Frontiers of Earth System Dynamics: Earth's Global Electric Circuit

<table>
<thead>
<tr>
<th>SECTION</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLOBAL ELECTRIC CIRCUIT GUIDE</td>
<td>3</td>
</tr>
<tr>
<td>EARTH'S ELECTRIFIED ATMOSPHERE</td>
<td></td>
</tr>
<tr>
<td>Earth's Global Electric Circuit</td>
<td>5</td>
</tr>
<tr>
<td>Earth's Sun</td>
<td>7</td>
</tr>
<tr>
<td>Earth's Magnetosphere</td>
<td>8</td>
</tr>
<tr>
<td>Earth's Atmosphere</td>
<td>9</td>
</tr>
<tr>
<td>Earth's Ionosphere</td>
<td>11</td>
</tr>
<tr>
<td>Transient Luminous Events (TLEs)</td>
<td>13</td>
</tr>
<tr>
<td>Earth's Clouds</td>
<td>15</td>
</tr>
<tr>
<td>Earth's Lightning and Electrified Storms</td>
<td>16</td>
</tr>
<tr>
<td>MEET THE SCIENTISTS</td>
<td>17</td>
</tr>
<tr>
<td>RESOURCES</td>
<td></td>
</tr>
<tr>
<td>Educational Sites</td>
<td>19</td>
</tr>
<tr>
<td>Websites and Other Resources</td>
<td>20</td>
</tr>
<tr>
<td>Atmosphere Graphic</td>
<td>22</td>
</tr>
<tr>
<td>Global Electric Circuit Graphic</td>
<td>23</td>
</tr>
<tr>
<td>GLOSSARY of TERMS</td>
<td>26</td>
</tr>
</tbody>
</table>
This Booklet and the complementary video introduce students to a natural system in Earth’s atmosphere commonly referred to as the Global Electric Circuit. The circuit encompasses the various phenomena in our atmosphere that influence the many pathways of electricity that flow between Earth and the atmosphere’s ionosphere: lightning, electrified clouds, cosmic rays, ions, magnetic fields, radon emanating from beneath Earth’s surface…. These phenomena encompass a complex system of electrical circuits that scientists are just beginning to understand.

The goal of scientific researchers working to advance our basic understanding of the Global Electric Circuit is to develop a model that captures the system’s complexity and immense variability across space and time. This will allow scientists worldwide to study the system and better understand connections between Earth’s atmospheric electricity and other components of the Earth system.

Next Generation Science Standards Addressed

Next Generation Science Standards: Earth Science*

ESS1.B Earth and the solar system
ESS2.A Earth materials and systems
ESS2.D Weather and climate
ESS3.B Natural hazards
ESS3.C Human impacts on Earth systems

Next Generation Science Standards: Physical Science*

PS1.A Structure of matter
PS1.B Chemical reactions
PS2.A Forces and motion
PS2.B Types of interactions
PS2.C Stability and instability in physical systems
PS3.A Definitions of energy
PS3.B Conservation of energy and energy transfer

Next Generation Science Standards: Life Science*

LS2.B Cycles of matter and energy transfer in ecosystems

* These standards address the Next Generation Science Standards – second draft, January 2013
We are all aware of lightning flashes and the tremendous power that they can transfer from electrical clouds to Earth’s surface in the form of electric current. But did you know:

- millions of lightning flashes occur per day over the Earth;
- lightning discharges also occur between the clouds and the edge of space, producing luminous displays called sprites and elves;
- cosmic rays from other galaxies and x-rays from the Sun make the edge of space electrically-conducting so that these events can occur;
- currents in the ionosphere can induce dangerous current surges in our power grid system;
- the signatures of interactions between charged particles from the Sun and Earth’s outer magnetic field can be measured at the ground in the polar regions?

How might lightning modify ionospheric conditions that affect communications and navigation (e.g., GPS) systems? How might changes in the space environment affect electrical processes in polar-region clouds relevant to weather and climate, or how might society be impacted in other ways through electrical connections within the Earth-atmosphere-geospace system?

