation for, and rapid recovery from, a HILF event. Another strategy is to retrofit current transformers with devices that harden them against various HILFs. This approach shows promise to harden against GMDs and EMP attack. An EMP attack is an explosion of electromagnetic energy, caused when charged particles burst into the ionosphere. Solar storms, nuclear weapons, and even lightning can enable an EMP charge and result in an EMP burst. Various designs have been proposed that block or reduce geomagnetic induced current (GIC) flow in transformers and lines to mitigate GMDs, including series compensation, use of blocking capacitors in the neutral ground, and use of neutral resistors to reduce GIC flow. However, this may be a challenging approach due to the number of high-voltage transformers, the number of different designs and sizes, and the need to ensure that any retrofits do not adversely affect normal operation. With regard to design variation, impedance of most units covers a wide range and MVA ratings vary from 150-750 MVA. Other design variations include single-phase versus three-phase; shell form versus core form; three-, five-, or seven-leg models; and others. Another limitation of this approach refers to the inadequate hardening against other types of HILFs, including physical attack. Various operational measures, such as reducing load on some high-voltage transformers in advance of an impending GMD or severe weather, will certainly help to mitigate transformer damage. However, depending on the severity and character of the HILF (e.g., HILFs with little or no warning such as physical, cyber, or coordinated attacks), such measures may not protect all high-voltage transformers from overload, damage, or failure. After the HILF, traditional recovery measures (e.g., rerouting of power, load shedding, islanding, use of backup generation, and others) would certainly be deployed, but these may be insufficient to restore the power system in a timely fashion, depending on the impact of the HILF. And the Department of Energy (DOE) is working on a "strategic transformer reserve" — a supply of extra transformers that can be trucked throughout America if necessary [24]..

Power transformers are the backbone of the grid. Transformers are also subject to a number of vulnerabilities such as natural disasters, solar storms, or man-made attacks. To address this risk to the grid vulnerabilities, S&T's Resilient Systems Division has designed, developed, and demonstrated a prototype Recovery Transformer (RecX), a mobile spare transformer designed to be rapidly deployed in the event of a transformer failure. The RecX was successfully fielded in 2012 with a pilot demonstration that transported, installed, and energized the prototypes in less than six days as compared to two months or more using conventional methods. The RecX program has produced a final report discussing lessons learned, functional specifications for recovery transformers, evaluations of existing spare transformer strategies, and considerations for develop new ones.

Some transformers at power stations increase voltage so that it can be transmitted many miles, while others "step down" voltage so it can enter homes at safe levels. Large ones can take months to repair or rebuild, resulting in long-term blackouts, according to the Electric Power Research Group. In an emergency, federal agencies could set up temporary transformers to act as a stopgap, much like FEMA sets up temporary housing after disasters. The Department of Homeland Security has a Recovery Transformer program devoted to designing and building a type of easily deployable transformer that can be installed anywhere in an emergency. Extra high voltage (EHV) transformers are critical components of our nation's backbone transmission grid. Approximately 90 percent of consumed power flows through the transmission grid and through such a transformer. These EHV transformers are very large, challenging to transport, and often have lengthy procurement times of one year or greater [25].



Also, there are other technological means that may be used to prevent problems due to space weather in systems. For example, concerning GIC in power grids, the installation of capacitors in high-voltage transmission lines or in groundings of power transformer neutrals block the DC-like GIC (but let the 50 or 60 Hz current flow), and harmful GIC consequences can in principle be avoided [26]. However, the use of capacitors is not a cheap solution. The design of appropriate capacitors is not straightforward either since they should not disturb the operation of the system or decrease the level of safety. The effect of blocking capacitors on GIC in the entire high-voltage power grid shows, contrary to what might be expected, capacitors may even increase average GIC flowing through transformers [27]. A study about the effect of neutral point reactors on GIC in the Finnish 400 kV system also supports the observation that increasing the resistance experienced by GIC thus decreasing GIC, at some sites tends to increase GIC at other sites; so, the overall situation may get worse [28].

Safety Management

When developing space weather prediction methods, analogies can be made with forecasting of terrestrial weather. However, differences between the two types of weather also have to be clearly recognized. Concerning effects on power systems, it is important to note that while a terrestrial weather impact is usually confined to a small region at a time only to propagate to a larger area; space weather can affect several transformers of a wide network simultaneously, making the whole situation clearly worse.

