Weatherman's Guide to the Sun

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Space Weather News

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PART 1

Space Weather, Introduction to Solar-Terrestrial Climate

Reading This Book

Despite the thousands of years in which humans have looked at the sun and studied it, we have learned more in the last decade than in the previous millennia combined. Satellites such as the Solar Dynamics Observatory have allowed us to see our star in a new light, literally, as we can see in ultraviolet and x-ray wavelengths. Most importantly, these satellites have opened the door for progress, understanding, and the imagination. This area of science isn't just for the experts; the public is involved and hungry for more. It takes a few seconds to fall in love with the sun when seen through our best technologies, a few hours to become a near expert in what you are seeing, and a lifetime to get bored with it.

Despite the infant status of the new science of studying the sun at this level of detail, there are already many resources available for the public. In addition to data portals from government organizations, including NASA, NOAA, ESA and IPS, there are numerous citizen science resources.

There are already millions of people who have fallen in love with the sun, and they are making a big difference in the development, perception, and popularity of the field. If two minds are better than one, then a million enthusiasts are better than a handful of the scientists who would otherwise be working alone.

With widespread interest and involvement come problems. There are few areas of science that are as misunderstood as solar-terrestrial interactions, the interplay of heliophysics (study of the sun) and planetary sciences. Most of the correlations and patterns of how space weather (the effects of the sun and solar events) affects our planet could not have been conceived just a few years ago, let alone more-recent work that details the mechanisms by which these events modulate our climate and short-term weather events.

If we aimed to write this text using only 100% accepted/settled solar-terrestrial physics principles (ignoring the best new ideas, theories, and citizen-science contributions), this book would be only a few pages long, or it would need to wait for decades of peer review, experimentation, observation, and analysis.

In lieu of those less-appealing options, this book presents information and characterizes it by its current status in the mainstream lexicon. Much of the information contained herein is accepted science but some will be unconfirmed, hypothesized, disputed, or 'fringe' material. These distinctions will be important for your contextual placement of this information within your brain. Remember: settled science has a 100% track record of changing over time. Every model was once a hypothesis, and before that, an idea.

Many things make this field of study difficult, not the least of which is that it requires an interdisciplinary understanding. However, an equally frustrating aspect of this field is the overbreadth problem. In the world of law, overstatements of fact and overreaching of conclusions gets you no points with a judge, but in the world in which your grants, your job, and your life depend on publishing, exposure, and even headlines, the tendency to go too far appears attractive to many.

> On one hand: We've seen papers identify a weak cyclical period on earth match a strong one on the sun and declare a grand correlation.
>
> On the other hand: We have seen situations where a scientist fails to find a correlation between one of the dozens of solar inputs, to something specific such as changes in average global temperature, and then proceeded to claim that the sun does not appear to affect the climate at all.

I hope that you can see how each of those studies may have value in what was observed and analyzed, even though their conclusions go further than the data should allow. A good example of this would be looking at your pointer, middle, ring, and pinky fingers and saying, "80% of my fingers are not thumbs; therefore there is not a strong relationship between thumbs and human hands.” If you can understand that example and how silly a statement it is despite the fact that the statistics are technically correct, you will do just fine with this book.

You are going to learn about the sun, about how the sun sends energy to the earth, about how the earth handles that energy, and how the sun and planets are modulating everything from day-to-day storms to major earthquakes to heart attacks and strokes. More importantly, you will be given a list of resources that you can use to be part of the process and begin learning/observing the sun and earth yourself. The field of space weather is a practical culmination of astronomy, physics, and chemistry. Space weather is poised to become one of the most important and fastest-growing fields of science over the next 20 years.

There is much more to the weather, climate, sun, space weather, and solar influence on climate change (solar forcing) than what is found in this text; however, the goal is to give the reader an open door to investigate these topics and keep up with current advances in the field. This is also intended to help the reader understand what to expect on earth when certain things happen on the sun.

- Ben Davidson, Founder, Space Weather News & The Mobile Observatory Project

1.0 Space Weather

The sun is much more than the star that gives us light each day with earth's rotation. The sun's output spans a broad spectrum. Its emissions come in particle form and electromagnetic (EM) energy, if not other forms of plasma and solar system resonance. Below, you see a basic chart of electromagnetic energy and some of the ways the sun operates.

EM Spectrum	Solar Events	Ionising?	Damages DNA?
Gamma Rays	Rare, Major Solar flares	Yes	Yes
X-Rays	Solar Flares	Yes	Yes
UV Rays	~Constant EM Solar Output	Sometimes	Yes
Visible	~Constant EM Solar Output	No	Rarely
Infrared Waves	~Constant EM Solar Output	No	Very Rarely
Microwaves	~Constant EM Solar Output	No	Very Rarely
Radio Waves	~Constant EM Solar Output	No	Very Rarely

The sun operates across nearly the entire spectrum of electromagnetic energy. The fluctuations of the constant outputs and occurrences of the higher-energy-output events are an important part of space weather.

This book is meant to be an introduction to the earth/sun interplay in meteorology, so diving deep into the specific topic of space weather is outside its context. However, it is necessary to have the most basic understanding of the terminology, processes, and important events affecting the relationship between our planet and our star. More thorough information and video learning can be found for free at SpaceWeatherNews.com, with a complete tutorial series available by clicking the "What is Space Weather?" button at the top of that website's homepage (see below). You can practically become a space weather expert in about one hour.

For the purposes of reading this book, this first chapter will provide the basis for your space weather understanding that is needed to begin learning about the earth/sun relationship.

1.1 Solar Wind

Before we get into detail about the electromagnetic output of the sun, we first have to learn about the solar particles known as the solar wind. The sun emits solar wind in every direction all the time. NASA's Genesis mission discovered that nearly every element can be found in the solar wind, but most are there only in trace amounts. The majority of the solar wind is made up of +Hydrogen ions, electrons, protons, and some neutral elements like Helium. The solar wind acts like an electric field of plasma.

These solar wind particles race away from the sun in various densities, ranging from a few particles per cubic foot to dozens, hundreds, or even thousands of particles per cubic inch, especially as the solar wind slows down near Mars, bunches up, and becomes extremely dense.

The speed of these particles at earth generally ranges between 200 - 275 miles per **second** (*not* miles per hour!) during normal quiet times, but can they spike to over 600 miles per second, which is more than 2 million miles per hour, during significant space weather events. Solar wind density and particle speed are usually given in metric units, so 300 - 400 kilometers per second would be average speed, along with 0.1 to 10 protons per cubic centimeter. More intense streams can exceed 700 kilometers per second and can be dozens to hundreds of protons dense per cubic centimeter. These intense waves of solar wind tend to be hotter by a factor of 10 to 100 (usually given in kelvin scale) and can have drastically different presentations in terms of their magnetism and angle of approach.

The next image displays solar wind telemetry from the DSCOVR satellite. The bottom three panels tell us what kind of space weather we are experiencing: the solar wind density (orange), speed (purple), and temperature (green). In this

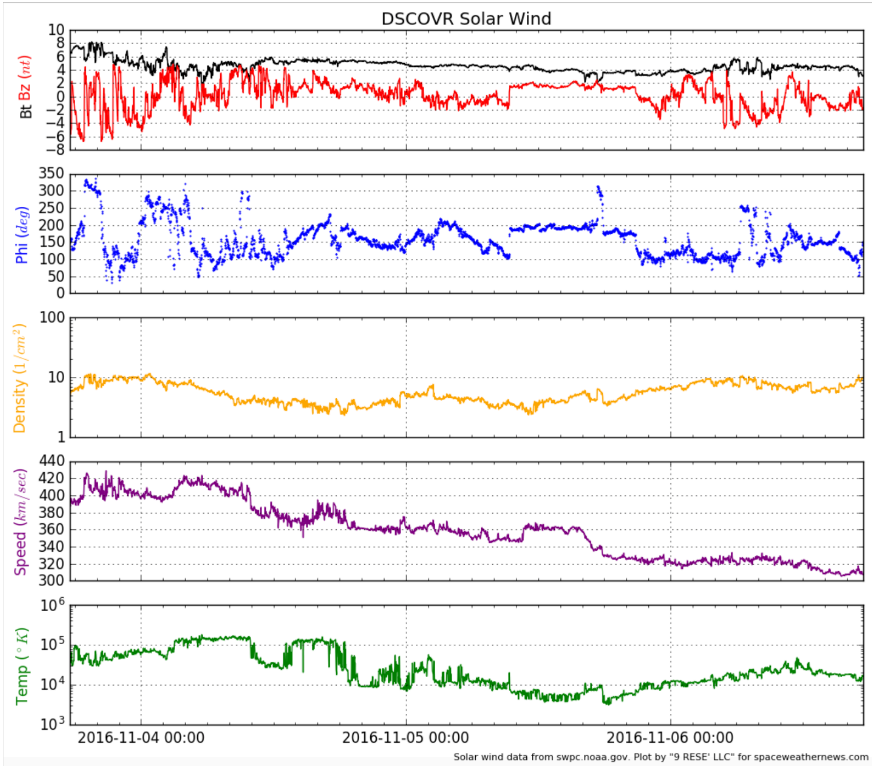
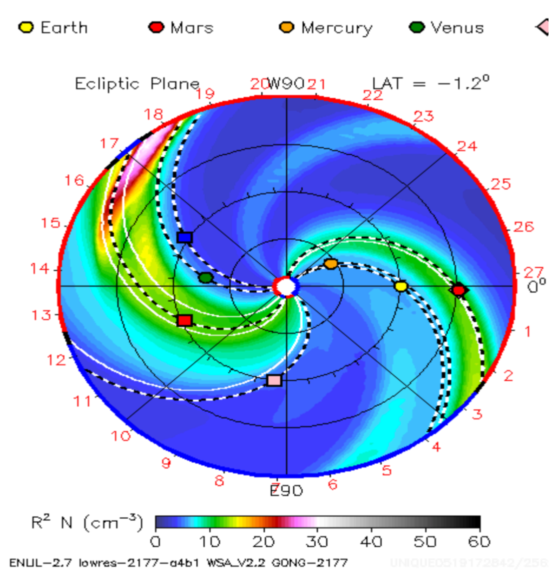


image we see the speed of the solar wind decreasing from about 400 km/sec to under 350 km/s, indicating that a faster solar wind stream was ending at this time, accompanied by a return to normal calmer conditions. The drop in plasma temperature (Nov.4-5) confirms this analysis.

The differences between the quiet and intense streams of solar wind are central to studying and monitoring space weather. Solar flares and coronal holes can intensify the normally calm streams, delivering interplanetary shockwaves and strong solar wind streams that directly affect the global electric circuit, magnetic field, atmosphere, and lithosphere. There are secondary (indirect) effects as well and those that have lagged-forcing effects over days to years.

The particles moving away from the sun create a streaming electric field of charged material and plasma. This field of solar wind particles encompasses the entire solar system and technically means that outer space is not a true vacuum in our galactic neighborhood and others. The solar wind and trace dust/gases make up the heliospheric current sheet, and this relatively broad term refers to the invisible electric field in which the earth and all planets orbit the sun.

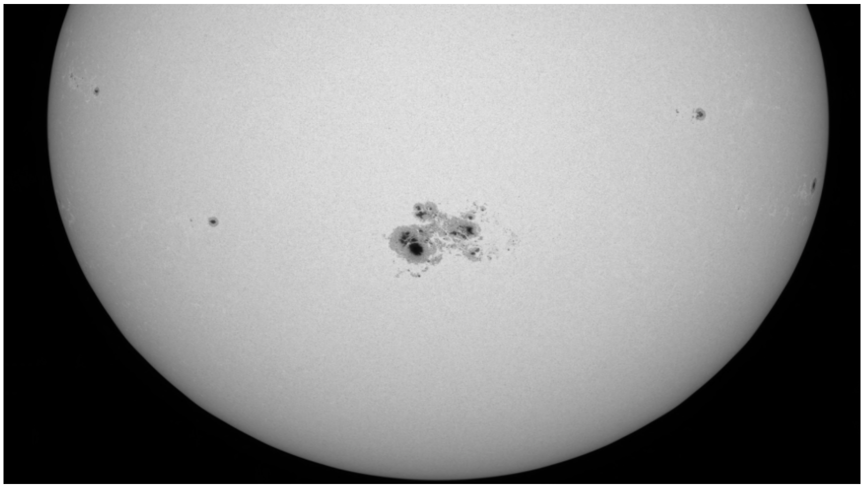
An interesting phenomenon occurs within this current sheet: As the sun and planets are sphere magnets, with either intrinsic or induced magnetic fields existing in some form at each of the planets, direct magnetic connections between the planets and sun arise within the electric field of solar wind, which acts much like a wire connecting the spheres. These are called interplanetary magnetic fields (IMF), they can drive charged particles across space at incredible speeds, and they can bypass a planet's defenses against space energy, their magnetic fields. These IMF can allow the solar wind plasma to enter the planetary system. We see this on earth every eight minutes in energetic exchanges called flux transfer events (FTEs).



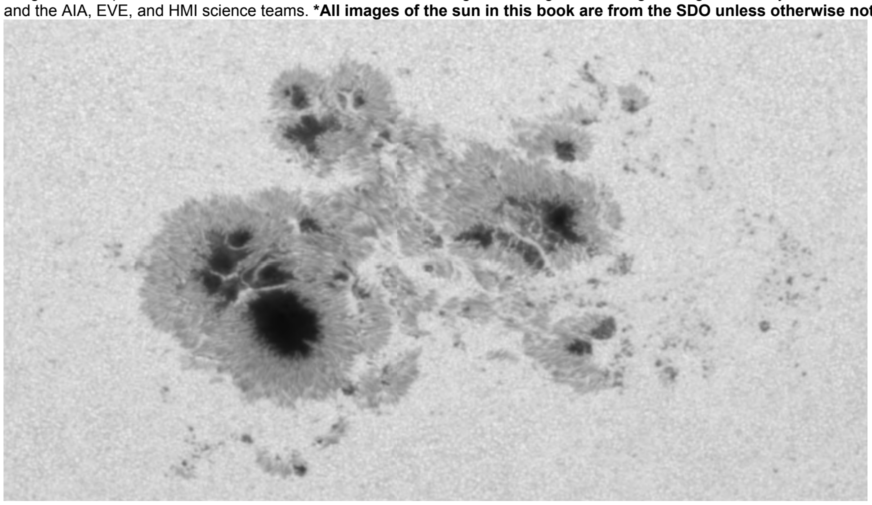
This image is from the National Solar Observatory and is called the ENLIL spiral (Enlil was the Sumerian god that controlled the wind and gave the breath of life). It shows the density of the solar wind in the planetary orbital plane from above (north) and also the IMF connecting the planets and sun, seen as black and white curved lines bending with the rotation of the system. The following sections of this chapter involve things that affect the solar wind, the heliospheric current sheet, or the IMF, as well as other aspects of the solar system and the earth.

1.2 *Sunspots*

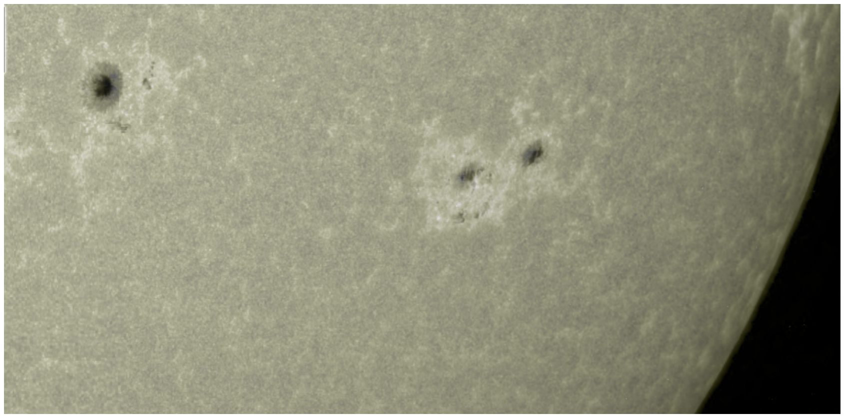
Sunspots were one of the first pieces of space weather to be studied. Long before fancy satellites and telescope filters, humans were able to see sunspots and even keep records of their numbers. Sunspots are areas where magnetic fields enter and exit the solar surface, causing unstable areas in the corona (solar atmosphere) above and around them.



Images of sunspots on October 23rd, 2014, zoomed-in on the large active region on the right. Images courtesy of NASA/SDO and the AIA, EVE, and HMI science teams. ***All images of the sun in this book are from the SDO unless otherwise noted.**

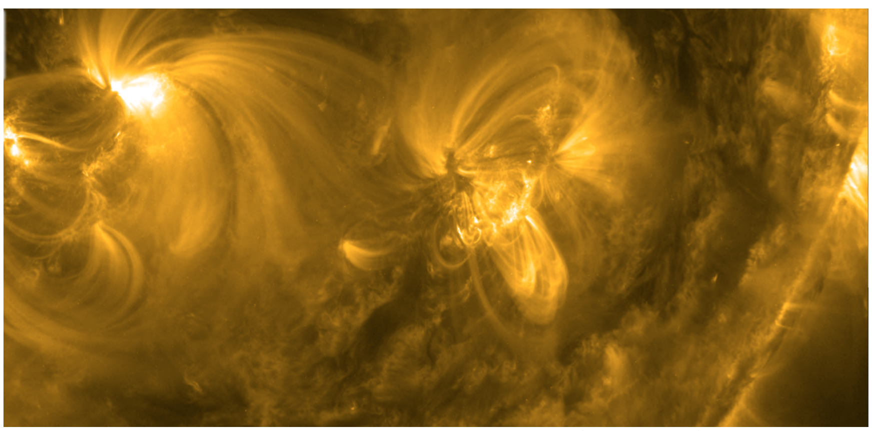


The dark cores of sunspots are called sunspot umbra, and the interface area surrounding the umbra is called the penumbra. The umbra is where the magnetic fields enter or exit the surface of the sun, and the interaction of these spots is key to understanding much of space weather.