The goal of research on the Global Electric Circuit is to create a realistic global model of Earth’s electrical system from the surface into the ionosphere. It will then be used to better understand how electric fields, electric currents, and magnetic fields are redistributed globally in response to lightning discharges, electrified clouds, and disturbances in interplanetary space and the geospace environment. We invite you to join us and learn about the Global Electric Circuit, too!

Earth’s Global Electric Circuit – It’s difficult to comprehend the world before electricity was put to use to power our homes, streets, and cities over 100 years ago. The truth is that electricity has always been with us, just unharvested for human use until relatively recently in human history.

Electricity extends throughout our atmosphere in what is collectively called the Global Electric Circuit. In fact, a flash of lightning is not an isolated event within a thunderstorm. It is part of this vast global circuit, creating a voltage of current 200,000 to 500,000 volts (200 to 500 kV) between the ground and the ionosphere. Thunderstorms alone send 1 amp (A) of current skyward. But the circuit courses through the atmosphere even on fair-weather days when a slight current of two picoamps (or 0.0000000000002 A) flows from every square meter of ground upward to the ionosphere.

Scientists have long been interested in understanding various parts of the Global Electric Circuit, but the system is vast and varies over time from seconds, hours, and days, to months, seasons, and decades. Understanding the system in its entirety is in its beginning stages, but that doesn’t mean that scientists haven’t been studying its various components and trying to make sense of them. They’ve been doing so for at least 200 years!

From 1909 to 1929, Carnegie, a yacht that was nearly entirely non-magnetic and wood-hulled, sailed around the world – nearly three hundred thousand miles through its oceans – carefully locating and measuring then-unknown magnetic influences in the atmosphere. Its many voyages were part of the Carnegie Institution’s program that included an ambitious magnetic, electric, and oceanographic survey, coupled with magnetic and electric surveys of land areas in many parts of the world. Eventually it carefully located and measured unknown magnetic influences in the atmosphere, and gave scientists the Carnegie Curve, the characteristic and universal variation of Earth’s atmospheric electric field, which is still used today.

Scientists at the National Center for Atmospheric Research, the University of Colorado, Pennsylvania State University, and elsewhere around the world are interested in verifying and quantifying the circuit’s many pathways, sources, and influences in order to build a scientific model. This will allow scientists to test their ideas about how the system works and its impact on and/or connection with other parts of the Earth system. It may be that Earth’s Global Electric Circuit has profound implications on Earth’s climate and/or weather. Society will never know the true role it plays within the Earth system until such a model is available for further exploration, experimentation, and discovery.

On the pages that follow, we invite you to explore the vastness and many components of the Global Electric Circuit – from lightning and electrified clouds, to influences such as microscopic particles that can interfere with the conductivity of the atmosphere, to cosmic rays and currents induced from solar storms from external electrical processes. It’s true that the system is complex and difficult to unravel and understand in its entirety, but scientists are well on their way to unlocking its many mysteries.
The Sun provides Earth with energy that makes life on our planet possible. The Sun gives off electromagnetic energy in many wavelengths, including radio waves, microwaves, infrared, visible light, ultraviolet, high-energy x-rays, and gamma rays. The Sun also emits a stream of radiation in the form of charged particles that make up the plasma of the solar wind emitted most notably during solar storms called coronal mass ejections (CMEs).

A coronal mass ejection (CME) is an explosive outburst of solar wind plasma from the Sun. The blast of a CME typically carries roughly a billion tons of material outward from the Sun at speeds on the order of hundreds of kilometers or miles per second. A CME contains particle radiation (mostly protons and electrons) and powerful magnetic fields. These blasts originate in magnetically disturbed regions of the corona, the Sun's upper atmosphere - hence the name. Occasional outbursts from these huge explosions on the Sun send space-weather storms hurtling outward through our solar system. Some of these storms smash into Earth's magnetosphere, the protective magnetic bubble which surrounds our fragile planet. Particle radiation spiralling down along our planet's magnetic field lines can damage satellites, disrupt communications systems, and even short out electrical power systems.