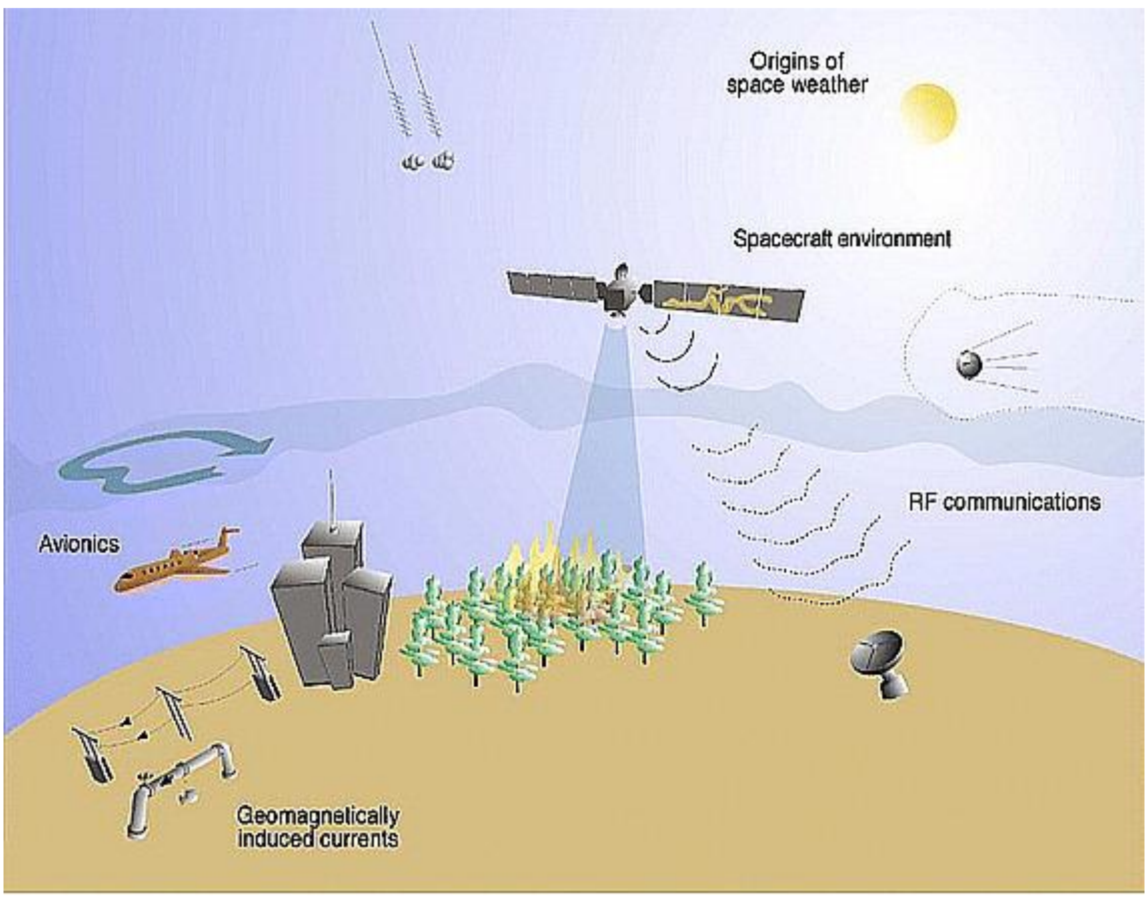


Figure: How space weather may disturb risk management, in this case the operation of a satellite monitoring a forest fire [*Pirjola et al.*, 2003a]

A different way to reduce space weather risk is obviously to develop forecast and warning techniques of prospective space storms. When receiving such a warning, for example, power system operators are ready for increased reactive power demands, and they can take all actions given in predetermined guidelines. Such actions are costly, so power utilities may be reluctant to follow the guidelines unless the forecast is certainly reliable. Similarly at the time of an impending space weather event, members of spacecraft crew need to know how to avoid extravehicular activities; spacecraft operators need to consider the possibility of disturbances in the performance of satellites; and in telecommunication links, users of satellite positioning and navigation need to consider the application of back-up systems and that pipeline control surveys will be postponed, and so on. The accuracy of space weather forecasts decreases if the time span is increased. Necessary lead times vary from one application to another. Thus forecast services have to be designed and tailored carefully in order to be useful. For example, power system operators can do something if a warning is received tens of minutes to an hour before the GIC impact. Moreover, statistical predictions of space storms are obtained on the basis of the 11-year sunspot cycle or of the 27-day rotation period of the Sun. Observations of solar electromagnetic radiation permit forecasts for the following 1 to 2 days. More reliable space weather warnings can be made by applying satellite monitoring of the solar wind at the L1 point located at about 1.5 million km from the Earth toward the Sun. Intensifications in the solar wind cause space weather events at the Earth about 30 to 60 min after having arrived at L1.