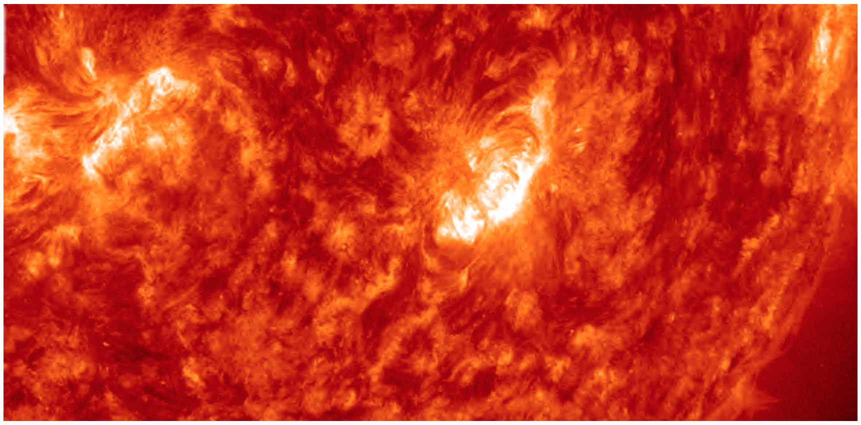
In this image, we see two sunspot groups. The group on the right has two main umbral cores, while the one on the left is based around only one. Sunspots like the one in the black and white image above are extremely volatile and contain numerous smaller sunspot umbra.

In the next image we see ionized Iron trapped in the magnetic fields coming in and out of the same sunspots. These are called umbral magnetic fields. Unlike IMF, these only connect the sun to the sun. We usually see a spot-spot connection, but



they can also loop back down to areas of the surface that are magnetically polarized. The left side umbra has too many fields to be contained to the smaller surrounding umbra, so it reaches out for other connection points towards the right side umbra.

In the third image (red) on the next page, we see ionized Helium, which indicates just how active and unstable the sunspot areas are compared to the rest of the solar surface and corona.



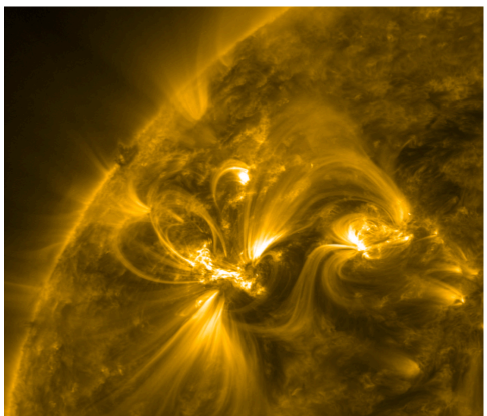
Although the umbral magnetic fields (yellow image) were more numerous, and therefore brighter, than the two-umbra sunspot group on the right, multiple large umbra means more activity close-by, and more interaction at the sunspot group itself. The interactions of the plasma and ions in the umbral magnetic fields are the driver of the primary space weather event: the solar flare.

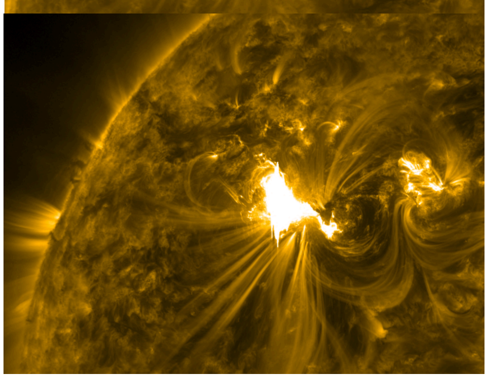
Note: Sunspots are a general indicator of the sun's activity and the character of the heliospheric current sheet. During times when there are lots of sunspots, we tend to see a denser and more intense electric field of solar wind throughout the solar system, and this bubble of charge material is an important buffer for cosmic rays from the galaxy and other galaxies. We will discuss cosmic rays in greater detail at the end of this chapter.

1.3 Solar Flares

Perhaps the most exciting (and potentially dangerous) aspect of space weather is the solar flare. Solar flares are X-ray explosions on the sun that can sometimes even produce gamma rays in the strongest events. This electromagnetic radiation emanates at the speed of light and can produce ionization (excitement) of earth's upper atmosphere, which can disrupt high-frequency radio communications. When a strong solar flare excites the upper atmosphere to the point of disrupting communications, we call it a *radio blackout*. Only the earth-facing (daytime) side of the sun is affected by the solar flare, and the event begins to fade the moment the solar flare ends. Solar flares can last from just a few minutes to a few hours. Short flares are called ‘impulsive’ flares, and longer ones are called ‘long-duration’ flares. Long-duration solar flares not only produce longer-lasting radio blackouts, but also have more of a chance of disrupting the solar wind. [More on this in section 1.5]

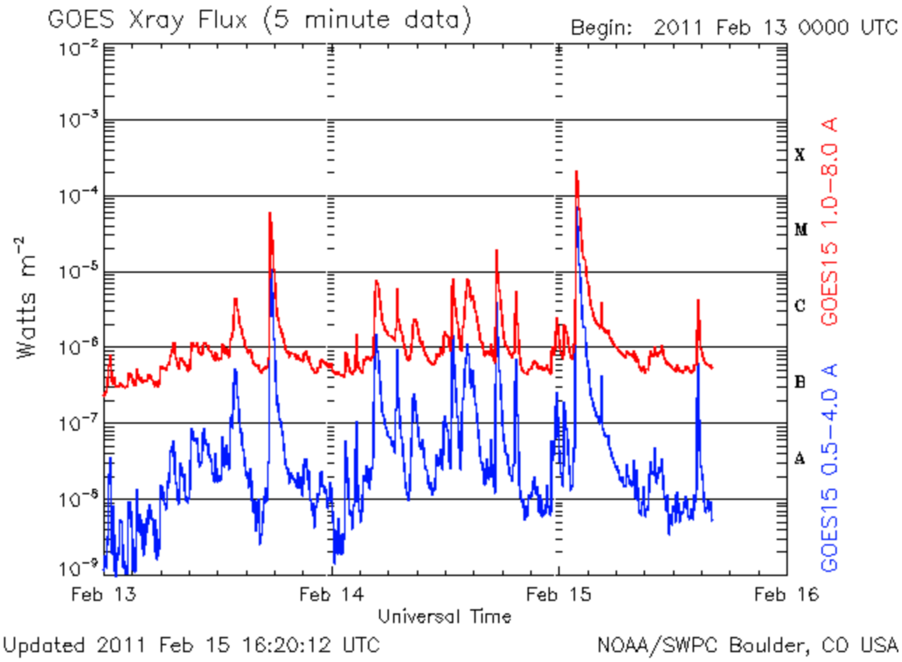
Below, we see two images taken just hours apart. On top, we see arching umbral magnetic fields of sunspots in a complex arrangement. On the bottom, we see a solar flare. The charged material in the magnetic fields above the sunspots destabilized and either collided or accelerated particles to near-light speed.





The energetic release is mostly in the X-ray spectrum, but there are also strong increases in the extreme UV output as well.

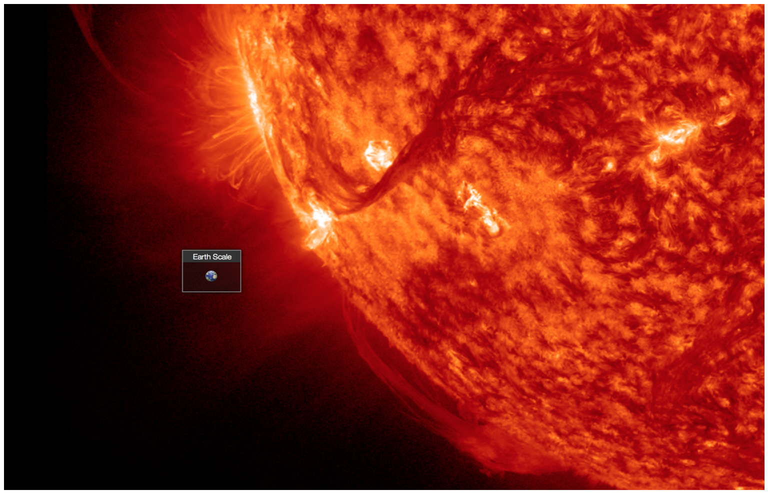
Solar flares are classified on a logarithmic scale; from lowest energy to highest, the rating levels are A, B, C, M, and X. On the next page, we see an example of how these data are delivered to us from NOAA’s GOES satellites:



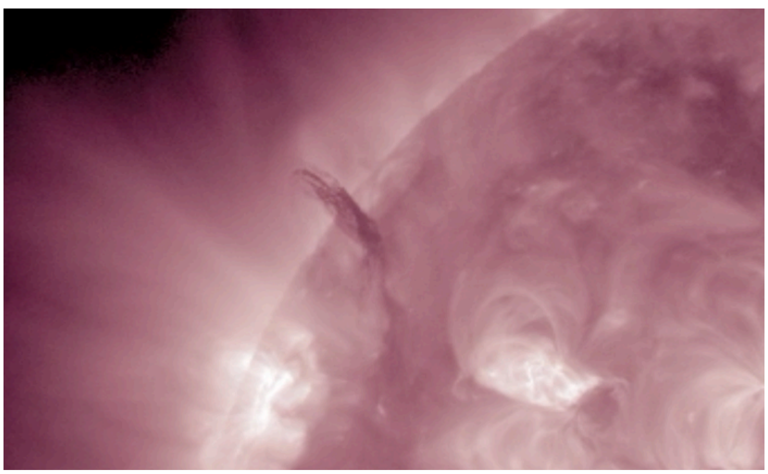
On this chart, we can see one X-class solar flare (~X2.1), two M-class solar flares (~M5.3, ~M2.2), and a number of C class solar flares. In general, solar flares are not going to produce significant space weather unless they are M-class or higher, except for long-duration (>1hr) C-class flares, which can also be significant. An A1 flare is 10x weaker than a B1, which is 10x weaker than a C1 . . . X1. Since X class is the highest, an X10 is 10x weaker than an X20, which is 10x weaker than an X30 . . .

1.4 Plasma Filaments

Plasma filaments, sometimes called solar prominences, are large rope-like structures of plasma hovering in the corona. They can contain billions of tons of plasma and stretch out in thin lines hundreds of thousands of miles long.



In the first image (above, red), we see three plasma filaments, two arching over the limb (side of the sun from our perspective) and one horizontal filament already on the earth-facing side. Note the size of these structures compared to the earth. Just to the right of the earth scale is a bright-white area above a sunspot; note the filament touching it for section 1.5.

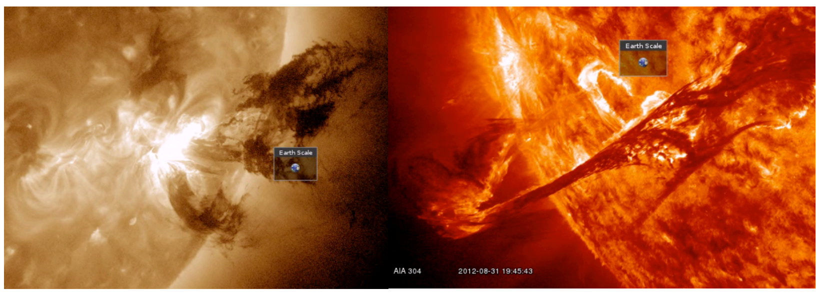


Plasma filaments can be seen in other wavelengths as well. Seven of the nine AIA color-enhanced views offered by NASA allow us to see these filaments. They are suspended by magnetic forces and can come in any orientation, including standing straight up from the surface like a tornado on the sun. X-ray flares and plasma filaments are the two solar phenomena that can produce a “coronal mass ejection.”

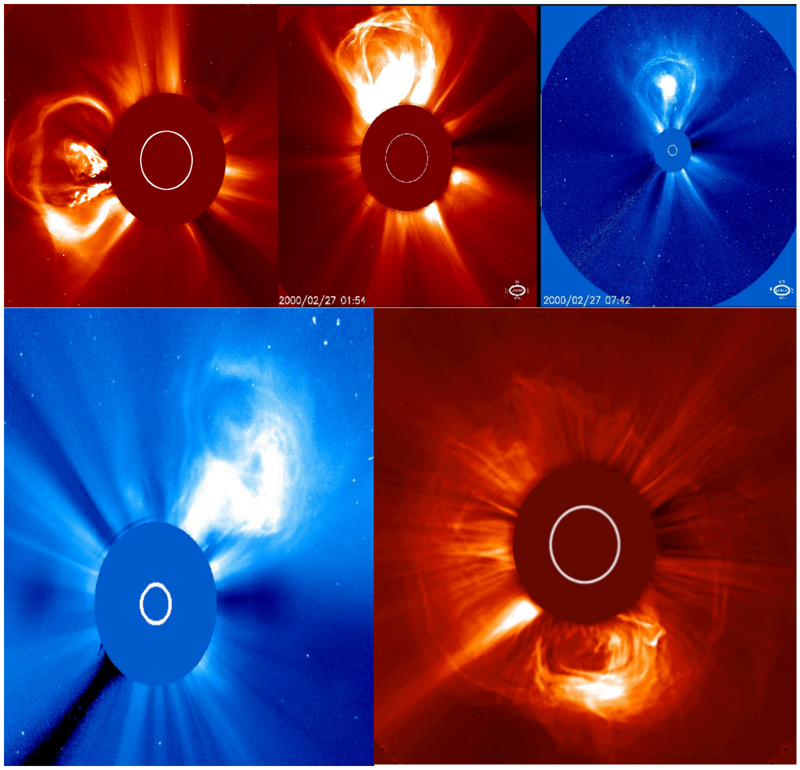
1.5 Coronal Mass Ejections (CMEs)

If the solar flare is the most exciting space weather event, then CMEs are a close second place. CMEs are the main producer of significant space weather events on earth. While a solar flare sends electromagnetic radiation out at the speed of light, a CME is made of ions and plasma (just like the solar wind) and is either blasted out by a solar flare or released as a plasma filament lifts up and breaks free from the sun.

Below, you see two images of CMEs leaving the corona. On the right, you see a plasma filament ripping away from the sun (the one you'll recall from the end of section 1.4), and on the left, you see material ejected from a sunspot group during a solar flare.



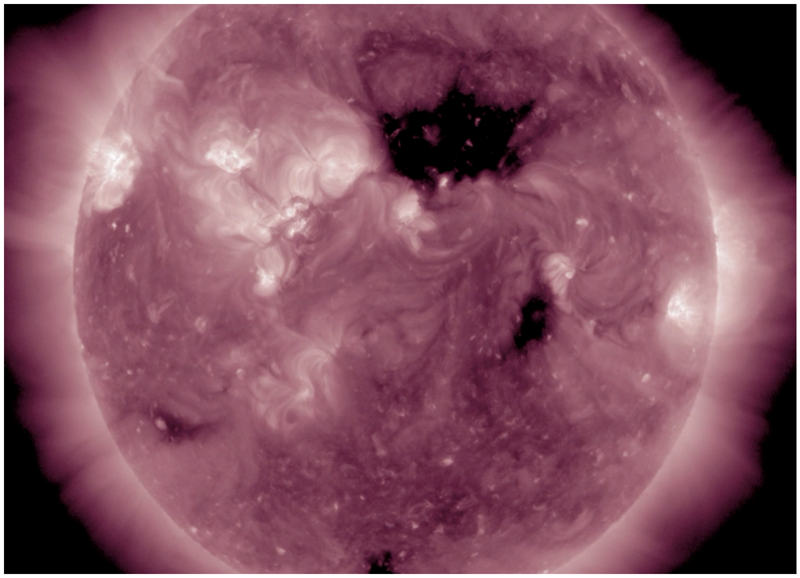
These CMEs act like shockwaves in the solar wind, delivering streams that are fast, dense, and hot. On the next page, you can see a number of images of these CMEs from the SOHO satellite's coronagraph cameras. They are ultra-sensitive to solar plasma, so an opaque disk is centered to block the sun's glare; otherwise, each image would be white. The bottom-right image shows a CME that is coming towards earth, which is called a 'halo' eruption because as it expands, it looks like a halo around the sun. As these cameras always look from earth, each of the other images show CMEs that will miss us (they are going to one side).



Consider the size of these eruptions; the sun is a tiny dot behind the central inner circle, so within hours of a solar flare or filament eruption, there can be a CME cloud big enough to hold dozens to hundred of suns. CME impacts at earth are one of the primary causes of geomagnetic storms- which is a disruption to earth's global magnetic field. The CME particles that hit the earth near the poles create the colorful auroral displays such as the northern lights. CMEs are one of the primary causes of geomagnetic storms at earth, and coronal holes are the other.

1.6 Coronal Holes

To be more precise, the changes in the solar wind driven by coronal holes are the other primary cause of geomagnetic storms.



If you can see the black areas just right and north of center in the solar image here (and the smaller ones near the bottom and lower left side), then you can locate coronal holes. These are areas in the corona that are devoid of charged particles and plasma, a nearly-empty area that extends from the solar surface into outer space. Plasma filaments are dark, but they are thin and often visible separate from the solar surface up in the corona. The coronal holes are usually larger patches such as what you see here, not at all long and thin, and they easily contrast with the bright white umbral magnetic fields above sunspots. The outgoing IMF takes all the charged material out with them, leaving the area vastly less populated than the surrounding regions. Since the image processors of this satellite data assigns color/brightness to the particles we are looking to find, the areas without them show up black, as do like the outside corners of the area looking off into space, where the camera also detects virtually nothing.

The practical effect of this extra outward force is extra-intense solar wind. The streams from coronal holes themselves are not tremendously dense, just very fast and hot, but they catch up to slower-moving solar wind out ahead of it, bunching up those particles like snow on the blade of a shovel. This creates a density shockwave at the leading edge of the fast coronal hole stream that acts very much like a CME. Just as with a CME, coronal hole solar wind streams can cause auroras and geomagnetic storms at earth. Coronal holes are caused by the IMF, and as far as we can tell, all magnetic connections of the planets to the sun (seen in the ENLIL spiral, section 1.1) are connected back to coronal hole areas.