Sunspots are dark, planet-sized regions that appear on the "surface" of the Sun. A large sunspot might have a central temperature of 4,000 K (about 3,700° C or 6,700° F), much lower than the 5,800 K (about 5,500° C or 10,000° F) temperature of the adjacent photosphere. Sunspots are only dark in contrast to the bright face of the Sun. They are caused by disturbances in the Sun's magnetic field welling up to the photosphere, the Sun's visible surface. They form over periods lasting from days to weeks, and can persist for weeks or even months. The powerful magnetic fields in the vicinity of sunspots produce active regions on the Sun, which in turn frequently spawn disturbances such as solar flares and CMEs.

Historical records of sunspot counts, which go back hundreds of years, verify that this sunspot cycle has an average period of roughly eleven years, beginning with few spots during what is referred to as the solar minimum, and gaining in spots and solar activity as the 11-year cycle progresses.

In terms of Earth's Global Electric Circuit, the Sun is central to its existence. It provides most of the ionizing radiation that produces ions (charged atoms) within Earth's atmosphere, especially in its upper layers and regions, including the aptly named ionosphere. This is especially true during coronal mass ejections that head Earth's way.

First, high-energy sunlight, mostly x-rays and ultraviolet light, ionize Earth's upper atmosphere. Next comes a radiation storm. Finally comes the coronal mass ejection, a slower moving cloud of charged particles that can take several days to reach Earth's atmosphere. When a CME hits, the solar particles can interact with Earth's magnetic field to produce powerful electromagnetic fluctuations. They also cause auroras, or the northern and southern lights, mostly seen near Earth's poles, where charged particles in the solar wind collide with atmospheric gases.

Earth's Magnetosphere refers to the protective envelope constantly surrounding our planet where Earth's magnetic field dominates. It is created by Earth's rapidly spinning liquid metal core that results in a planetary magnetic field similar to a bar magnet's, with a north and south pole. It ultimately provides a magnetic shield that protects Earth from energetic charged particles that bombard Earth during coronal mass ejections.

When CMEs travel outward through the Solar System toward Earth, ions in the solar plasma interact with Earth's magnetic field and are swept around it. In fact, the collision of the solar wind impacts the shape of Earth's magnetosphere. On its Sunward side, it becomes compressed to a size six to ten times the radius of the Earth, and a shock wave, called a bow shock, occurs that is similar to a sonic boom. This bow shock diverts much of the charged particles from solar storms around the outer boundary of the magnetosphere.

On the opposite or night-side of Earth's magnetosphere, the solar wind is believed to extend the magnetosphere's magnetic field outward for millions of miles (1,000 times Earth's radius). Scientists refer to this impact as the magnetotail.

During a solar storm, much of the radiation is trapped in three inner and outer areas within Earth's magnetic field called the plasmasphere, the ring current, and the Van Allen Belts. Some highly energetic particles in the Van Allen Belts will follow the magnetic field lines to Earth's polar regions and enter the upper atmosphere. Sometimes, magnetic field lines from incoming plasma connect with the field lines of the magnetosphere and catapult charged particles into it.

The disturbance can also trigger a series of events that send a burst of particle radiation into Earth's upper atmosphere. As the radiation crashes into gas molecules in Earth's atmosphere, it causes them to glow... creating the magnificent light shows of the auroras (the northern lights and southern lights).

Earth’s atmosphere is a mixture of gases that surrounds our home planet. Besides providing us with something to breathe, the atmosphere helps make life on Earth possible in several ways. It shields us from most of the harmful ultraviolet (UV) radiation coming from the Sun, warms the surface of our planet by about 33 °C (59 °F) via the greenhouse effect, and largely prevents extreme differences between daytime and nighttime temperatures.

The atmosphere grows thinner (less dense and lower in pressure) as one moves upward from Earth’s surface. It gradually gives way to the vacuum of outer space. There is no precise “top” of the atmosphere. Air becomes so thin at altitudes between 100 and 120 km (62-75 miles) up that for many purposes that range of heights can be considered the boundary between the atmosphere and space. However, there are very thin but measurable traces of atmospheric gases hundreds of kilometers (miles) above Earth’s surface.

There are several different regions or layers in the atmosphere. Each has characteristic temperatures, pressures, and phenomena. We live in the troposphere, the lowest layer. Most of the mass (about 75-80%) of the atmosphere is in the troposphere. Clouds, too, are found in the troposphere, and almost all weather occurs within this layer. It extends upward to about 10 km (6.2 miles or about 33,000 feet) above sea level.