A detailed physical description of the consequences at the Earth due to a solar wind disturbance at L1 would require the use of global magneto-hydrodynamic simulations of the coupling of the solar wind to the magnetosphere-ionosphere system and of the interaction between the magnetosphere and ionosphere [29]. Such physical models are still too slow to be applied to forecasting purposes when run with relevant spatial and temporal resolutions. Therefore, today's most promising space weather forecasting techniques are evidently based on neural networks [30], [31]. An L1 spacecraft monitoring the solar wind is certainly not sufficient for space weather purposes but data collected by instruments on board an L1 satellite should be supplemented by versatile observations of the Sun and recordings of different geophysical parameters.

Solar particles of the natural space environment interact with magnetic field near earth to impact radio communications, GPS signals, and utility grids on the ground. The effects of SRP (solar radiation pressure) are particularly important for communication satellites equipped with large solar arrays [32]. Scientists at NASA and NOAA give warnings to electric companies, spacecraft operators and airline pilots before a CME comes to Earth so that these groups can take proper precautions. NOAA's Space Weather Prediction Center provides the space weather forecasts, alerts, watches and warnings. Improving these predictive abilities the same way weather prediction has improved over the last few decades is one of the reasons NASA studies the sun and space weather [33]. Satellite data helps scientists predict these solar eruptions, but there are still plenty of questions about how the sun works; answering them would improve forecasts of space weather. Researchers found their forecasts to be 20 per cent more accurate, providing improved estimates of the solar wind speed and its impact on CME movement [34].

Table 1. Time Sequence of Solar Storm Events[1]

Solar Flares		
	Arrival Time:	Instantaneous[†]
	Effect Duration:	1-2 hours
Solar Proton Event		
	Arrival Time:	15 minute to a few hours
	Effect Duration:	Days
Coronal Mass Ejection		
	Arrival time:	2 or 4 days
	Effect Duration:	Days

Earth’s magnetic field protects us against the sun’s firehose of energy, but sometimes the sun overpowers the planet’s defenses. When that happens, solar radiation heats the upper atmosphere and charges it with electricity, which is what causes auroras at the northern and southern poles. When coronal mass ejections arrive a day or so later, Earth’s magnetic field changes [34]. CMEs reach Earth in as little as 15 hours and have the potential to damage electrical equipment — from orbiting satellites to ground-based energy grids. Solar storm forecasts are currently based on observations of coronal mass ejections as soon as they leave the Sun's surface, meaning they come with a large degree of uncertainty [35].The value of additional CME observations demonstrates how useful it would be to include cameras on board spacecraft for more accurate predictions that help prevent catastrophic damage to infrastructure and could even save lives [36]. Energy that heats the corona and is channeled, stored, and dissipated by the magnetic fields, emerges from the photosphere and structures the coronal plasma. Several fundamental plasma physical processes—waves and instabilities, magnetic reconnection, turbulence—operating on a vast range of spatial and temporal scales are believed to play a role in coronal heating and solar wind acceleration.

Solar energy particles (SEPs) consist of protons, electrons and heavy ions with energy ranging from a few tens of keV to GeV (the fastest particles can reach speed up to 80% of the speed of light). SEP events are divided into two types: short-lived *impulsive* events, in which the particles accelerate in solar flares, and *gradual* events, in which particles accelerate at shocks driven by fast coronal mass ejections (CMEs) in the near-Sun coronal environment. Both processes operate together in some events, but gradual events produce the largest fluences of particles and most dangerous radiation environments. SEP events occur most frequently during a 6-7 year period centered on solar maximum.