1.7 Solar Radiation Storms (Solar Energetic Particle Events [SEPs])

We have discussed a number of space weather phenomena on the sun and how those things affect the electromagnetic and particle outputs that interact with earth. However, this book is primarily about the earth/sun relationship, and so far, we have only learned about how high-frequency radio communications can be disrupted by a solar flare x-ray ionization of the upper atmosphere. These next two sections deal with the primary particle-based space weather events here at earth.

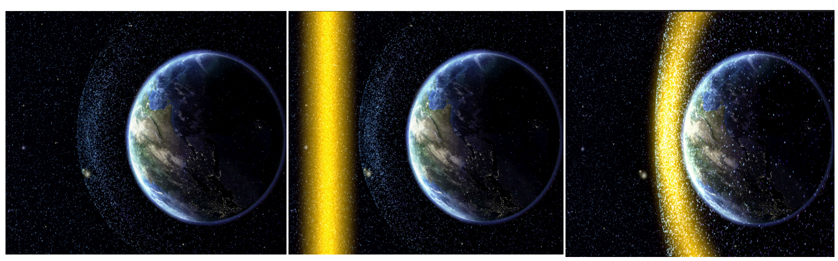
Section 1.1 briefly discussed the IMF that connect the planets back to the sun, and we learned that every eight minutes, a flux transfer event sends charged particles directly between earth and sun along this IMF, which bypasses earth's magnetic field defenses against space energy and pours solar plasma into the upper atmosphere. Sometimes, the surge of particles to earth is extreme, often following a large solar flare or CME. Evidence suggests that when the flare or CME hits earth's magnetic connection to the sun, it helps fuel these extreme events, so the IMF has become a focal point of solar radiation storms, also called solar energetic particle events or SEPs.

During these events, either protons or electrons or both are streaming towards earth and undergo a large spike in particle counts. This influx of charged material occurs near the polar regions, spreading to lower latitudes only in the most extreme circumstances. Our main protection from these events is the atmosphere because these events often bypass our magnetic field; the atmosphere does a very good job protecting those on the ground. Astronauts and passengers on high-latitude flights are most at risk from SEPs, which is why space stations have shielded safe rooms and airlines will reroute polar flights during major solar events. However, in all but the most extreme SEPs, there would be little risk to those on the ground, even near the poles.

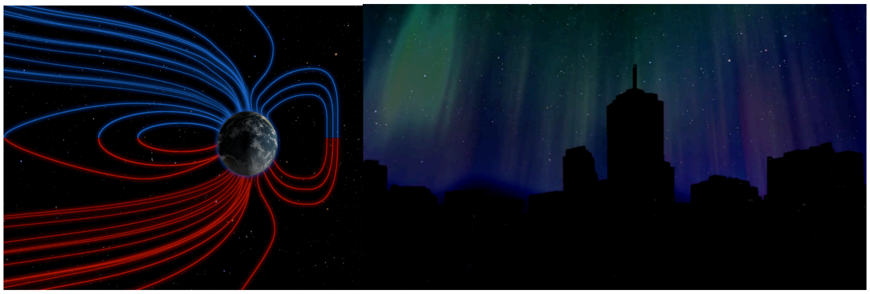
1.8 Geomagnetic Storms

Geomagnetic storms are the bread-and-butter of earth-focused space weather. Solar flare energy can ionize the atmosphere, and SEPs can deliver solar plasma directly into the upper atmosphere near the poles, but neither is as powerful in influencing planetary systems as the geomagnetic storm.

CMEs and coronal hole solar wind streams present sharp changes in the electric environment of near-earth space. Earth's magnetic field is an invisible bubble that protects earth against the dangerous outputs of the sun and the galaxy. When a CME strikes our planet, the magnetic field is compressed, driving two key processes that end up affecting our weather and climate, as well as our technology and our health. The compression of earth's magnetic field can be seen below in the sequence in which a CME shock wave (yellow) hits earth's magnetic field and is directed around our planet. The compression of the field affects the Van Allen radiation belts and the ionosphere; during CME impacts, electrons are driven downward towards the atmosphere. However, the real essence of the geomagnetic storms can be found at the poles.



Earth's magnetic field comes out of the earth at the polar region, between where the fields bow forward towards the sun, and are blown towards the night side by the solar wind. An entry point exists where IMF plasma can enter the earth system. During CME and coronal hole stream impacts, charged particles enter these areas. The magnetic field of earth also helps to guide the impacting particles around to the polar regions, adding to the impact that already affects that area. On days when the auroras are exceptional, it is almost certain that a CME or coronal hole stream has impacted our magnetic field, and caused a geomagnetic storm which has allowed solar plasma to enter the auroral electrojet.



The aurora are not randomly situated at the polar regions. It is no coincidence that only during the strongest geomagnetic storms do the aurora spread to lower latitudes. A ring of energy called the auroral electrojet exists at both poles. A third one, called the equatorial electrojet, sits above the tropical regions, but does not often present itself visually.

Space weather impacts cause enhancement and strengthening of these electrojets, which help drive the aurora and can actually induce ground currents that have blown transformers, set electrical fires, and caused groundings of air travel and various disruptions of power, transportation and communications. Notable geomagnetic storms in history include the Carrington Event, a major storm in 1859 that set fire to telegraph wires and shocked operators. In 1921, a significant geomagnetic storm knocked out the New York railroad system. In 2015 three separate geomagnetic storms caused groundings of air travel in New Zealand (June), the eastern United States (September), and Sweden (November). In early 2016, the BART system in San Francisco encountered two mysterious power surges during a geomagnetic storm caused by a coronal hole stream, resulting in major failures.

There are no absolute rules when it comes to CMEs and coronal hole streams; each is different and somewhat unpredictable beyond its general speed and density.

1.9 Cosmic Rays

Earth's magnetic field protects the earth from more than just the sun's rays and solar wind; it protects against X-rays, Gamma rays and interstellar particles. We generally lump all the non solar space dangers such as those into the category of cosmic rays or Galactic Cosmic Rays (GCR). However, the earth has two shields against cosmic rays: our planet's own magnetic field, and the sun's magnetic field. The electric field and IMF streaming throughout the solar system protect the planets just as earth's magnetic field bubble protects us. The dangerous particles and energy are either charged (+ or -) or electromagnetic energy, so the electric field of solar wind acts like a shield against the rest of the galaxy and the universe.

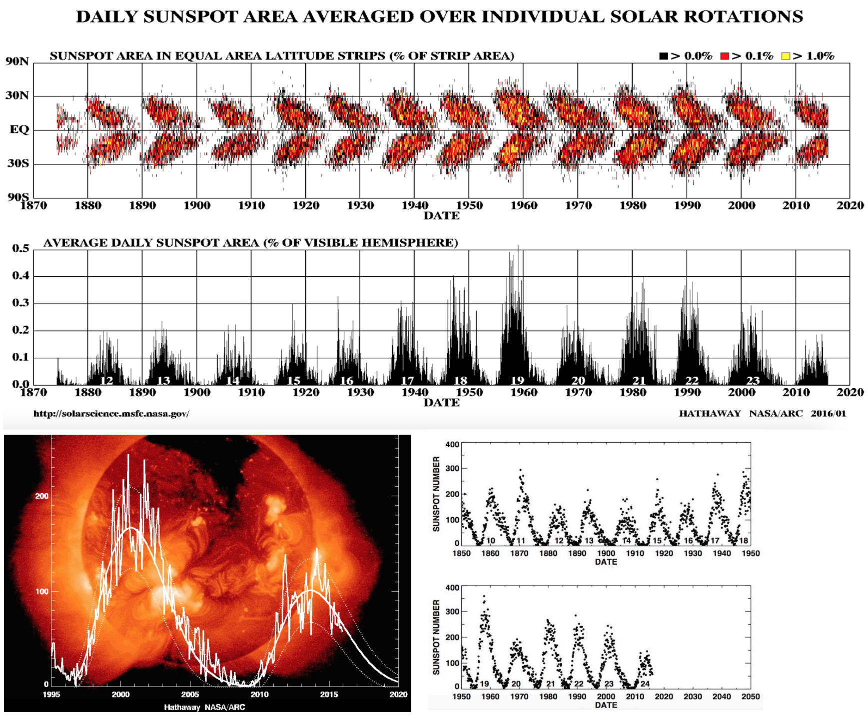
During times when solar activity (sunspots, solar flares, CMEs, and geomagnetic storms) is high, cosmic rays are low, and during periods of a quiet sun, we see far more cosmic rays. This inverse relationship is entirely based on the premise with which we began; the important aspects of space weather are about how the sun's activity affects the solar wind. High solar activity enhances the solar wind, and therefore, one shield against cosmic rays.

A specific event known as a Forbush Decrease describes the sudden drop is cosmic rays just before and during impact from CMEs. In the same way that the electric field of solar wind acts like an electromagnetic shield against the outside, when intensified solar wind streams such as CMEs hit earth, those streams help to block cosmic rays at the same time.

2.0 Solar Cycles

2.1 The 11-Year Cycle

The most well-known and fundamental solar cycle is ~11 years long. It can actually range between 9 and 13 years, and is often called the sunspot cycle. There is a predictable rise and fall to sunspot activity, and therefore, a predictable rise or fall to solar flaring, CME, SEP, geomagnetic storms and cosmic ray activity.

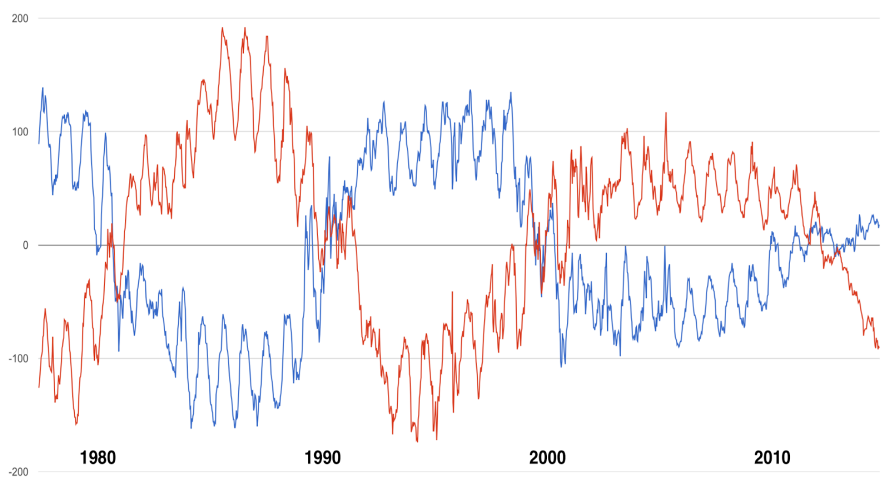


These images come from NASA's Marshall Space Flight Center and David Hathaway. You can see how the cycles are not always the same size, but they are approximately the same duration and distance apart. The 'butterfly diagram' in the top image shows where the sunspots appeared over time; they trend towards the equator over the cycle and then get back in line at higher latitudes for the next one.

The sunspot cycle is called that because for centuries, the sunspot has been the central focus of space weather. However, we now have much more information about things such as coronal holes and plasma filaments. As we will see in this book, cosmic rays are also very important for understanding the earth system, and they have an inverse relationship with sunspots.

Go back and look at the images from the previous page and imagine them with a similar sine-wave (up and down curve) for cosmic rays except that it peaks when sunspots are fewer and it drops lower when sunspots are more numerous. The more we learn about space weather, the more important cosmic rays seem to be and the more sunspots have to compete with on the other side of the table. So, are sunspots the best way to judge this ~11-year cycle?

There is another feature on the sun that also follows this ~11-year cycle. This feature determines when one sunspot cycle begins and when it ends. It determines how many sunspots there are and how active they are, where the coronal holes and plasma filaments are found, and the character of the solar wind current sheet and IMF, etc. The polar magnetic fields of the sun are actually the driving force behind many of the solar phenomena that we, as a species, are beginning to track. Below you see the solar polar magnetic field data:

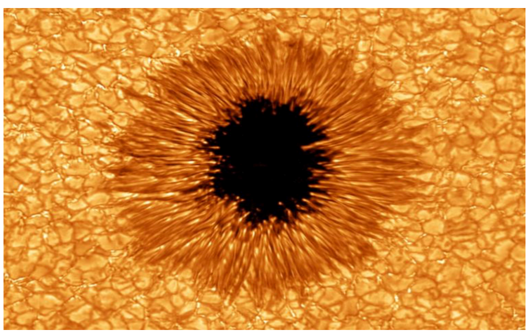


Comparing this image to the ones at the beginning of the chapter, we notice a similar duration matching the cycle length, but with peaks in magnetism (positive or negative) during times when sunspots were low (and cosmic rays were high). When the polar magnetic fields of the sun reverse and are weak, the sunspots are high (and cosmic rays are low). Blue is the northern fields and red is the south.

2.2 Other Solar Cycles

The ~11-year cycle involving the polar fields, sunspots, solar flares, etc. is the most recognizable large-scale cycle of the sun, although there are various other cycles on both large and small temporal scales. There appear to be solar cycles as long as 1000+ years, but for this introductory book we will be focusing on shorter timescales.

There are a number of oscillations and cycles on our star that are important for gauging climate events on earth, and many that are not. In and above sunspots such as the one in this image, we see oscillations of 1 to 2 minutes, 3 minutes, and 5 minutes. The 1-to-2-minute oscillations were imperceptible before the launch of the IRIS satellite, which allowed us to see images of the sun every few seconds.



Numerous periodicities, ranging from several minutes to a few months to a few years, have been proposed, but also disputed, and none has been proven to be as robust as the ~11-year oscillation. Additionally, these periodicities are not easily discernable in climate data and are only really relevant for space weather forecasting and analysis.

Solar cycles longer than the ~11-year cycle are often far more noticeable in climate data, and numerous such cycles have been identified and proposed for further investigation. Here are some interesting cycles that are good to know, or will be important later in this book:

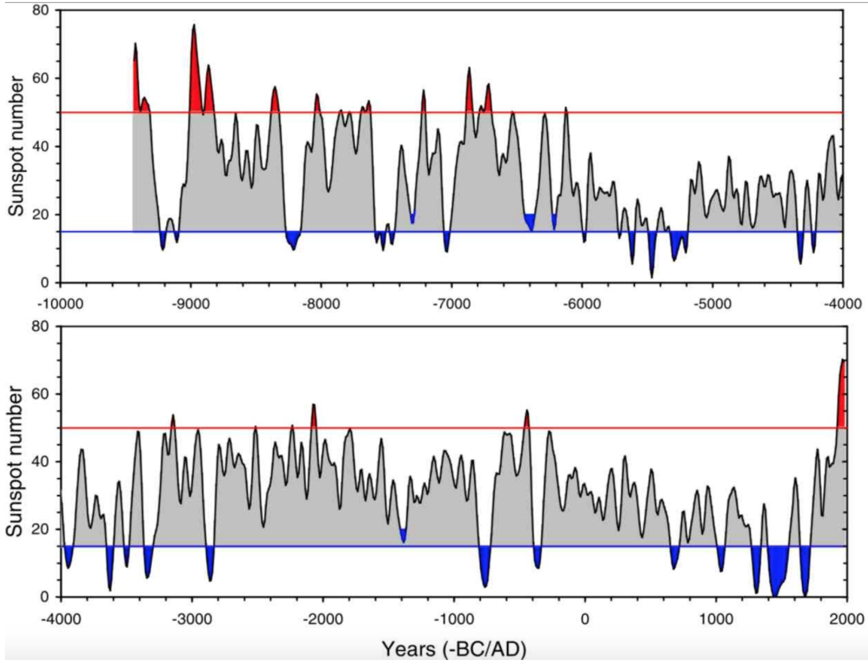
~28 Days: The length of one solar day (1 solar rotation). The polar regions turn a little slower (~30 days), and the equator can spin around in as fast as 26 days.

~22 Years (Hale Cycle): As the sun's polar magnetic fields reverse every ~11 years, a full magnetic cycle is two ~11-year cycles. Numerous other patterns have been discovered, such as the 'even-odd' rule where, for unknown reasons, an odd-numbered solar cycle is usually stronger than the even-numbered cycle that came before it.

~44 Years: A little-known likely-harmonic of the 11/22 year cycles can be seen in a hemispheric asymmetry on the sun, whereby every four ~11-year cycles, the opposite hemisphere of the sun gets active first during the solar cycle. It is rare that north and south are in sync in their rise and fall in activity over the ~11-year cycle (hemispheric asymmetry), and this lag of one hemisphere tends to persist for four sunspot cycles, or two Hale cycles of the sun. (Murakozy 2016; Abbott 1937).

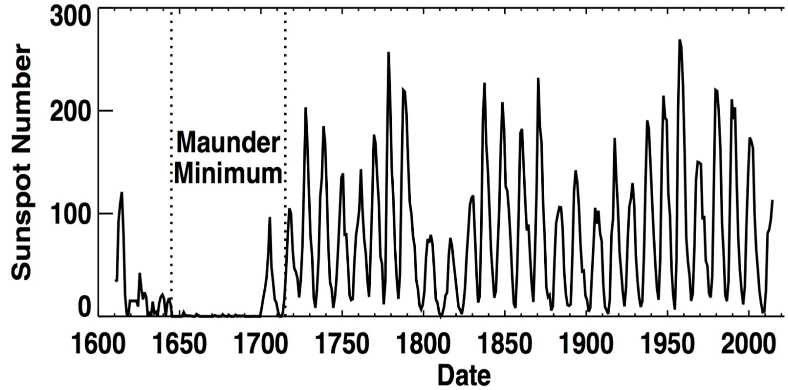
~80 - 88 Years: A well-known oscillation of solar activity over 80 years is known to occur. Often called the Gleissberg cycle, this is probably another harmonic of the sunspots/polar field cycles, with the variability due to the variability in the ~11 year cycle itself. This cycle is easily seen in radiocarbon data, with some evidence in the geomagnetic data and auroral records.

~200 Years: A much debated and often-differently-named cycle has been shown in radiocarbon and geomagnetic data, but is not easily noticeable over long-term sunspot reconstructions. A harmonic of this cycle can easily be seen in long-term sunspot data, however.