Some jet aircraft fly in the next higher layer, the stratosphere, which contains the jet stream and the ozone layer. A rare type of electrical discharge, somewhat akin to lightning, occurs in the stratosphere. These blue jets appear above thunderstorms, and extend from the bottom of the stratosphere up to altitudes of 40 or 50 km (25 to 31 miles).

Higher still is the mesosphere. This layer is directly above the stratosphere. It extends from about 50 to 85 km (31 to 53 miles) above our planet. Odd electrical discharges akin to lightning called sprites and elves, occasionally appear in the mesosphere dozens of kilometers (miles) above thunderclouds in the troposphere below. The stratosphere and mesosphere together are sometimes referred to as the middle atmosphere.

The thermosphere is directly above the mesosphere. It extends from about 90 km (56 miles) to between 500 and 1,000 km (311 to 621 miles) above our planet. Temperatures climb sharply in the lower thermosphere (below 200 to 300 km altitude or 124 to 186 miles), then level off and hold fairly steady with increasing altitude above that height.

Solar activity strongly influences temperature in the thermosphere. It is typically about 200 °C (360 °F) hotter in the daytime than at night, and roughly 500 °C (900 °F) hotter when the Sun is very active than at other times. Temperatures in the upper thermosphere can range from about 500 °C (932 °F) to 2,000 °C (3,632 °F) or higher. This is especially true during a period called the solar maximum, the period of greatest solar activity in its approximately 11-year solar cycle.

Although the thermosphere is considered part of Earth’s atmosphere, the air density is so low in this layer that most of the thermosphere is what we normally think of as outer space. In fact, the most common definition says that space begins at an altitude of 100 km (62 miles). The space shuttle and the International Space Station both orbit Earth within the thermosphere.

High-energy solar photons also tear electrons away from gas particles in the thermosphere, creating electrically-charged ions of atoms and molecules. Earth’s ionosphere, composed of several regions of such ionized particles in the atmosphere, overlaps with and shares the same space with the electrically neutral thermosphere. Moving ions, dragged along by collisions with the electrically neutral gases, produce powerful electrical currents in some parts of the thermosphere.

Finally, the aurora (the southern and northern lights) primarily occur in the thermosphere. Charged particles (electrons, protons, and other ions) from space collide with atoms and molecules at high latitudes, exciting them into higher energy states. Those atoms and molecules shed this excess energy by emitting photons of light, which we see as colorful auroral displays.

Earth’s atmosphere gradually fades into the vacuum of space. The outermost limit of the atmosphere’s uppermost edge occurs in the region around 190,000 km (120,000 miles), about halfway to the Moon. There, in the vastness, is space.
The Ionosphere - Earth’s atmosphere contains a series of regions that have a relatively large number of electrically charged atoms and molecules. As a group, these regions are collectively called the ionosphere and they extend from about 56 to more than 1000 km above Earth’s surface (35 to 620 miles) from the middle of the mesosphere through the entire thermosphere and further.

Interestingly, the existence of an electrically conducting region of the atmosphere was not confirmed until the first decade of the 20th Century. Its discovery ushered in the long-distance transmission of radio waves by the ionosphere’s reflective properties, which acts like a mirror in the sky making the transmission of radio waves possible.

The ionosphere is made up of three horizontal regions commonly referred to as regions D, E, and F. Region D extends from approximately 40 to 60 miles or 64 to 96 km; Region E extends from 60 to 80 miles or 96 to 129 km; and Region F extends from about 100 to 1,000 miles or 160 to 1610 km or more above Earth’s surface. The ionosphere reaches its maximum density of charged particles in this last region, Region F, from 125 to 375 miles or 201 to 603 km altitude. It then decreases in density with height.

It is in constant flux over time and place in both its charged particle density and its structure. Its variability is due to the variability of the Sun. Not only does the Sun’s energy change throughout a 24-hour period, the Sun’s x-ray and ultraviolet emissions also change and impact the ionosphere due to the Sun’s highly variable 11-year sunspot cycle, changes in the Sun’s rotation, solar flares, and more. The ionosphere not only varies greatly with time, but also by geographical location (polar, auroral zones, mid-latitudes, and equatorial regions), and with certain solar-related ionospheric disturbances.