Since its launch on Dec. 7, 2001, TIMED's (Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics) long-term study of the middle and upper atmosphere has shown how the regions react to an array of solar activity, including flares, coronal mass ejections, high-speed solar wind streams and a total solar eclipse. TIMED's observations have also shown that Earth's upper atmosphere's energetics and dynamics are greatly influenced by varying inputs from the magnetosphere, such as electrical fields and auroral particles.

3. Conclusion

As seen from Earth, the rotation period of the Sun averages about 27 days. Solar storms originating from sunspots stay active for several solar revolutions in a cyclical ~27 day pattern. Thus, solar winds appear as a continuous flow of charged particles and constitute a fluid that has an electromagnetic interplay with flow obstacles, such as planetary magnetic fields. One of the largest solar storms in the past 450 years occurred in September 1859. Because civilization has evolved into a technologically driven /technology dependent society, a solar storm of this magnitude today would produce a major global calamity. Space weather analysis primarily focuses on the rare massive solar storms occurring at a rate measured in terms of decades and centuries. The subsequent danger of these great storms results from lacking an adequate assessment whereby emergency public officials are caught unawares or blindsided to very real threats. One way to reduce space weather risk is to develop forecast and warning techniques of prospective space storms. A spacecraft in L1 orbit monitoring the solar wind is certainly not sufficient for space weather purposes but data collected by instruments on board an L1 satellite when supplemented by versatile observations of the Sun and recordings of different geophysical parameters help scientists predict solar eruptions. But, there are still plenty of questions about how the sun works; answering them would also improve forecasts of space weather. Satellite missions such as DEMETER and TIMED aim to provide those answers.

Notes and References

[1]. Wright, J. , Lennon, T., Corell, R., Ostenso, N., Huntress, W., Devine, J., & Crowley, P. (1995), The National Space Weather Program: The strategic plan, *Rep. FCM-P30-1995*, 18 pp., Off. of the Fed. Coord. for Meteorol. Serv. and Supporting Res., Washington, D. C..

[2]. Basu, S., Groves, K., Basu, S., & Sultan, P. (2002), Specification and forecasting of scintillations in communication/navigation links:Current status and future plans, *J. Atmos. Sol. Terr. Phys.*, 64(16), 1745–1754.

[3]. Turner, K. (April, 2014). Solar flares can affect communications and power grid. *Guardian Liberty Voice*.

[4]. Bell, T. & Phillips, T. (May, 2008). *A Super Solar Flare*. Retrieved from www.science.nasa.gov

[5]. Fox, N.. *Coronal Mass Ejections*. NASA/International Solar-Terrestrial Physics. Retrieved from https://pwg.gsfc.nasa.gov

[6].Boyle, R.(June , 2017). *How We'll Safeguard Earth From a Solar Storm Catastrophe* Retrieved from https://www.nbcnews.com

[7]. Fenner, J. (October , 2013). *Sun Emits Wave of Dazzling Solar Flares*. Retrieved from https://guardianlv.com

[8] Turner, K. (April, 2014). *Solar Flares Can Affect Communications and Power Grid*. Retrieved from https://guardianlv.com

[9]. Fox, K. (May, 2013). *Impacts of Strong Solar Flares*. NASA_GSFC

[10]. Citizen Scientists (September, 2020). *Space Weather: Solar storm forecasting system developed*. Retrieved from https://theworldnews.net/uk-news

[11]. Retrieved from gsfc.nasa.gov

[12]. Daglis, I. Space Storms, Ring Current and Space-Atmosphere Coupling. *Critical elements of space weathe.* Institute for Space Applications and Remote Sensing, National Observatory of Athens Penteli, 15236 Athens, Greece

[13]. Ritz, M. (1984). Short communication: A high conductiviity anomaly on the West African craton (MALI). *Journal of Geophysics, 55*, 182-184

[14]. Serrano, I., Zhao, D., Morales, J., & Torcal, F. (2003). Seismic tomography from local crustal earthquakes beneath eastern Rif Mountains of Morocco, *Tectonic Physics, 367*, 187-20

[15]. Tavares, M. & Azevedo, A. (2011). Influences of solar cycles on earthquakes. *Natural Science*, *3*(06), 436.

[16]. Inan, U.., Piddyachiy, D., Peter, W.., Sauvaud, J., & M-Demeter, P. (2007). Satellite observations of lightning induced precipitation. *Geophysical Research Letters, 34*, L07013.