~400 - 440 Years (Grand Solar Cycle): Long-term reconstructions of sunspot data, over hundreds to thousands of years, look very similar to shorter-term data. This image is one such reconstruction from Ilya Usoskin, and it demonstrates how these peaks and troughs occur at quasi-regular intervals, even if their amplitude varies a great deal. We saw that exact same pattern in sunspot numbers over the ~11-year cycle, in which regular cycles acted differently apart from their duration (wavelength).

The image on the next page is the current Grand Solar Cycle - from the last grand minimum (Maunder minimum) to the grand maximum just after 1950. Many forecasters, including this author, see every sign that the sun is heading for another grand minimum this century and the start of another cycle. Of note: The current grand maximum is the highest solar activity since the last glacial period. The closest thing to another glacial period, the so-called little ice age, happened during the ultra-low activity seen just before this grand maximum and ended as the Maunder minimum did.



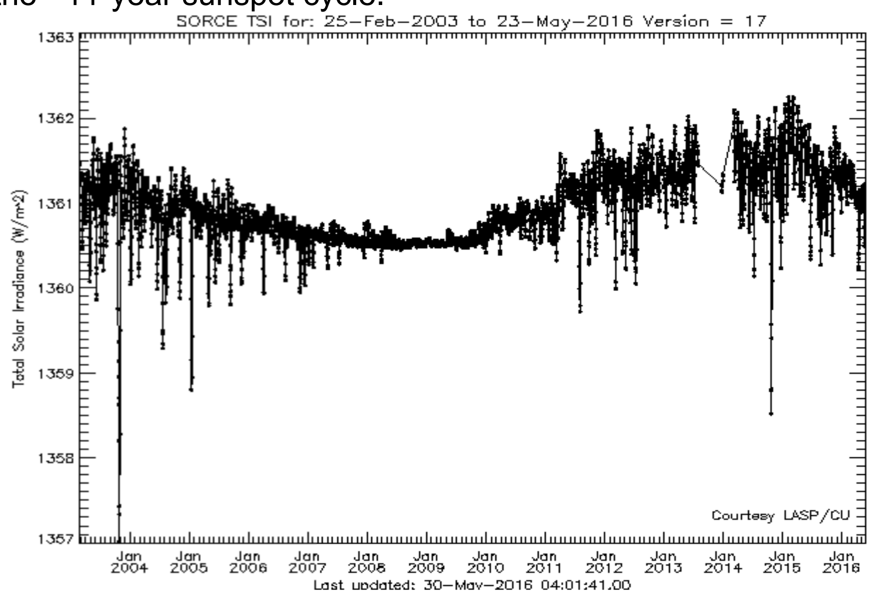
300
200
100
0
Sunspot Number
Maunder
Minimum
1600
1650
1700
1750
1800
1850
1900
1950
2000
Date

3.0 Introduction to Solar (Space Weather) Forcing

3.1 The Historical Dominance of the Total Solar Irradiance (TSI) Model

Until the last decade, very few studies of solar forcing on earth's climate looked at anything other than sunspots or total solar irradiance (TSI). There has been a prevailing (and likely false) theory that the sun is relatively constant in its output and that its effect on the climate is minimal over decades in comparison with anthropogenic forcing.

Images such as this one are emblematic of the history of solar forcing. We have data and reconstructions going back centuries but this short window provided by the Laboratory for Atmospheric and Space Physics essentially shows what the entire timeline shows: TSI varies by approximately 0.1% over the ~11-year sunspot cycle.



As this 0.1% variability perfectly matches the sunspot variability, it has been considered that while the activity on the surface of the sun can vary greatly over a few years' time, the practical effect of this ~11 year fluctuation is imperceptible and negligible in terms of its effects on the global climate system. This notion has been so pervasive that the global climate leader, the International Panel on Climate Change (IPCC), has often restricted the reporting and included-studies to those which quantify and promote anthropogenic forcing sources. It was completely outside the scope of its mandate to include anything other than human pollution, deforestation, urban development effects, and other manifestations of human activity.

3.2 The Fall of the Solar Constant

There is little debate that pollution of various forms, including carbon-based pollution, affects the environment chemistry and system dynamics, including the climate. However, a simple problem has come about in climate science that requires a significant reassessment in the fields of climatology, meteorology, and solar-terrestrial physics.

In 2013, it began to become clear to the world that we were approaching 20 years of vastly overestimated global-warming predictions. This was especially confusing because many of the drought, flood, and other extreme events seemed to be occurring as predicted, and the global greenhouse gas levels grew more than ever. During this time, we have seen higher CO2 rates and faster rates of greenhouse-gas emission (driven mostly by countries in Asia) than ever before, and yet a well-documented “global warming pause” occurred, with the 2015/2016 El Niño (the most intense on record) finally driving temperatures further upward. Recently, the head of the IPCC, Dr. Pachauri, stepped down amidst controversy over a number of issues, including failed temperature forecasts; even the record warmth of 2015/2016 was well below what had been predicted based on carbon emissions alone, and it took the most severe El Niño in history to do so.

While every model and explanation of human effect on global warming dictated that we should have seen a vast spike in global temperatures the last two decades, we saw a definitive plateau at the turn of the millennium, with record cold and snow events persisting and even intensifying across the northern hemisphere before the record El Niño of 2015. While a few commenters have disputed the validity of the most-accepted temperature records, there is no doubt that the official predictions of record have been able to predict the extremes of climate change with the exception of perhaps the most important piece: global warming. The image below is from one of the earliest IPCC reports, and its paradigm prevailed through the 2012 report. The IPCC is not looking at anything other than human activities.

> Fluctuations of climate occur on many scales as a result of natural processes; this is often referred to as natural **climate variability**. The **climate change** which we are addressing in this report is that which may occur over the next century as a result of human activities. More complete definitions of these terms can be found in WMO (1979) and WMO (1984).

The climate of earth has never been stable. Much of the earth's reconstructed history indicates that the earth is not usually as benign to life as it has been since the 1700s. Between periodic ice ages, vastly hotter temperatures during the times of the dinosaurs, and even the stories of our ancestors, it is likely that our planet is ever-changing and capable of throwing climate curveballs that simply have not occurred during the time of science.

Apart from the obvious heating of the earth provided by the sun's rays, little credit has been given to space weather effects apart from TSI, which itself has very little variability. **Here is the problem:** Take something like a solar flare, which can increase X-ray and EUV output by factors of 10 to 1000, and which rarely lasts longer than a few hours; solar flares do not increase the Watt energy delivered to earth over time in any meaningful way. However, as we will see in this book, such increases in flare energy, along with SEPs, CME impacts, and other space weather events, reach thresholds of forcing that are simply not seen without those events, which do not show up in long-term TSI data, and which are not seen in 11-year, 22-year or longer sunspot cycle data.

Certain space weather events are not variable in terms of percentages. They are a simple yes or no, on or off, El Niño or La Niña, positive or negative phase of a major atmospheric oscillation. When these events are triggered, the use of TSI is no longer relevant for that time period.

Consider the example of raw chicken: How dangerous is raw chicken at room temperature vs 99 degrees F? 150 degrees? The answer is about the same because at 150 degrees, the harmful bacteria in the chicken will still be alive, and you run the risk of food poisoning. However, something happens at ~165 degrees F: all the bacteria die. Once you hit a threshold event, the situation changes completely, and gauging the effect of temperature on the safety of that piece of chicken is suddenly relevant although it was not relevant before. Right now, the scientific community has been unable to understand fully the threshold events in space weather, instead being fooled by the same flaw in the initial chicken example in which one might look at the two temperatures and determine that temperature was not a factor in safety of eating chicken. Without the full set of facts, one cannot reach a reliable conclusion, and in this example, as with the climate, you don't need to be at 165 degrees (significant space weather activity) for very long in order to see a lasting effect that completely changes the chicken (climate).

The studies on space weather forcing on weather and climate are numerous; more than 300 papers and other published works on the topic have been released since 2010. This book will examine many of those works to construct the framework of the future of many fields of science. Everything from climate predictions to your local forecaster missing the mark, to unexplained power surges outside thunderstorm/peak power usage times is poised to get a boost in understanding from the volume of work that the world is still trying to process.

PART 2

The Sun and The Earth

4.0 Cycle and Pattern Modulation

Now that we have reviewed some space weather basics, the history of our understanding of solar forcing on the climate, as well as the status and possible missing pieces of failed climate forecasting, we can begin to take a look at some of the studies that will be used as the foundation for driving this field of science forward. The first chapter in Part 2 of this book will look at some of the patterns and oscillations of earth's weather and climate, plus how they are modulated by space weather events and cycles.

A complete historically-contextual review of the entire sun-earth relationship would contain thousands to tens of thousands of references, with paragraphs to pages of citations per point in some cases. Instead, we will focus on many of the latest works, as they paint a clear picture of space weather effects on the weather and climate, and the direction of the field. This is will allow for a complete survey of the latest perspectives within the field, without the burden of its overwhelming totality.

4.1 Major Oscillations and Circulation

ENSO, AMO, PDO, NAO, QBO, SAM -- each is an acronym or initialization for a major atmospheric or oceanic oscillation of earth. In this first section of chapter 4 we will describe which oscillations and other atmospheric dynamics are likely to be affected by the sun and space weather.

4.1.1 El Niño/La Niña (ENSO)

The most well-known of the climate oscillations is the shifting between El Niño and La Niña conditions, which is known as the ENSO cycle. El Niño/La Niña refers to the warming or cooling cycle of the tropical east Pacific Ocean sea surface temperatures. The extremes of the cycle, the strongest El Niños and La Niñas, increase extreme weather events worldwide, such as droughts, floods, and winter storms. These events affect temperatures and precipitation across much of the world. El Niño conditions result in the largest spikes in global temperature, as occurred in 1998 and 2015/2016.

El Niño is usually seen along with high pressure in the tropical west Pacific, while La Niña comes with lower pressure. The changes in pressure are known to be part of the Walker circulation, and it is commonly believed that these atmospheric dynamics significantly modulate the strength of the ENSO cycle itself. It has been suggested that the sun and solar activities help modulate the ENSO cycle (Hassan 2016; Rädel et al. 2016; Zhou 2013; Kirov and Georgieva 2002), and it is likely that the mechanism at work involves modulation of atmospheric dynamics of pressure, jets, and circulation.

4.1.2 Atmospheric Pressure, Jets, & Circulation

Over very short timescales, solar activity and cosmic rays have demonstrated harmony with pressure fluctuations (Artamonova and Veretenenko 2014; Bogdanov 2014) whereby an increase in surface pressure is seen three to five days after the occurrence of a Forbush Decrease. Solar flare-heating tends to have more atmospheric transmittance of energy at lower latitudes, while cosmic ray modulation/CME impacts and the resulting geomagnetic activity appears to have a stronger effect at higher latitudes, especially on the Icelandic low (Georgieva et al. 2007; Zaitseva et al. 2003). Various Arctic and Antarctic sites have shown surface pressure dependence on the IMF (Burns et al. 2007).

Over very long timescales, there is evidence of millennial-scale solar activity minima driving cooler temperatures over the northern continents via a southward shift in the intertropical convergence zone (ITCZ) (Moreira-Turcq 2014), which allowed polar air to migrate southward and would have been accompanied by warming in the polar region and some equatorial confinement of tropical storm systems. Over long periods, this may help explain the activity of long-term monsoon variability.

The primary action on pressure and circulation is hypothesized to be on atmospheric centers of action (Zhou

2013) and tropical circulations such as the Walker, Atlantic meridional overturning circulation and others (Moffa-Sánchez et al. 2014; Roy 2013; Gray et al. 2013; Haigh and Blackburn 2006; Kodera and Kuroda 2002; Kirov and Georgieva 2002 and numerous others). For example, in the northern hemisphere, the Siberian high, Aleutian low, Icelandic low, etc., change in intensity and location based on large-scale oscillations that are modulated by space weather (more on these oscillations will follow in this chapter). Zhou 2013 also indicated that the aspects of the ENSO cycle that drive the East Asian climate show stronger winter variability during low solar activity.

Solar minima have a particularly strong forcing on the Aleutian low, pushing it eastward, with a weaker polar vortex, causing more extreme winter storms and an acceleration of the Brewer-Dobson circulation, along with increased chances for anomalous lower stratospheric circulation (Hood and Soukharev 2011). In addition to an eastward shift, solar minima have also been suggested to suppress the Aleutian low and enhance the Northern Pacific highs (Patterson et al. 2013). Kodera and Kuroda 2002 found similar results in a weakening of the Brewer-Dobson circulation during solar maximum, with lower chances for extreme winter events.

Other studies have also suggested that solar minima result in worse winter polar vortex events, or that solar maxima strengthen and tighten those vortices up to the poles, reducing those extreme cold events (Veretenenko and Ogurtsov 2014; Lu et al. 2008, Claud et al. 2008). Strong solar activity can actually disrupt the vortex structure ahead of annual/seasonal schedules via sudden stratospheric warmings (Li and Tung 2014), leading to a less intense end to winter.

Most recently, during the prolonged and extremely low minimum of 2007 - 2010, polar vortex events on a 2 - 5 year lag brought severe winter storms across various parts of the Northern Hemisphere from 2009 to 2013, including stretches during which cold records were outpacing heat records for weeks or months in some cases.

Disruptions to subtropical jets and to the mean meridional circulation in the troposphere (Haigh and Blackburn 2006), changes in sea-level pressure (Gray et al. 2016; Gray et al. 2010), and large-scale effects on circulation and/or regional atmospheric dynamics (Zhou et al. 2014; Adolphi et al. 2014; Veretenenko and Ogurtsov 2012; Woollings et al. 2010; Tinsley et al. 2007; Tinsley 2000 and numerous others) have been suggested to be related to solar activity over days to weeks, often on longer timescales as well.

The subtropical jet shows a 10m/s difference between solar maximum (faster) and solar minimum, and the state of the sun can even affect the timing of seasonally and annually expected jet shifts (Kodera and Kuroda 2002). The strength and position shifting of the subtropical jets has alternatively been said to be driven by sea surface temperatures (Misios and Schmidt 2013), however those temperatures may themselves be modulated by solar activity (more on this in Section 4.2). Jet stream blocking appears to be strongest during solar minima (Gray et al. 2016; Adolphi et al. 2014; Moffa-Sánchez et al. 2014; among others) and can result in abnormal fluctuations of temperatures and the enhancement of vertical temperature gradients.

The positions of the jets and Hadley cells may be related to the distribution of the heating, where equatorial heating pushes them poleward while more heat distributed to the north pushes them towards the equator (Roy 2013; Haigh and Blackburn 2006). Hadley cell interaction has also been implied using sea-level pressure records compared with the 11-year solar cycle (Wang et al. 2016; Gray et al. 2013), and various north Atlantic/Europe climate parameters against cosmic rays (Wirth et al. 2013). At the polar region itself, the interplanetary electric field appears to have a direct relationship to atmospheric pressure and wind changes (Troshichev and Vovk 2004; Shirochkov and Makarova 1996) and to geopotential height anomalies (Lam et al. 2014). Geopotential height anomalies also exhibit evidence of a strong relationship with solar and geomagnetic activity (Bochníček et al. 2012, Thejll et al. 2003), and others found a ground-up mechanism whereby the lower troposphere reacts to changes in the interplanetary electric field first, followed by the mid-troposphere and the tropopause (Lam et al. 2014).

The jets, circulation systems and pressure dictate nearly everything that we experience in meteorology. The effect on these systems due to solar forcing can lead to long-term changes and have much stronger and wide-ranging effects than has been noted in reviews just a decade or two ago.

4.1.3 Significant Oscillations other than ENSO

Day-to-day oscillations in both the NAO and AO can be correlated with both solar wind speed and relativistic electron precipitation (which itself is primarily driven by changes in the solar wind and other space weather parameters that also influence solar wind speed), as well as to minima (negative phase) in the NAO and AO indices that correspond with minima of solar wind speed (Zhou et al. 2014). Stronger negative phase signals of the NAO are centered around stronger Icelandic lows and involve increased jet-stream blocking at solar minimum (Gray et al. 2016). Over longer time periods the correlations between solar activity and both NAO and ENSO have been described as a ‘close relationship’ (Kirov and Georgieva 2002) and are said to correlate with harmonics of the 11-year and 22-year solar cycles (Mazzarella and Scafetta 2011).

Periods of higher sunspot/geomagnetic activity present similar anomalies associated with the positive phase of NAO (Gimeno et al. 2003) that appear to stretch further into Eurasia than normal (Woollings et al. 2010). Short-term events such as powerful solar flares tend to create temporary (~9 days) positive forcing of the NAO phase driven by lower Icelandic low pressure and higher Azores highs (Georgieva et al. 2007).

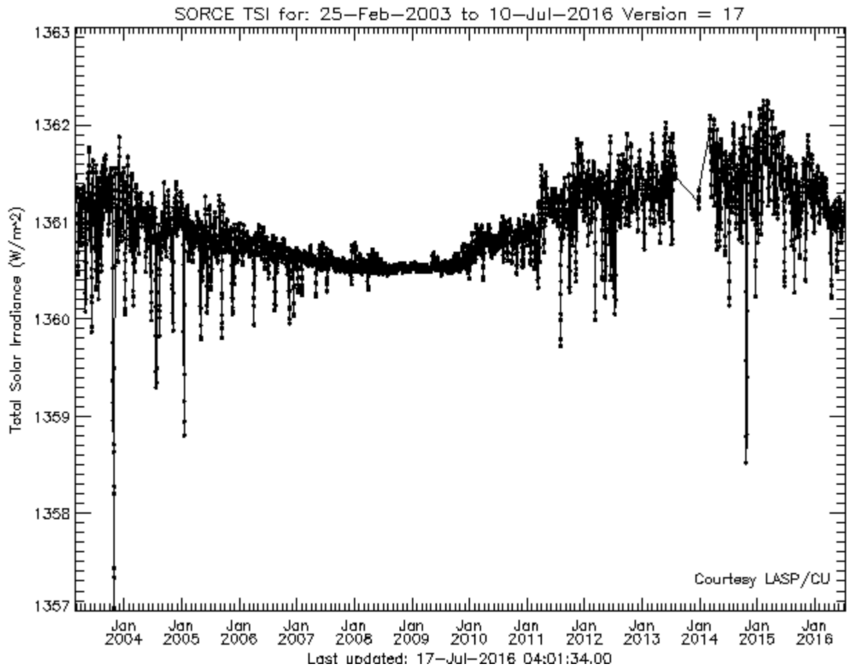
Other studies have shown similar effects: Short-term and long-term effects on the NAO index resulting from electric field changes propagated downward by impacting solar wind and solar flare heating of the stratosphere, or based on longer-term correlations with common solar indices. Positive NAO phases tend to occur more often during solar maxima, and especially during active solar/geomagnetic time periods. Despite Gimeno et al. 2003 not finding a significant negative NAO phase signal during solar minimum or quiet solar/geomagnetic conditions, much of the recent literature does (Hall et al. 2016; Thiéblemont et al. 2015; Scaife et al. 2013; Gray et al. 2013; Bochníček and Hejda 2005; Zaitseva et al. 2003; Boberg and Lundstedt 2002; among others).