Interestingly, Region F is also an exporter of ions and electrons. Ions are neutral atoms that have become electrically charged by the addition or loss of one or more electrons. Electrons are sub-atomic particles within atoms that carry a negative charge. An atom that gains an electron, therefore, is negative, while an atom that loses an electron is positive. Protons are the corresponding positively charged particles within all atoms.

As the Sun’s energy reaches the ionosphere in the day, the ionosphere expands and carries ions upward into an area surrounding our planet called the magnetosphere. As the Sun sets and night arrives, the ionosphere cools and contracts, which draws lost ions and electrons back to the ionosphere until the Sun’s return each dawn. Here, the atmosphere crackles with electric current, and dances with curtains of light over the poles due to Earthward solar storms’ solar plasma.

The presence of these charged particles makes the upper atmosphere an electrical conductor, which supports electric currents and affects radio waves. This ionization depends primarily on the Sun and its activity. Ionospheric structures and peak densities in the ionosphere vary greatly with time as already noted.

The major part of the ionization is produced by solar x-ray and ultraviolet radiation, and by radiation from the solar wind of the Sun and space rays. The most noticeable effect is seen as the Earth rotates with respect to the Sun; ionization increases in the sunlit atmosphere and decreases on the shadowed side. Although the Sun is the largest contributor toward the ionization, cosmic rays make a small contribution, as do auroras caused by solar storms. Any atmospheric disturbance affects the distribution of the ionization.

The ionosphere is a dynamic ever-changing system controlled by many things including acoustic motions of the atmosphere, electromagnetic emissions, and variations in the geomagnetic field. Because of its extreme sensitivity to atmospheric changes, the ionosphere is a very sensitive monitor of atmospheric events. The most accurate way of measuring the ionosphere is with a ground-based ionosonde, which records data as ionograms. It is an essential component of Earth’s Global Electric Circuit.
Earth’s Transient Luminous Events (TLEs)

Transient Luminous Events (TLEs) – Rising high in the upper atmosphere, often starting just above large thunderstorms, are electrical phenomena called sprites, blue jets, and elves—collectively known as Transient Luminous Events or TLEs. They are essentially electric discharges and pulses that can deliver large quantities of current to the upper atmosphere – from the tops of thunderstorms to the atmosphere's upper edges. These upper atmospheric optical phenomena are a relatively new discovery with definitive data emerging since only the 1990s.

TLEs are not easy to see with the naked eye, as they are usually hidden above thunderstorms. However, astronauts and high-altitude pilots have been reporting TLE-like phenomena, often above violent thunderstorms, for the last 40 years or more. Reports of TLE’s came as early as 1895, but were not taken seriously until special video and camera technologies in the 1990s were able to record them at frame rates as high as 4,000 frames per second.

Little is known about TLEs as they occur in a region that is too high for most aircraft and too low for most satellites to study them. Being a relatively new discovery in atmospheric physics, TLEs’ initiation and development are not yet fully understood. Other types of luminous events have also been recorded called crawlers, trolls, and pixies.

Sprites can appear just above an active thunderstorm, extending up to 96 kilometers or 60 miles from the top of a thundercloud. They are seen as a large but weak flash, lasting no more than a few seconds. They are sometimes described as resembling jellyfish, carrots or columns in shape. They are red due to the nitrogen (the main element in our air) that is ionized by strong electrical fields.

Blue jets are also seen emerging from the top of thunderclouds, extending in narrow cones at heights of 15-22 km or 25-35 miles, and lasting only a fraction of a second. Sometimes airline pilots witness these. Recently, blue jets have been observed occupying a volume of the Earth’s atmosphere as large as 30,000 cubic kilometers (about 7,200 cubic miles), or, the size of ten billion Olympic-sized swimming pools.

Elves are expanding disc-shaped glowing regions that can be very large, up to 300 km or 186 miles across. They last less than a thousandth of a second. A low-light video camera on the space shuttle in 1992 was needed to discover and verify these phenomena. They tend to occur above active cloud-to-ground lightning and are believed to be energetic electromagnetic pulses that extend up into the ionosphere—the energetic region of charged particles ionized by solar radiation—extending from the upper mesospheric layer of the Earth’s atmosphere all the way into space.