[17]. Gousheva, M.., Georgiva, K., Kirov, B., & Atanssov, D. (2003). On the relation between solar activ-ity and seismicity. *Proceedings of International Conference on Recent Advances in Space Technologies*, 20-22 November 2003.

[18]. Namgaladze, A., Zolotov, O., Zakarenkhova, I., Shagimuratov, I., & Martynenko, O. (2009). Iono-spheric total electron content variations observed before earthquakes: Possible physical mechanism and modeling. *Proceedings of MSTU, 12*, 308-315.

[19]. Tavares, M. & Azevedo, A. (2011). Influences of solar cycles on earthquakes. *Natural Science*, *3*(06), 436.

[20]. Turc, L., Roberts, O., Archer, M., Palmroth, M., Battarbee, M., et al.. (2019). First observations of the disruption of the Earth's foreshock wave field during magnetic clouds. *Geophysical Research Letters, American Geophysical Union*.

[21]. Felzer, K., Abercrombie, R., & Ekström, G. (2004). A common origin for aftershocks, foreshocks, and multiplets. *Bulletin of the Seismological Society of America*, *94*(1), 88-98.

[22]. Kayal, J. (2008). . "Earthquake Physics and Fault-System Science". *Living on an Active Earth: Perspectives on Earthquake Science.* National Research Council (U.S.). Committee on the Science of Earthquakes, Washington D.C.: National Academies Press. p. *418*. Microearthquake seismology and seismotectonics of South Asia. Springer. p. 15.

[23]. Evans, K & Lotto, A. (January 2019). *Geomagnetic Disturbance Monitoring Approach and Implementation Strategies.* Infrastructure Security and Energy Restoration (ISER), Office of Cybersecurity, Energy Security, and Emergency Response, U.S. Department of Energy.

[24]. Lordan, R. (September, 2014). Considerations for a power transformer emergency spare strategy for the electric utility industry. The Electric Power Research Institute, Science and Technology Directorate, U.S. Department of Homeland Security.

[25]. Boyle, R. (June, 2017). How we'll safeguard Earth from a solar storm catastrophe. Retrieved from https://www.nbcnews.com/mach

[26].Molinski, T. (2002). Why utilities respect geomagnetically induced currents, *J. Atmos. Sol. Terr. Phys.*, 64(16), 1765–1778.

[27]. Erinmez, I., Kappenman, J., & Radasky, W. (2002). Management of the geomagnetically induced current risks on the national grid company's electric power transmission system, *J. Atmos. Sol. Terr. Phys.*, *64* (5–6), 743–756.

[28] Pirjola, R. (2004). Averages of geomagnetically induced currents (GIC) in the Finnish 400 kV electric power transmission system and the effect of neutral point reactors on GIC. *Journal of Atmospheric and Solar‐Terrestrial Physics*.

[29]. Janhunen, P. (1996). *GUMICS‐3: A global ionosphere‐magnetosphere coupling simulation with high ionospheric resolution.* ESA Symposium on "Environment Modelling for Space‐Based Applications,"Eur. Space Res. and Technol. Cent., Noordwijk, Netherlands, 18 – 20 Sept..

[30]. Lundstedt, H. (1998). *The Swedish space weather initiatives*. ESA Workshop on Space Weather, Eur. Space Res. and Technol. Cent., Noordwijk, Netherlands, 11 – 13 Nov.

[31] Boberg, F., Wintoft, P., & Lundstedt, H. (2000), Real time *Kp* predictions from solar wind data using neural networks, *Phys. Chem. Earth, Part C,* 25(4), 275–280..

[32].Spiridonova, S. & Kahle, R. *Relative orbit dynamics in near-geostationary orbit.*

[33]. Cane, H., Erickson, W., & Prestage, N. (2002). Solar flares, type III radio bursts, coronal mass ejections, and energetic particles. *Journal of Geophysical Research: Space Physics*, *107*(A10), SSH-14.

[34]. Boyle, R. (June, 2017). How *We'll safeguard Earth from a solar storm catastrophe* Retrieved from https://www.nbcnews.com/mach

[35]. Lordan, R. (September, 2014). Considerations for a power transformer emergency spare strategy for the electric utility industry. The Electric Power Research Institute, Science and Technology Directorate, U.S. Department of Homeland Security.

[36]. Citizen-Scientists (September, 2020). *Space Weather: Solar storm forecasting system*. Retrieved from https://theworldnews.net/uk-news