The correlations between NAO and AO have been shown most strongly with the earthly effects lagging a few years behind solar effects (Scaife et al. 2013) with positive NAO phase appearing strongly a few years after solar maximum (Thiéblemont et al. 2015; Maliniemi et al. 2014; Gray et al. 2013), although it should be noted that geomagnetic peaks tend to follow the sunspot maximum by one to three years, so perhaps a more direct correlation, with less lag, could be inferred by focusing on the geomagnetic effects rather than the solar events. One study suggested that the lag for NAO correlation is much longer, on the scale of decades (Swingedouw et al. 2011).

Author's Note: The appearance of sunspots does not necessarily indicate that geoeffective space weather will occur, so monitoring the geomagnetic effects is perhaps better than monitoring sunspots. The majority of short-term effects and a significant portion of the longer-term effects noted here are the result of solar wind impacts, heliospheric/interplanetary magnetic field changes, solar flares, and GCR flux at earth.

However, in the world of weather and climate, the virtually unchanging irradiance measure and the indirect space weather observations of sunspot numbers have (1) trumped actual earthly effects of flares and intense solar wind streams, (2) led to the sun being ignored in most models, and (3) led to nearly two decades of dismal temperature predictions by the IPCC. An excellent example of when geomagnetic effects trump sunspot number is Roy et al. 2016, which demonstrated that the lagging geomagnetic peaks may actually be better measures of solar forcing on winter surface climate than sunspot numbers.

The following image shows total solar irradiance from the Laboratory for Atmospheric and Space Physics with the up/down of the ~11-year sunspot cycle:



The solar dimming that takes place during solar maxima may improperly reduce the TSI signal used in most studies. During solar maxima we see more x-ray events (which are often associated with the dimming events) and more geomagnetic disruptions, so the use of TSI may be even less indicative of solar forcing than sunspot numbers and can inversely indicate solar effects. **A chart showing the real energy exchange would have spikes upward during the high points of the cycle, instead of spikes downward.**

Some scientists have suggested that the extent of solar forcing on the NAO depends on whether the oscillation is in phase with sunspot peaks, with positive NAO anomalies stronger in phase with sunspot peaks and negative NAO anomalies when out of phase (Van Loon 2014; Van Loon and Meehl 2013); however, it could be argued that high solar activity offers regular opportunities for phase alignment, while periods of grand solar minima offer far fewer (if any) opportunities for phase alignment, so they should promulgate the negative phase of the NAO.

The most well-documented of these phenomena is the trend toward negative phase in solar minima, which has the practical effect of directly modulating the severity of winter storms due to polar vortex events. The variations in these oscillations tend to be the result of changes in pressure and other atmospheric dynamics as discussed in the previous section. In the first decade of this millennium, scientists began to argue that the mechanism at work is the result of solar activity affecting the global electric circuit (Tinsley et al. 2007; Bochníček and Hejda 2005; Tinsley 2000 among others); this mechanism will be detailed in Chapter 5.

NAM
On short timescales, Northern Annular Mode (NAM) positive phase anomalies due to high speed solar wind streams lag only slightly longer than the NAO, and are most strongly seen near the surface (Georgieva et al. 2007). Similar high solar/geomagnetic activity forcing of positive NAM anomalies were reported in Roy et al. 2016 and Ruzmaikin 2007. There is speculation that more anomalies are present with seasonal vulnerability of the NAM to both solar maximum (positive anomalies) and minimum (negative anomalies (Lu et al. 2008).

SAM
Positive Southern Annular Mode (SAM) patterns manifest more often during solar maximum (Petrick et al. 2012) and are seen more strongly in the stratosphere, while the solar minimum effect is more to the negative phase, is confined to the troposphere, and disappears much more quickly than that of solar maximum (Kuroda and Yamazaki 2010).

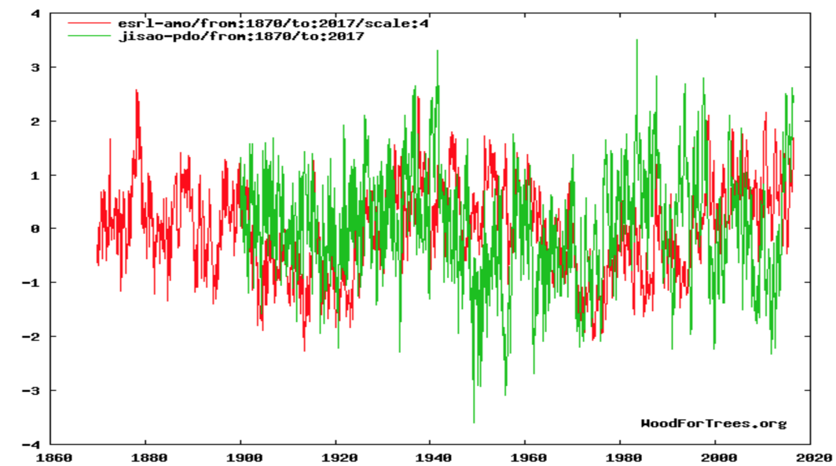
PDO and AMO
The PDO phase directly corresponds to the 11-year cycle, with strongest relationships peaking at a harmonic of the Hale cycle at 40 - 45 years and best matches the cosmic ray reconstructions. Higher solar activity leads to positive phase of the PDO, while low solar activity leads to a negative phase (Velasco and Mendoza 2008).The influence of solar forcing

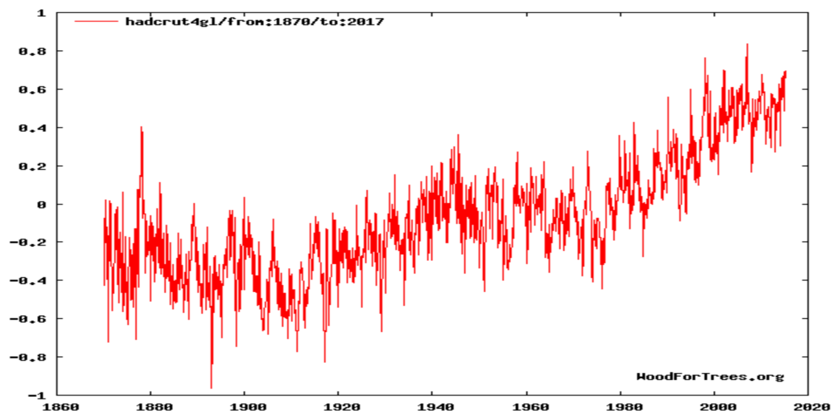
on the PDO in the Gulf of Alaska may depend on phase matching with the 11-year sunspot cycle, in which high pressure anomalies are more confined to the Gulf when in phase and can spread more to the south and west when the cycles are out of phase (van Loon and Meehl 2013).

Solar and volcanic forcing demonstrate excellent correlations with the Atlantic Multidecadal Oscillation (AMO), but those disappeared during the little ice age, when many oscillations were not as they are today. This may also be related to the ultra-low solar activity during that period (Knudsen et al. 2014). The AMO shows ~11-year cycles and harmonics of the Hale cycle, but the correlation is not consistent in its effect (Velasco and Mendoza 2008).

The PDO and the AMO are extremely important for global temperatures, so any modulating factor not currently included in their modelling will harm the accuracy of forecasting and analysis.

In the images on the next page, you see two time-locked charts; the top chart has the AMO in red and PDO in green, while the bottom chart shows global temperatures without the effect of the ENSO cycle. The longer-term peaks near 1880, 1940, and 1990/2000 occur for both positive phases and global temperatures, and similar low/negative points can be found around 1910 - 1920 and 1970 - 1980.





The Quasi-Biennial Oscillation (QBO)

The QBO presents one of the best examples of why solar activity has been overlooked. Using sunspot cycles, it is difficult to find a correlation between solar activity and high-latitude stratospheric temperatures; however, when the east vs west phase of the QBO is accounted for, there are many evident relationships in the stratosphere and the troposphere (Labitzke and Van Loon 1988). Solar maximum tends to decrease the effects of the QBO, and solar minimum enhances the signal. It has also been suggested that this phase-dependent modulation of solar forcing is confined to the northern hemisphere, whereas the solar signal is amplified by comparison in the southern troposphere (Petrick et al. 2012).

There is speculation that solar activity can actually modulate the strength of the QBO (Lu and Jarvis 2011; Gabis and Troshichev 2004), which itself has been shown to modulate or interact with most, if not all, of the atmospheric oscillations already discussed above.

4.2 Temperature and Precipitation

In addition to generally recognizing anthropogenic sources, recent studies have partially attributed changing global temperatures in recent decades and/or in the past to changes in solar and geomagnetic activity (Airapetian et al. 2016; Tiwari et al. 2016; Aslam and Badruddin 2014; Stauning 2014; Avakyan 2013; de Jager and Nieuwenhuijzen 2013; Burn and Palmer 2013; Gupta et al. 2013; Sirocko et al. 2012; Courtillot et al. 2007 among others). It is estimated that solar activity during the grand solar maximum of ~1950 - 2000 (the primary period of global warming) produced twice the number of CMEs as solar cycles just 100 years ago (Richardson et al. 2002), so much of the short-term forcing is missing from current models when the focus is placed on longer-term TSI or sunspot number.

On day - week timescales, interplanetary shockwaves and solar wind interaction regions stream past earth and appear to cause notable temperature fluctuations in the polar regions (Seppälä et al. 2009; Troshichev and Vovk 2004; Shirochkov and Makarova 1996) and help modulate global temperatures (Biktash 2014). Harrison et al. 2013 found rapid surface temperature fluctuations during a particularly turbulent solar wind event, **indicating simultaneous changes in both geospace and the lower troposphere.**

An increase in incoming space energy through the daylight hours results in ground heating and tropopause cooling, but the opposite temperature effects can occur when the interplanetary electric field decreases over the daylight hours, due to the descent of cool air masses (Troshichev and Vovk 2004). In winter, in the absence of daylight at the poles, the geomagnetic signal in the surface air temperatures is strongest and utterly evident (Seppälä et al. 2009).

There appears to be a bidecadal oscillation of global temperatures and humidity near the tropopause (Wang et al. 2016), which has been well-correlated to the solar magnetic fields' modulation of galactic cosmic rays' effect on near-tropopause ozone over the solar cycle (Kilifarska 2015). Numerous other studies have identified this general link or modulation of global temperatures by the sun, usually in concert with anthropogenic and volcanic forcing (Kodera et al. 2016; Spiegl et al. 2016; Adolphi et al. 2014; Maliniemi et al 2014; Liu et al. 2014; Chen et al. 2013; Powell Jr. and Xu 2012; Barnhart and Eichinger 2011; Miyahara et al. 2008; Claud et al. 2008 among others). The existence of a relationship appears likely, but the practical effects of that relationship are difficult to determine.

Solar maximum appears to bring warmer temperatures in the northern hemisphere (Usoskin et al. 2005; Gimeno et al. 2003), especially in the summer, when accounting for major oscillations such as the AO, ENSO, and QBO. This effect is also enhanced in the month of February, with adiabatic cooling present at higher latitudes (Claud et al. 2008). This northern hemisphere correlation also is evident on centennial timescales (Ogurtsov et al. 2015), but is seen most clearly in the declining phase of the sunspot cycle (Maliniemi et al 2014), which makes the geomagnetic activity maximum (which is 1 - 3 years after sunspot maximum) the best indicator, with a smaller potential lag. Solar minimum can also bring warmer temperatures, specifically to northwestern North America, with drier conditions in the Pacific Northwest, the Canadian prairies, and the Ohio-Tennessee-lower Mississippi River Valley (Liu et al. 2014).

When the jet stream blocking increases during solar minimum, the temperature effects on Europe can be 'particularly acute' and are unlikely to be the result of the oceanic forcing described by Misios, but of strong temperature gradients resulting from space weather-driven changes in pressure (Gray et al. 2016, Hall et al. 2016). Similar blocking during the minima also increases snowfall over Greenland (Adolphi et al. 2014). Geomagnetic activity, solar flares, solar wind, and open solar radio flux records indicate that Eurasian winter temperatures present strong correlations with solar activity (van Loon 2014; Gray et al 2013; Lockwood et al. 2011; Lockwood et al. 2010; Woollings et al. 2010) and that **severe cold events plague the northern hemisphere more-often during solar minima** (Spiegl et al. 2016; Adolphi et al. 2014, Sirocko et al. 2012), often the result of jet-stream blocking (Moffa-Sánchez et al. 2014) and polar vortex events, rather than changes in total solar irradiance and albedo.

Both temperatures and precipitation in Serbia show evidence of modulation by the solar wind streams from coronal holes (Todorović and Vujović 2014). Century-scale temperature variations in Fennoscandia have been correlated with both sunspot numbers and cosmogenic isotopes, according to the Gleissberg cycle (Ogurtsov et al. 2013). Numerous other studies have examined this relationship in Europe, and it appears that the most commonly hypothesized mechanisms for this effect in Europe involve (1) cloud cover modulation due to cosmic rays (Chapter 5), (2) the aforementioned disruptions and effects on tropospheric jets and the polar vortex cold events (Lockwood et al. 2010) and (3) the effect of low solar activity on the NAO, which brings colder events during negative phase.

Two thousand years of Chinese temperature records indicate significant harmony with known solar cycles and periodicities (Tiwari et al. 2016). Temperatures on the Tibetan Plateau show 11-, 54-, and 204-year periodicities, which correlate with known solar variability cycles (Duan and Zhang 2014). Temperatures in India also show strong correlations with solar activity (Aslam and Badruddin 2014, Maitra et al. 2014).

In the tropics, solar maximum appears to present strong cyclical forcing on lower tropospheric temperatures lagged about one week behind the UV peak (Hood 2016). Powell Jr. and Xu (2012) found significant solar cycle forcing on the polar surface temperatures in winter. They also determined that the central and western Pacific air surface temperatures were only correlated with solar activity in summer. Over the water, solar effects on atmospheric circulation drive surface air temperatures via controlling the position of deep convection and heat release, or Outgoing Longwave Radiation, from the surface (Xiao et al. 2016).

Some of the mechanisms by which solar activity may influence sea-surface temperatures (SST) are: through the reinforcement of the wintertime NAO cycle (Gray et al. 2016), changes in atmospheric circulation and modulation of the Atlantic meridional overturning circulation (Moffa-Sánchez et al. 2014), Atlantic Multidecadal Oscillation (Knudsen et al. 2014), and modulation of surface air temperatures above the water (Xiao et al. 2016).

Evidence exists of SST correlation with solar wind events and resulting geomagnetic activity (Zhou et al. 2016 [1]; Seppälä et al. 2009), sunspot number (Wörmer et al. 2014; Roy and Haigh 2010), solar radio flux (Xiao et al. 2016), cosmic ray reconstructions from ice-core data (Wurtzel et al. 2013), tree ring data (Wu et al. 2012), and total solar irradiance (Knudsen et al. 2014; Hood and Soukharev 2011). Cycles of ocean temperature have been linked with known cycles of solar modulation in the Pacific (Douglass and Knox 2015 [1]) and global (Douglass and Knox 2015 [2]) data sets, and with solar activity modulation of circulation coupling with the subtropical ocean gyre in the Pacific (Liang and Wu 2013). While scientists are still wrapping their heads around the implications of all the periodicities and elements of forcing, the existence of SST modulation via space weather has strong evidence.

Precipitation

In the southwest United States, high solar activity appears to force lower precipitation, and low solar activity brings more precipitation (Asmerom et al. 2007), but the reverse is true of the northwest states (Lui et al. 2014). The idea of a solar cycle influence over drought areas in the western United States is not a new one (Cook et al. 1997). Solar minima appear to force droughts in the central-eastern United States (Springer et al. 2008).

Rainfall in Brazil shows short-term correlations with space weather events, along with 22- to 24-year periodicities that match the solar magnetic reversal cycle period (Almeida et al. 2004, Gusev et al. 2004). This author believes that much of the effects on Brazilian rainfall are driven by modulation of galactic cosmic rays (Chapter 5) because the South Atlantic Anomaly (the weakest part of earth's magnetic field) straddles the rainforest and the Atlantic. Further to the south in Argentina, northern regional rainfall was found to be positively correlated with both sunspot number and geomagnetic activity (Heredia and Elias 2013), but that result failed to present in a subsequent analysis (Heredia and Elias 2016). Extended droughts appear in the Jamaican records during the little ice age, which was also the last solar grand minimum; a southward push of the Hadley cell is likely responsible (Burn and Palmer 2013).

The region of the Alps is prone to greater and more numerous flood events during solar minimum due to the effect on Hadley cells and a more southerly position of the North Atlantic circulation (Wirth et al. 2013). The studies that have discussed harsh European winters (previous sub-section) during solar minima included the increased snowfall that plagues the region during such solar minima, which can lead to melt-driven flooding across the Alps.

Sediment analysis in northern China indicates that centennial monsoon oscillations could be linked with solar activity (Chu et al. 2014), and in greater Eastern Asia, we see solar maximum push the monsoon flow northward and create more variability from year to year than occurs during solar minimum (Zhao and Wang 2014). Geomagnetic maximum (the declining phase of the sunspot cycle) appears to correlate well with extreme flooding and course-shift events of the Yellow River (Wang and Su 2013).

Australia and Indonesia's monsoon seasonal variability appears to be driven by solar activity (Heredia and Elias 2016). More specifically, it was found that grand minima drive more extreme rainfall across the entire region (Steinke et al. 2014).

Using both global data sets and ground-based observations in India, a relationship to the tropical easterly jet was found, whereby solar maximum increased wind speeds and solar minimum decreased wind speed, and a relationship was found to the Indian monsoon rainfall totals on a delay of approximately 13 years (Ratnam et al. 2014). Others have found similar correlations (Hiremath et al. 2015), but the effects of the solar activity/GCR is of some dispute. Specifically, low solar activity (higher GCR) may enhance the monsoon, while high solar activity (lower GCR) may decrease precipitation overall (Badruddin and Aslam 2015). However, Chaudhuri et al. (2015) found a chance for lower rainfall during higher GCR flux. Maitra et al. (2014) may resolve this issue in finding both positive and negative correlations that have oscillatory behavior over time, but nevertheless confirm finding the existence of a relationship. Van Loon and Meehl (2012) found a positive enhancement of the monsoon with sunspot peaks, but more so near the coastlines than farther inland. Xu et al. (2015) found a correlation between solar activity and the millennial abrupt monsoon failures in India. Author's note: There are numerous reports of mega-drought and famine during world-wide the last solar grand minimum, including million-death famines in India, Africa, Eastern Asia, and Europe.

Many of the changes in temperature and precipitation are likely to be the result of shifting atmospheric jets and other pressure and circulation effects previously discussed. There are no general rules for the globe when it comes to a specific space weather event; some areas will be hotter, others cooler, while some areas see more rainfall, others less.

The existence of the correlation across the globe, despite the often polar opposite effects, is evidence of short-term forcing in the atmosphere, rather than a long-term input of heat energy to the ground. It is clear, however, that while there is not simply a globally applicable rule for surface temperature and rainfall for any given space weather event, there is little about the weather that is insulated against the effects of energy from space. It is likely that the side of earth facing the sun during solar flares or impact from solar wind streams plays some role in the modulation of the effects discussed here, and not one study has taken the timing of impact, and the sun-facing portion of earth at that time, into account.

5 It’s Electric

5.1 Coupling

It has been known for more than 30 years that solar UV affects the lower stratosphere, but the strength of its coupling effects with the troposphere below were uncertain (Donnelly and Heath 1985). Numerous studies have now strengthened the case for strong dynamical coupling resulting when space weather effects the stratosphere (Harrison et al. 2013, Solanki et al. 2013, Troshichev 2008 among others). One researcher, Dr. Sergey Pulinets, of the Space Research Institute in Moscow, has published numerous papers and a comprehensive book on the proof and mechanisms of the electric action of earth, and the relationship between areas deep beneath our feet and the very top of the sky, which is most-affected by the sun. For those interested in the foundation built by Dr. Pulinets, which paved the way for the following revelations, please see his research website: Researchgate.net/profile/Sergey_Pulinets

5.2 GCR, SEP, Relativistic Electrons & Clouds

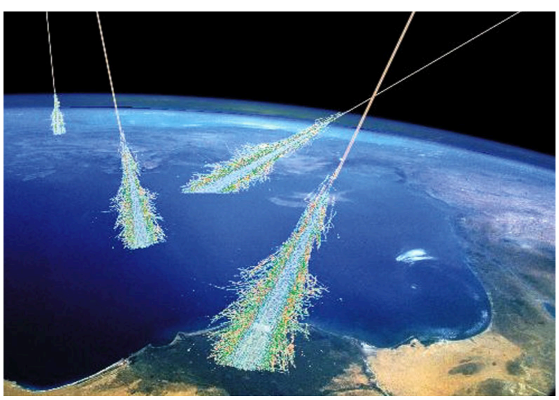
This section focuses on a significant scientific debate about whether GCRs, SEPs, and relativistic electrons from the magnetosphere can affect cloud cover.

Studies have disagreed on a number of items in this field for nearly three decades: It has been unclear whether the GCR modulation of the lower-altitude clouds is significant (Vieira and da Silva 2006; Tanaka 2005) or not (Rawal et al. 2013). Some studies found a small correlation at low altitudes (Brown 2008), but not so much in the total cloud cover (Erlykin and Wolfendale 2011), a 20 - 30% correlation in low/mid-altitude clouds (Erlykin et al. 2010 [1]), and uneven or anti-phase forcing of high vs low clouds (Erlykin et al. 2010 [2]).

Krissansen-Totten and Davies (2013) failed to find any correlation using the MISR data from the Terra Satellite. Similarly, Calogovic et al. (2010) failed to find a cloud signature related to GCR in the ISCCP D1 cloud-cover data.

Sun and Bradley (2002) found no correlation whatsoever when analyzing 1983 - 1993 using ICSSP data. One study found an immediate decrease in global liquid water cloud fraction upon Forbush Decrease but failed to find it significant (Laken et al. 2009). Kancírová and Kudela (2014) found a correlation over longer periods, but when averaging over one-year timescales (which is between the days - weeks scale of short-term space weather effects and the ~11-year scale of GCR modulation), they found no correlation. Several significant, but weak, correlations were discovered in mid- to high-altitude cloud cover by Rohs et al. 2010. Many of the discrepancies are claimed to be the result of looking at Forbush Decreases as a reduction of GCRs (fewer clouds) rather than an introduction of SEPs and relativistic electrons (more clouds) from the space weather that caused the Forbush Decrease. In addition to particle introduction to the GEC, large-scale atmospheric dynamics are involved in the general cloud processes (Troshichev 2008).

Recently, in accounting for the confusion between GCR decrease and SEP/electron increase and in reconciling conflicting past findings, the scales have been tipping in favor of a correlation, with numerous studies corroborating past evidence of these correlations between space weather and cloud cover (Artamonov et al. 2016; Didebulidze and Todua 2016; Lam and Tinsley 2016; Lam and Tinsley 2015; Avakyan et al. 2014; Maitra et al. 2014; Yu and Luo 2014; Voiculescu et al. 2013; Patterson et al. 2013; Harrison et al. 2013; Troshichev 2008; Tinsley et al. 2007; Shea and Smart 2004 among others).



The image to the left comes from NASA.gov by Simon Swordy, and it depicts how cosmic rays penetrate with expansive effect as they travel to the ground, ionizing the air and creating cloud condensation nuclei.

Author's Note: A source of error exists apart from the confusion between GCR decrease/SEP increase upon short-term space weather impacts. It is probable that some of the no-correlation findings indicate that the data set, method, or model used was not fruitful, rather than that such a correlation might not be found by other means. You might think of this as a group of people searching for one object; only a tiny fraction of the available pathways will lead to finding the object, or in this case, the truth about the correlation, while the majority of individuals will fail to find the object. Until the object was found, none of the individuals could even be certain that the object that they sought even existed.

~

The energetic particles introduced and forced or forcing their way through the atmosphere appear to be excellent controlling drivers of condensation and ice nucleation in clouds (Yu and Luo 2014). In some circumstances, these particles may be dominant over more well-known nucleation processes. Increases in energy from space results in ionization of ambient air (Artamonov et al. 2016), cloud modulation and invigorated storms (Zhou et al. 2014; Tinsley et al. 2007; Tinsley 2000), and consequently, an increased risk of major hail events. The mechanism was similarly described as redistribution of condensation nuclei in the lower-troposphere by the vertical electric component of the GEC (Zherebtsov et al. 2005).

While neither a unified set of terms nor a generally accepted model exists, the conclusions of these studies are essentially the same: Over both short and long timescales, space weather modulates both the ionization conditions of ambient air and the vertical current density that affects storms and cloud cover. In the short term, SEPs and relativistic electrons precipitating during geomagnetic disruptions enhance the GEC, and over longer time periods, the solar modulation (anticorrelation) of GCRs determines the ambient conditions outside geoeffective space weather events. The mechanisms of cloud forcing implied by the available literature indicate that lightning rates should increase alongside the introduction of

GCRs, SEPs, and relativistic electrons- more lightning in general during solar minimum, but with strong event during solar maximum over short periods due to space weather impacts at earth.

5.3 Lightning & Storms

The study of lightning induced by space weather is in its infancy, but researchers already have seen numerous similar findings. The most easily tracked correlation in this area is over the 11-year solar cycle, in which the solar maximum decreases GCR rates via a stronger heliospheric magnetic field, and the solar minimum offers and increase of GCRs introduced to the earth system, and corresponding modulation of lightning and atmospheric electricity have been noted (Neto et al. 2013, Harrison and Usoskin 2010 among others)- an anticorrelation between sunspots and lightning activity. During solar minimum, the increase in quantities of surface atmospheric electricity is greater proportionally than the increase in GCRs. If you recall our note on Brazilian rainfall and the South Atlantic Anomaly, and our discussion of clouds (previous section), then this section on lightning may help pull things together. It is also probably not a coincidence that the only nearly constant lightning in the world is nearby in Venezuela (Photo: Lightning on the Catatumbo River, from article by iO9).

Some researchers have suggested that while GCRs can penetrate directly to storm levels, it is SEPs and relativistic electrons (e-) from the magnetosphere and Van Allen belts (forced downward by impacting space weather) that probably modulate lightning activity over short timescales via their effect on the medium: the AC and DC global electric circuit systems (Williams et al. 2014; Nicoll and Harrison 2014). Solar cycle modulation also includes shifting position and variation of energy distribution in the vertical current density and current flow in the global electric circuit (Williams et al. 2014; Harrison and Usoskin 2010). The variability during short-term space weather events can match the baseline variability expected over an entire solar cycle.

High-speed solar wind streams drive lightning rate increases across Europe that can reach 33%, persist for ~40 days, and are confirmed by MET-observed ‘thunder days’, and the author suggests that it is the accompanying increase in SEPs and e- that drive the lightning (Scott et al. 2014), indicating a connection to the global electric circuit.

This input of energy is seen in explosive extratropical cyclones and invigorated storms as well, which tend to occur after impact from those high-speed streams (Artamonov et al. 2016; Prikryl et al. 2016). While solar maximum reduces GCRs significantly and offers a modest SEP increase, high-speed solar wind events and solar flares offer larger doses of those particles (a 9% SEP increase in one case) over short periods compared with a smaller (2%) reduction in GCR during the Forbush decrease (Scott et al. 2014). Even without geomagnetic disruptions or detectable GCR modulation at ground level, ionization increases of up to 26% have been detected in the wake of SEP events, with associated changes in atmospheric electricity at the surface (Nicoll and Harrison 2014).

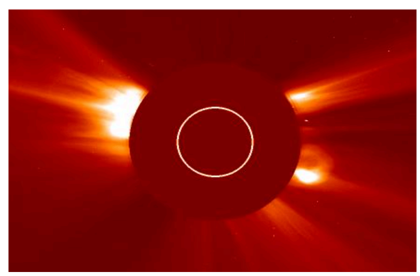
When isolating the sector boundaries in the solar wind, which produce geomagnetic disruptions from the change in the magnetic character of the solar wind alone (rather than from a CME cloud or speedy particles from a coronal hole), short-term lightning increases over Europe can reach 40 - 60% during the events (Owens et al. 2014). Owens et al. (2014)

determined that the changes to earth's magnetospheric and ionospheric structure were driving the change in lightning rates, but they also speculated that it was merely a redistribution of lightning rather than a change in global strike rates. Numerous studies *do* find such an increase in strike rates, including many already cited in this section and others involving variation in Schumann resonances (Williams et al. 2014).

In the United States, the heat-driven lightning in the summer drowns out any correlation with space weather; however, winter months show a strong correlation with the modulation of GCRs (Chronis 2009). In Brazil, most of the country shows a significant anticorrelation over the sunspot cycle (Neto et al. 2013). Trivandrum, India, demonstrates this anticorrelation with lightning in both sunspot activity and geomagnetic records (Girish and Eapen 2008).

There is a growing body of evidence for a connection between lightning counts and ice-mass precipitation (Deierling et al 2008, Latham et al. 2007 and others) which further increases the chances that hail is connected to the GEC and is subject to space weather modulation.

Take a deep breath; we're about to hit the accelerator...



Hurricanes Katrina, Rita, and Wilma all demonstrated a connection with space weather modulation of the atmosphere (Todorović and Vujović 2014). For Katrina specifically, the plunge into sunspot minimum was violently interrupted with CME activity across heliographic longitudes during the formation and intensification of the storm. After a few weeks of return to solar minimum behavior, another unexpected uptick in activity drove a rare five-Pacific-cyclone event not seen again until 2015. (Image: SOHO Coronagraph of CMEs taken during the intensification of Hurricane Katrina. This took place during a period of the 11-year cycle when solar activity should have been low/weak.)

A recent model purports to be able to predict ~25% of hurricanes based on solar storm activity. (Vyklyuk et al. 2016). This author is inclined to encourage that line of work:

From October 20 - 23, 2012, a major uptick in solar activity triggered a late-season hurricane, Sandy, which became the largest gale diameter Atlantic hurricane on record before hitting the East Coast of the United States.

In early November 2013, a powerful X-class solar flare surged electric currents through earth's atmosphere, and within days, Typhoon Haiyan became one of the most powerful west Pacific typhoons on record.

Let's take a look at the short period from Summer in the northern hemisphere 2015 to Fall 2016: In late June, a rare Level 4 solar storm resulted from multiple space weather events, and within two weeks there were six cyclones in the Pacific Ocean at the same time. This has only happened twice before.

From August 26 - 29, 2015, a brief flurry of solar flares ionized the earth's atmosphere and led to three category-4 hurricanes ongoing in the Pacific Ocean at the same time on August 30, the first such occurrence on record.

In early October 2015, a titanic solar eruption disrupted the entire inner solar system with SEPs and was immediately followed by Hurricane Joaquin in the Atlantic, which caused a 1000-years flood in South Carolina, and a rare Mediterranean hurricane-force storm.

A few weeks later, a Level 3 storm triggered significant cyclone intensification west of the Indian subcontinent and west of the State of Washington within hours. Before a long-duration solar flare and solar wind intensification occurred just days afterwards, Hurricane Patricia (which formed during the previous event) was a normal east Pacific storm, but afterwards, it became the strongest hurricane ever to strike Mexico.

One week later, two M-class solar flares erupted on October 31 and November 4, 2015, from the same sunspot. Each was followed immediately by a rare-location cyclone that formed in the same area of the northwest Indian Ocean, and both took similar tracks on their way to striking Yemen in the first week of November.

The sun was much quieter for two months, but in early January, the sun woke up with multiple CMEs and solar flares erupting just as a coronal hole stream was causing geomagnetic storms on earth. Pali became the earliest central Pacific cyclone on record on January 11 and Alex formed into a rare winter hurricane in the Atlantic later that week.

February 18 was the next solar uptick. A fantastic magnetic explosion on the sun was caused by a plasma filament (solar prominence), while a coronal hole was causing geomagnetic storms. Cyclone Winston became the strongest cyclone to make landfall in the history of the South Pacific Basin just 24 hours later.

The sun was very quiet until April 18 when an M6 solar flare erupted amidst weeks of near-complete silence in terms of solar flaring. Within 24 hours, cyclone Fantala intensified to become the strongest Indian Ocean storm in history.

The next major weather record wasn't set until June 2016 when Colin became the earliest 'C' named storm in the history of the Atlantic Basin. This occurred during a geomagnetic storm that included significant penetrations of solar plasma into earth's atmosphere.

In late September 2016, a powerful coronal hole ended another weeks-long stretch of quiet space weather. During the peak of the storm, Typhoon Megi intensified rapidly into a category-4 storm, and to the south, on the same longitude, an extra-tropical cyclone intensified and took out power to the entirely of South Australia.

The same coronal hole triggered Level-3 storm conditions on its next pass by earth in late October 2016; it matched the most powerful solar storm of the year. During the peak of the storm, Hurricane Seymore intensified to become the strongest East Pacific storm of the entire season.

Decades worth of storm records have fallen in just the last 18 months, and every one of them matched up with a solar storm during a period in which inactivity on the sun was vastly-more prevalent than activity. A well-documented shift in the QBO, from an anomalous state back to normal, in July 2016 appears to correspond with a complete silencing of solar activity that lasted throughout the summer, accompanied by a return to more normal tropical activity.

Valid Question: What was so different about this last year? Why doesn't this happen every time the sun is active? You may want to check out www.EarthChanges.org, *a free website dedicated to dissecting the macro and micro aspects of this exact scenario.*

The late June 2015 and Yemen events indicate the difference between multiple sources of space weather vs one sunspot group producing the space weather: Widespread cyclone activity vs upticks in one or two locations only. The five and six cyclone events occurred when the entire sun was active, with multiple source of space weather, while the two Yemen storms occurred when one sunspot released two significant solar flares. If it seems as if that was a lot of records for one year, we did not even list the record number of super-typhoons in the northern hemisphere, the record activity of the season in general, a record far-eastern Hurricane Fred, and more that also occurred in concert with short-term space weather events and the high geomagnetic activity of 2015. Nearly every space weather event for more than a year caused record-breaking storm activity.

While short-term geomagnetic events can drive individual storm events over short periods, in general, solar maximum produces fewer intense tropical cyclones due to heating of the upper troposphere, which disrupts the storm engine (Elsner et al. 2010; Elsner and Jagger 2008). There is evidence that small changes in top-troposphere heating can affect extratropical storm tracks and perhaps the position of the tropical rain belts (Bony et al. 2015; Butler et al. 2010). Outer rain bands in tropical cyclones appear to show a diurnal cycle that is probably related to solar radiation (Zhou et al. 2016 [2]).

5.4- The GEC Model

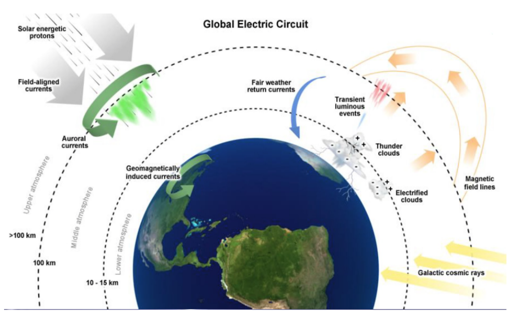
In 2000, Tinsley suggested that there were three main ways in which the solar wind affects the global electric circuit: cosmic ray modulation, relativistic electron precipitation from the magnetosphere, and magnetosphere-ionosphere coupling in the polar regions (Tinsley 2000). In addition to solar flare heating of the stratosphere and disruption of earth's magnetic field, electron temperature in the ionosphere was found to rise 28 - 92% during solar flares, and ion temperature increased 18 - 39% (Sharma et al. 2011). Other effects can be more subtle; Lynn et al. (2008) confirmed a previous finding that a CME impact triggered a wave and reverberation in ionospheric height of 300km travelling at more than a kilometer per second! Nobody on the ground noticed it, but it strongly affected the top layer of earth's electric system.

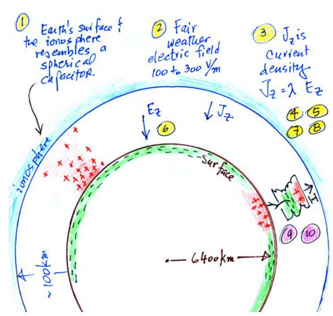
The primary space weather mode of action in the short term is an effect on the downward current density of the GEC, (Lam and Tinsley 2015), which is implied in the discourse surrounding GCRs, SEPs, relativistic electrons, and others such as interactions with Rossby waves and other planetary waves. [The primary importance of GCRs and magnetospheric electrons had already been well-established by Rycroft et al. (2012).] This is distinctly different from the longer-term stratospheric heating effects of UV irradiance, which propagates downward into the systems of circulation, pressure, oscillations, etc., often with some significant time lag. In a comprehensive review, Siingh et al. (2007) identified solar flares and solar wind/GCR modulation to be the controlling force over the GEC. Williams and Mareev (2013) found evidence of transient excitation of lightning by gamma ray bursts. This confirmed the cloud microphysical effects and ionization via cloud condensation nuclei modulation over the solar cycle, of up to a 25% variation in ionospheric potential over that same cycle. This translates to a decade of modulation (sunspot cycle) over a few days (individual space weather event.

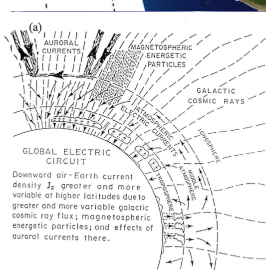
Atmospheric electrical processes may help explain statistical findings indicating that variable solar activity, such as solar flares or the Earth's position in the extended solar magnetic field, affects the weather. An atmospheric electrical mechanism bypasses difficulties associated with solar heating mechanisms. Understanding Sun–weather relationships offers a basis for long range weather forecasting.

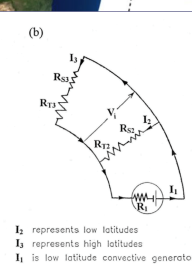
- Opening paragraph from *Solar Modulation of Atmospheric Electrification and Possible Implications for the Sun-weather Relationship*, by Ralph Markson (MIT) 1978.

It should be starting to become clear not only how the sun affects the climate over the long term, but also how there can be simultaneous changes in near-earth space and the tropospheric weather at the exact same time due to short-term space weather events. A simplification of the short-term forcing may be envisioned as a modulation of the energy that flows from the sky towards the ground around fair-weather areas and developing storms. This is part of the global electric circuit. This idea of a current circuit is beginning to be taught in universities and used by members of the field. The following images show some of the foundation of future knowledge in this area:









[Top, GEC model from UCAR. Bottom left, GEC diagram from U. of Arizona lecture notes. Bottom right, GEC model from Tinsley (2000) (references).]

5.5 Some If/Thens of Solar Forcing

While the solar cycles of 11 and 22 years appear to modulate a great deal of the temperature, precipitation, pressure, and other atmospheric trends, the grand solar maxima, extended minima periods, and the short-term intense space weather events tend to provoke the most significant changes. Because there is no golden rule when it comes to solar forcing over any timescale, here are some practical guidelines that can aid in meteorological forecasting (and some of the tricks used by some of the most expensive private companies to make their forecasts).

When you see a Solar Flare:

- Expect tropical storm formation/intensification
- Look for potential CME and Geomagnetic effects possible in the coming days
- Powerful flares can be expected to positively force NAO/AO for up to 9 days

When a CME impacts earth, creates a Forbush Decrease, and Geomagnetic effects:

- Expect tropical storm formation/intensification
- Expect stronger atmospheric jets; fewer blocking events for the following 5-10 days
- Expect rapid ground temperature fluctuations in the polar regions
- Expect atmospheric ionization due to SEPs and relativistic electrons causing increased lightning, hail, and possibly even tornadic activity (enhanced GEC)
- Geomagnetic storm-level events in winter may drive thunder-snow in the coming 5-10 days

During Sunspot Maxima:

- Expect an average 10 m/s increase in major jet speeds, decreased chances for blocking
- Expect wetter-than-average conditions in northwestern North America and in tornado alley in the United States

- Periods of grand maxima drive dryness in current desert zones

During Geomagnetic Maxima (1 - 3 years after sunspot maxima):

- Expect Positive NAO phase forcing trend
- Expect increased summer temperatures in the northern hemisphere
- Expect a cooler South Indian Ocean

During Solar Minima:

- **Expect a weaker polar vortex, leading to more major winter storms, especially in the USA (east, south, central) and in Europe**
- **Expect warmer weather in the northwestern United States**
- **Expect the Aleutian low to shift eastward, driving warmer maximum temperature days in the US northwest**
- **Watch for increased potential for jet-stream blocking; consider in forecasting 5-10 days ahead where models may otherwise be uncertain**
- **Expect a Negative NAO phase forcing trend during minima and for 1-3 years, bad winter storms in the north**
- **Expect periods of grand minima to increase rainfall in desert areas, especially the southwestern United States, while driving more droughts in India and in the central and eastern United States**
- **Expect more monsoon rainfall in Australia and Indonesia**

Other Notes:

A major eruption from a non-earth-directed heliographic longitude will present no flare and no geomagnetic impact, but numerous examples exist in which earth can still receive SEPs and witness tropical storm forcing during those events that put a great amount of energy into the interplanetary field and current sheet in every direction.

Positive and negative forcing on oscillation phases does not always mean that the oscillation index will be positive or negative, respectively. Over long timelines, the time spent in positive or negative phase *does* correlate with solar activity, but the best correlation can be found in the forcing of the amplitude of variability within their normal oscillatory periods.

While many areas of the world exhibit detectable modulation of surface temperatures over various known solar cycles, the short-term effects of the ENSO, other oscillations, the positions of the major jets, and other standard meteorological techniques are vastly more helpful for temperature predictions on a day-to-day basis. When it comes to day-to-day or week-to-week forecasting, only short-term space weather events should be considered.

When it's your call, and your models can't decide what will happen, ask the sun.

6 Space Weather, Human Health, and Technology

6.1 Space Weather and Human Health

The effects of space weather on biology is complex, with the cardiac effects being a perfect example: In healthy persons, heart rate and beat-interval fluctuations increase dramatically with the most severe geomagnetic storms (Mavromichalaki et al. 2012). When there is low geomagnetic activity and higher flux of cosmic rays, there is a higher incidence of acute myocardial infarctions and cerebral stroke (Stoupel et al. 2013) and deadly arrhythmia (Ebrill et al. 2016), especially in patients with left ventricular dysfunction and ischemic cardiomyopathy (Stoupel et al. 2008). There is also evidence for a correlation between arrhythmias and polarity reversals of the solar polar fields (Mavromichalaki et al. 2016). Medical emergencies of all kinds increase on days with zero geomagnetic activity (Stoupel et al. 2013). However, on days of the highest geomagnetic activity, there is a similar rise in the overall number of heart attacks (Vencloviene et al. 2016 [1]), strokes (Feigin et al. 2014), and sudden cardiac deaths of all kinds (Stoupel et al. 2006). During the days of lowest geomagnetic activity there is also a spike in total sudden cardiac deaths (Stoupel et al. 2016, Stoupel et al. 2013). Both ends of the spectrum appear to cause problems.

For patients with diabetes or other metabolic disorders, high geomagnetic activity, especially from high-speed coronal holes, creates an increased risk of acute coronary syndrome (Vencloviene et al. 2016 [2]). There are significant but varying risks for the conditions of both low (KP0) and high (KP5+) geomagnetic activity. For patients with multiple sclerosis, hospital admission rates increase dramatically in the weeks to months following the strongest geomagnetic storms, with a peak lagging seven to eight months behind the storms themselves (Papathanasopoulis et al. 2016). Geomagnetic storms have been shown to significantly increase arterial pressure, leading to cardiac events, and even small changes in local magnetic fields can induce anxiety and restlessness (Azcarate et al. 2016; Martinez-Breton and Mendoza, 2015; Babayev et al. 2012).

The direct biological response to space weather begins before the geomagnetic storm. It is well-known that solar flares and their ionizing effect on the atmosphere create rippling infrasound at the noon longitude of earth at that time. Infrasound can occur with density shockwaves from CMEs and waves that precede coronal hole streams as well, and these can be statistically correlated with biological parameters (Zenchenko 2011; Soroka 2008). These density shockwaves often occur an entire day before the geomagnetic storm. Solar flares occur even earlier before the storm, and sometimes there is no storm at all with solar flares. The potential effects of infrasound, electromagnetic variations and Schumann peak fluctuations are numerous; the studied effects have included migraines, digestive issues, cognitive diminution, vision impairment, decreased melatonin levels, slower reaction times, mood fluctuations, effects on the waking and dreaming states of consciousness, vascular calcification and more (Parihar et al. 2016; Gok et al. 2014; Shuvy et al. 2014; Persinger 2011; Babayev and Allahverdiyeva 2007; Cherry 2002). It is worth noting that the Schumann effects can be positive or negative in terms of the mental, emotional, and physical effects, etc., and are largely dependent on the specific frequencies to which the resonance peaks shift during the event (Persinger 2011).

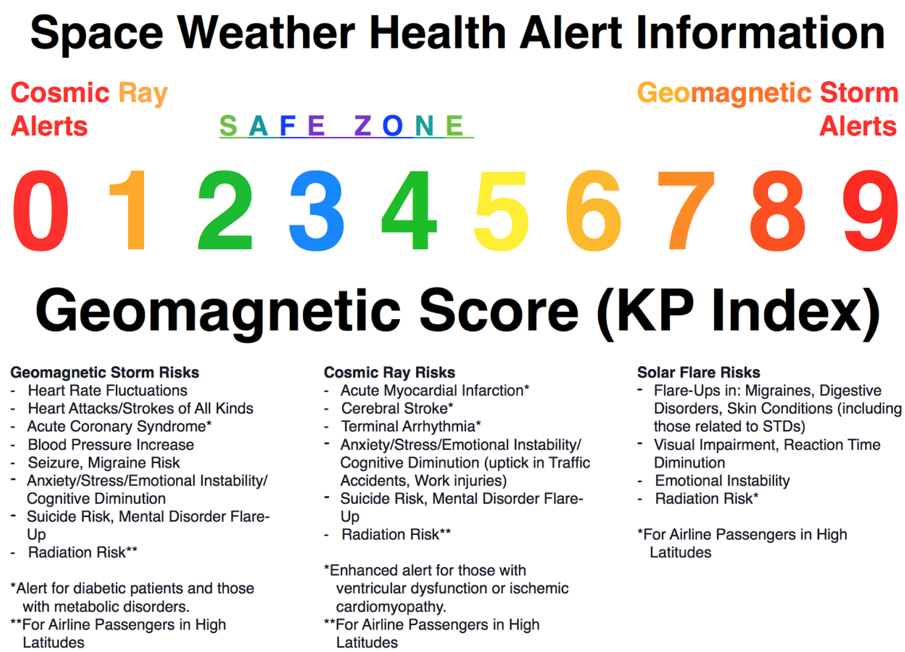
More on infrasound can be learned by exploring the topic of health problems in humans and animals living near wind turbines, which are a significant and often an enduring source of infrasound. The fact that there are an entire journals dedicated to these topics, such as *Electromagnetic Biology and Medicine* and *The International Journal of Biometeorology*, pretty much says it all. The future for these types of studies is wide open. Interestingly, the mostly-Western studies presented here follow decades of findings from Russia that are in agreement with more recent findings. The lack of global acceptance of this field until recently is the product of language barriers (with most studies only available in Russian) and suppression during Communist leaders' desire to blame other cultures and societies for domestic issues rather than being the result of any exogenous source.

Cherry (2002) reviewed much of the published literature available at that time. He found that: Over longer timescales, variations in sunspot number correlate positively with suicide rates (with highest storms), and negatively with pregnancy-induced hypertension. The correlations with heart attacks and strokes can be seen over annual/decadal scales in addition to daily timeframes. Geomagnetic storms positively correlate with convulsive seizures, loss of attention and memory, and with aviation incidents. Low geomagnetic activity (high cosmic ray flux) seems to induce vivid dreaming, increased crime rates, more suicide events, work injuries, sports injuries, traffic accidents, and psychiatric admissions. Both sunspot number and geomagnetic storms are positively correlated with mortality in general, and a drop in birth rate.

Many of the associated cognitive dysfunctions associated with cosmic ray exposure have been subsequently confirmed in forward-looking studies for Mars astronauts (Parihar et al. 2016). In the appearance of significant biological reactions of both cosmic ray surges and intense solar storms, the least risky periods appear to be when the KP index is between 2 and 4. Consider how many things in this life are needed in an equilibrium dose; even too much water or oxygen is toxic. It stands to reason that a similar biological optimum exists in electromagnetic energy/effects of space weather, where either extreme presents risk. This balance can be disrupted over the short periods described in this chapter, as well as longer ones. Apollo astronauts show increased incidence of cardiovascular disease-related mortality, likely due to their increased exposure to cosmic rays over long periods (Delp et al. 2016). Astronauts, pilots, and even the unlucky passenger on a bad space weather day could receive biologically relevant doses of solar and cosmic radiation (Phillips 2013). Even things like flu and other pandemics are likely related to the solar cycles, where lower solar output (including seasonal changes) correlates significantly with more biological outbreaks and deaths (Hayes 2010; Moan et al. 2009; Yeung 2006).

Author’s Notes: During one solar event in 2013, it is estimated that a harmful dose of radiation could have been received by a handful of airline passengers. This was only a

Level-2 storm. This information was released in a report about lack of radiation monitoring during the government shutdown of October that year, and the report remained one of the few official US government acknowledgements that space weather presents any danger at all until October 2016 when President Obama issued an executive order on Space Weather, stating that it presented a significant risk to our technology and human health worldwide. At Level 4, that storm would put thousands at risk, and at Level 5, everyone in the sky would be at risk.



6.2 Space Weather and Technology

In addition to the direct particle input of energy from solar storms, the flow of these particles can induce additional ground currents beneath the auroral and equatorial electrojets, which can even affect systems based underground.

There have been a few notable space weather-induced technological disasters. In 1859, the Carrington Event, a tremendous solar storm set fire to telegraph wires and shocked the operators. When they unplugged the machines, the messages kept coming in. Back then, there wasn't much to destroy, and we have yet to see another such event come towards earth. That was a once-every-few-centuries type of event, but lesser ones can be damaging none-the-less.

Throughout the early 1900s, telegraphs and railroads were plagued by disruptions from solar storms, and in the space age, we have already seen satellites and other craft taken out by solar storms, including the Sky Terra station, which was rendered useless during a 2012 storm. Once or twice every ~11-year cycle, a strong solar storm disrupts air travel or causes major power grid issues. Before 2012, the last major event was a power grid failure in Sweden/Norway in 2003, and before that, we had significant damage to NOAA satellites in the early 1990s.

However, in 2015, there were three national or regional groundings of aircraft during solar storms but none of them was the result of what anyone could call 'major space weather'. The same could be said of the grid shut-down and shed load orders in southern California during a solar storm in the fall of 2015. We've had decades of solar storm effects in just two years, and yet the cause was not nearly as strong of solar events as expected. There is an ongoing change in the earth's magnetic field; it is both shifting in structure and weakening in strength. Even slight geomagnetic disruptions are now accompanied by increases in reports of electrical and transformer fires, communications disruptions, transportation (such as the San Francisco BART anomaly), and incidents at nuclear plants and other digitally based systems. A recent study found that the railways have once-more become a dangerous place during geomagnetic storms, especially the high-speed rails now largely based on electromagnetism. (Liu et al. 2016).

Information on the earth's changing magnetic field is expanding; plenty of information is available for free at www.EarthChanges.org - a site dedicated to the published research and ongoing signals of earth's fading protective magnetism.

7 Solar-Triggered Earthquakes and Location Forecasting

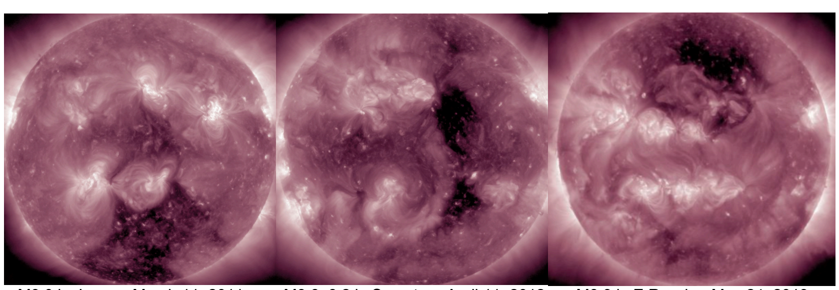
This topic is one you really have to see to believe. There are only two good ways we can help you with that.

7.1 The Evidence

First, you can watch our five-minute show every morning around 6:00AM eastern time - which details exactly what is going on with space weather and the earth. In that show you will find our ongoing tracking of times when the earth should have more big quakes and when it should be more quiet.

Over long periods, the earth has about three magnitude 6+ earthquakes per week, but when you actually track the data you often find many in a brief flurry of a few days and then go days to weeks without even one. We have are able to forecast ~ 90% of these ups and down in seismic activity at the M6+ level by using coronal holes, which contain the IMF (Section 1.1) and affect the magnetism of the entire solar system.

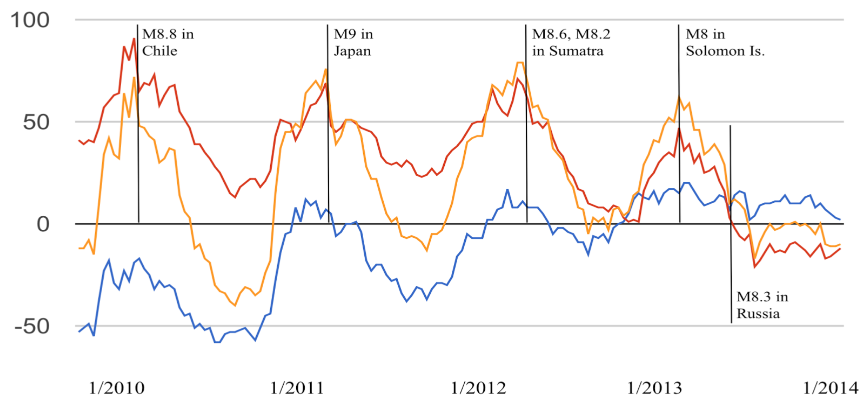
What does this mean for you? When a coronal hole enters the earth-facing ¼ of the sun (longitudinally), you can expect an increase in M6+ earthquakes, especially if we have seen multiple days without such seismicity in the days preceding the entry of the coronal hole. Here are just three among the hundreds of examples, using some of the biggest quakes:



M9.0 in Japan - March 11, 2011 M8.6, 8.2 in Sumatra - April 11, 2012 M8.3 in E.Russia - May 24, 2013

Second, when it became clear that we needed to find a way to quantify this relationship, we found that little information existed apart from data on the IMF from polar coronal holes, known as the solar polar fields (SPF). With the available data (1976 - 2013) we worked with Dr. Holloman (Professor of Statistics, The Ohio State University) and Dr. Kongpop U-yen (Goddard Space Flight Center, NASA) to test for a correlation with earthquakes.

To our surprise, it was the largest earthquakes (M8+) that showed the strongest relationship with the sun, demonstrating a result that was nearly impossible to find by random chance. The biggest earthquakes occurred close in time to the magnetic peaks and reversals of the solar polar fields.



This chart is from our foundational paper published by *New Concept in Global Tectonics* (The paper can be read for free at SpaceWeatherNews.com/SPF) and it shows a small portion of what nearly the entire timeline looks like.

The sun's magnetism is plotted in red, yellow, and blue, along with the biggest quakes. If it looks like the quakes happen at four straight spikes in magnetic force, and then a magnetic reversal of polarity, yes, it's that simple, and the whole timeline looks like this.

Since the end of the initial study period (2013) the model has proven highly successful in demonstrating that earth's largest seismic events occur when the sun's magnetism is peaking. Find the papers at www.SpaceWeatherNews.com/SPF , including all future updates.

7.2 Earthspot Energy Distribution

Earthspots: Places where electric currents, cold plasma, or magnetic fields that are part of the global electric circuit manifest as weather and other earthly phenomena as they travel up or down through the atmosphere and the ground. Under high pressure and clear skies the electric currents come down and help make clouds; currents fire back upward in storms. Some of that energy coming down goes into the ground, where it can trigger an earthquake or a volcano immediately, or it can build up charge and then release later as an earthquake or volcano, if a storm doesn't release it first.

We can monitor the global electric circuit in a number of ways and even use it to predict earthquake locations. There is a strong developing precedent for this pursuit in published work (Lu et al. 2016; Kong et al. 2015; Chen et al. 2010; Jing et al. 2010) looking at pressure, storms, electrical changes in the atmosphere, and thermal radiation escape.

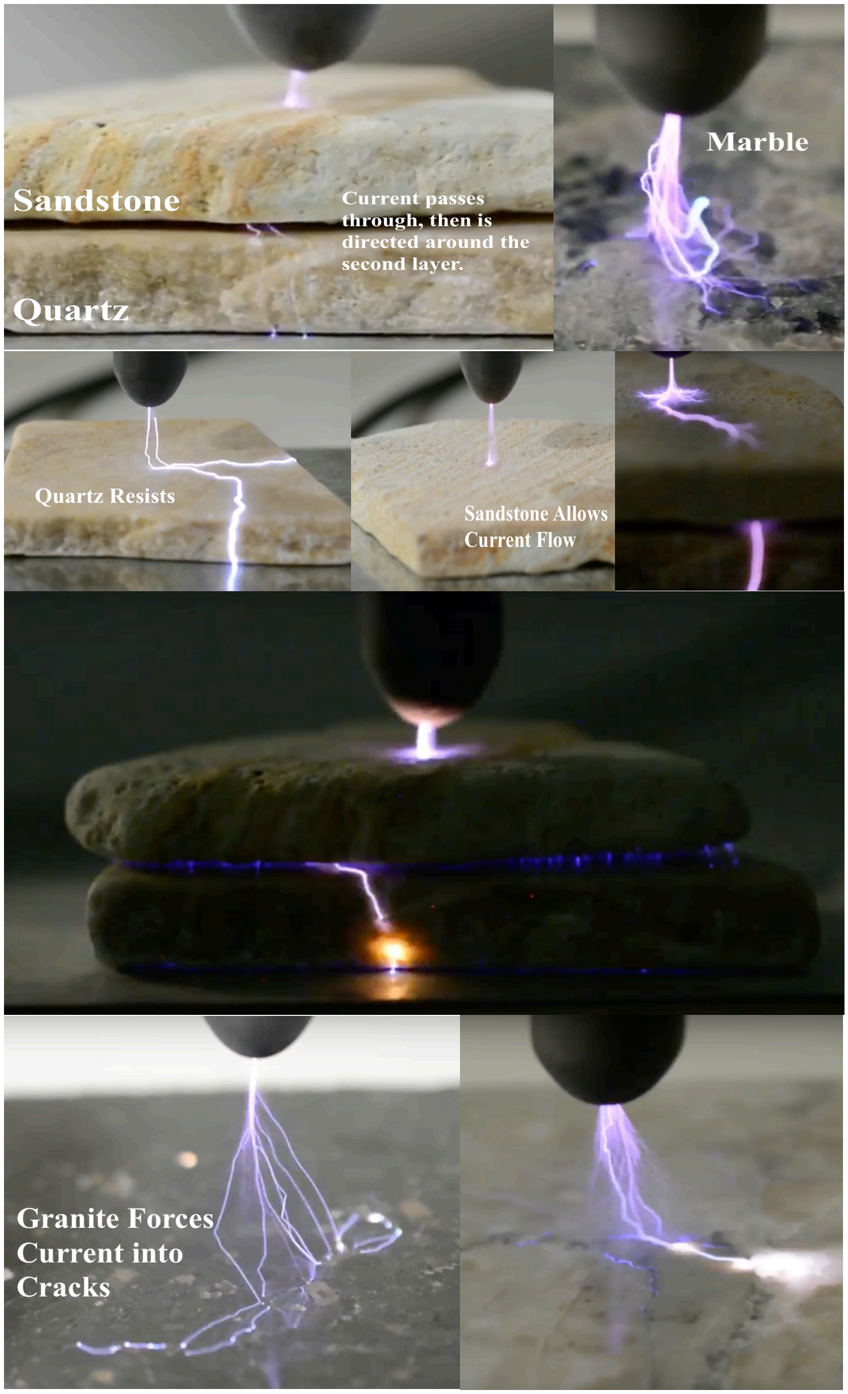
This science is brand new, but the first few attempts to use the earth's energy and solar energy signatures to predict earthquakes have been very successful. We predicted the location of 17 M6+ earthquakes from Nov.8.2015 to Nov.7.2016 (our first year of trying) and had more than 60% of our predictions fulfilled. The expected success rate based on random luck should have been ~6.5%. Year two began on November 8, 2016, and by November 24th seven M6+ earthquakes in a row (going back to October) struck in the alert zones most recently posted, from 2 hours to 24 days after the posting. More on this process and the full list of predictions can be found at www.QuakeWatch.net. This work has already received international attention in news media and academic circles.

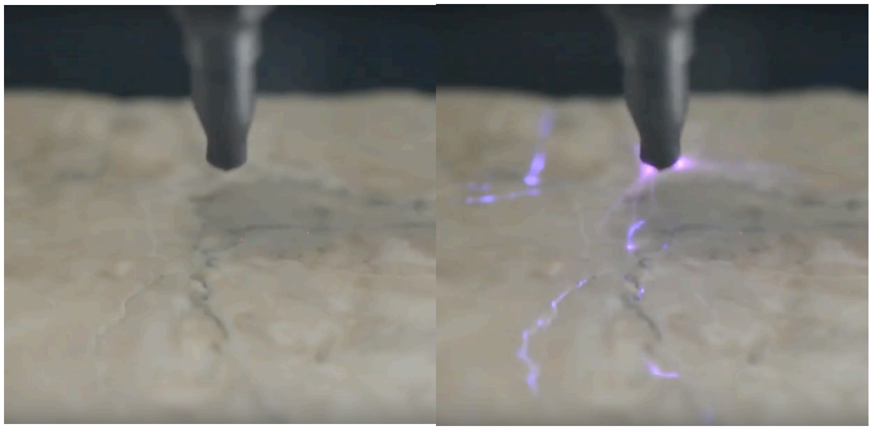
Specific areas of earth can to be forecasted simply by looking at skyward energy release from tight low pressure storms such as hurricanes and typhoons. The Philippines tends to get seismically active when storms are directly overhead. Back in 1991 a number of powerful solar flares preceded the formation of Typhoon Yunya, which hit the Philippines during an earthquake uptick that also included the eruption of the Pinatubo Volcano, whose ash cloud was visible shooting up through the typhoon clouds above. There are other examples: A rare hurricane force storm in the eastern Mediterranean Sea formed on the 26th of October 2016, just as a series of significant earthquakes caused major damage in central Italy on the 26th and 30th. The August 2011 Virginia earthquake that damaged monuments in Washington D.C. and was felt across the eastern states was centered on the line of Hurricane Irene, which took a rare path over the region less than one week later; a rare hurricane and a rare quake in the same area. Mexico tends to rumble when hurricanes are directly south of the coastline fault which ends up shifting. Japan often sees earthquakes prior to typhoon arrival and often on the path that the typhoon eventually takes. The Carlsberg Ridge can become abnormally active during a west Indian Ocean cyclone formation and intensification. Most of this is not very practically useful for you right now, but keep the relationship in mind for when you start to see it in the mainstream lexicon.

How do we know what earth's energy does when it gets to the ground?

Understanding the process by which earth's electricity triggers ground changes needs no time to work through the red tape of academia, you just need your eyes. The images on the following pages show how the circuit will bend, accumulate, and transfer through and around different rock based on their composition and water content.

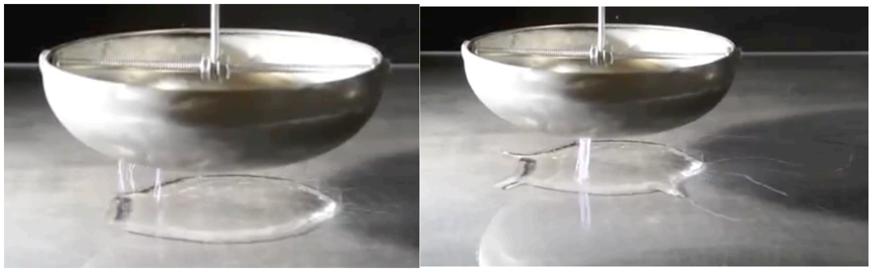
These are arc-discharges and glow-mode plasma, which allow you to see them, but on earth, the plasma is in ‘dark-mode’ while still very much flowing in currents.



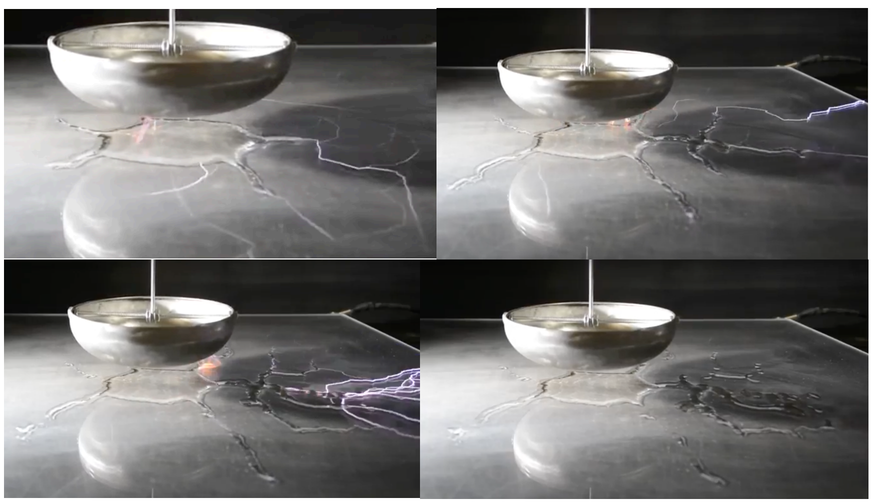


Above: The visualization of downward currents accumulated into the paths of least resistance (marble, left off / right on). Below: Lights off (granite).

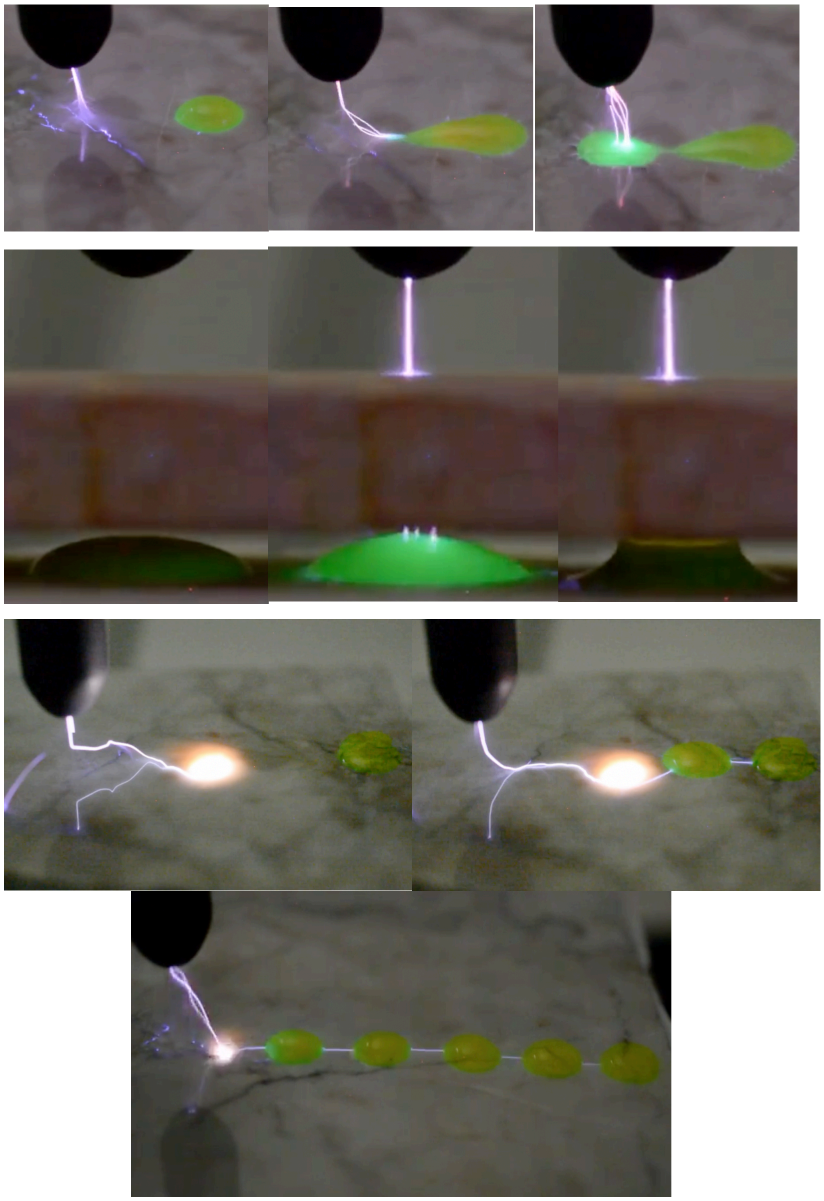
This is how the water in the ground will create a push/pull over large areas:



Above: We begin pumping current down into the water, sitting atop an insulator to induce lateral current flow. The current quickly begins exiting the water in multiple places, and the water begins to follow. Below: The water finger (dendrite) coming directly at the camera is forced so hard that it separated in the top/right image below, and we see no more current in that area.



Below: The top line shows salt water w/pyranine, sucked into the current. This works with or without the pyranine, but the effect is substantially diminished without the salt. In the second line, the current is increased to discharge levels in sequential images from left to right, and the water pushes up with the current in defiance of gravity. In the bottom line, we see that breadth of effect is based on what is nearby.



Final Comments

The subjects of space weather and its effect on the weather, technology, seismicity and biology are all relatively new. This text offers a broad exposure to covering these topics and trends in findings, but it is not a complete picture of the available literature. New papers are coming out in each of these fields almost every month, and given recent trends in funding and researcher interest, that is probably going to intensify. As a meteorologist, a space weather enthusiast, an industry professional or a layperson, know that there is now enough literature and consensus on some topics for you to begin integrating that understanding into your daily life and even your profession.

Better weather forecasting, earthquake prediction, and cosmic energy health alerts are all on the horizon. In the winter of 2016/2017, SpaceWeatherNews plans to release The Disaster Prediction App, which will serve as an in-hand warning system for technological, seismic, health, and even some weather risks resulting from solar storms and other cosmic events. If these topics directly affect your profession, if you want to be aware of how the universe is affecting our world, or if you are just interested in these topics, the best advice we can give you is to watch our free morning news program.

Our daily earth/sun updates appear at:

SpaceWeatherNews.com, EarthChanges.org, Suspicious0bservers.org, on YouTube: Suspicious0bservers, and on Facebook.com/ObservatoryProject

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Billy Yelverton runs our plasma lab in Leesburg, Georgia. The earthquake predictions hinged on his ability to turn my imagination into reality.

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