Currently, there is research looking into the possibility of sprites, jets, and elves playing an important role in the Earth’s Global Electric Circuit. It is believed that they may help reduce the difference in charges that build up between the surface and the ionosphere nearly 80 km (50 miles) or more above the ground. At this upper level of the Earth’s atmosphere, the ionization of its gases affects the propagation of radio waves, which can be essential to global communication.

There are approximately two thousand thunderstorms at any given moment raging across the Earth, and they are thought to act as the generator for the Global Electric Circuit. These thunderstorms are thought to drive electric charges upward into the ionosphere, to then return towards the Earth’s surface through regions of fair weather.

This happens through the weakly conducting atmosphere in a slow and continuous discharge. Think of it as if thunderstorms are acting as the battery-charging piece of the Earth’s Global Electric Circuit. TLEs help to off load some of the charge from the ionosphere and appear to emit radio waves in the process.

TLEs likely play an important role in the Earth’s atmospheric chemistry, including the formation of ozone and the planet’s chemical cycles. Meteors also may play a role in some TLEs. Not surprisingly, there is much still to learn to fully understand Transient Luminous Events and their magnificent, yet fleeting, visual displays.

At Right – Blue jets are a high altitude optical phenomenon observed above thunderstorms using low light television systems. As their name implies, blue jets are optical ejections from the top of the electrically active core regions of thunderstorms. They are not aligned with the local magnetic field. Intense efforts are presently underway to determine the full extent to which these newly discovered phenomena form a part of the terrestrial electrical environment. A clear view above a thunderstorm is required. This generally means the thunderstorm activity must be on the horizon. Additionally, there must be very little intervening cloud cover. Best viewing distance from the storm is 160-320 km (100-200 miles).

Source: University of Alaska, Fairbanks
Earth’s Clouds – Although cloud formation sounds matter-of-fact, many of the processes that lead to their formation and role in Earth’s electric pathways remain mysteries. Scientists interested in modeling Earth’s Global Electric Circuit must gather and analyze cloud data so that these mysteries are better understood.

Few things are more common in nature than clouds. They are made of water droplets or ice crystals that are so small and light that they stay afloat in the air. But how does the water and ice that make up clouds appear? Why do different types of clouds form? Are small particles needed for their formation? What accounts for cloud electrification that can produce lightning or no lightning at all? And how important are clouds’ contributions and role in Earth’s Global Electric Circuit?

The water or ice that makes up clouds travels into the sky as water vapor, the gas form of water, mainly by evaporation from oceans, lakes, and rivers on Earth’s surface. When air rises in the atmosphere in areas of low pressure and/ or weather fronts, air eventually will cool. When it does, it’s not able to hold all of the water vapor it once held. Air also cannot hold as much water when air pressure declines. Consequently, the vapor condenses and becomes small water droplets or ice crystals, and a cloud is formed.

It’s easier for water vapor to condense into water droplets when it has a particle to condense upon. These particles, such as dust and pollen, are called condensation nuclei. Eventually, enough water vapor condenses upon condensation nuclei to form a cloud. Scientists involved in modeling the Global Electric Circuit are interested in the role these particles play in impacting the electrical conductivity of the atmosphere as well as in cloud formation.

Cloud questions are plentiful, especially in terms of their microphysics and their role in the Global Electric Circuit. How do electromagnetic fields develop, and how do they influence clouds to produce powerful lightning or no lightning at all? What role do thunderstorms and other electrified, non-lightning or lightning-producing clouds play in maintaining the potential difference in electricity between Earth’s surface and the upper atmosphere? What type of electrical currents do these clouds produce, and are the currents stronger, weaker, or the same over land and ocean?

These are the kinds of questions that scientists need to find answers to in order to adequately build a model of the system. The physics and microphysics that occur on very small scales to produce electricity in a cloud are also critical. Research suggests that precipitation-based charging is the strongest precursor for an electrified thunderstorm. In fact, thunderstorms are thought to play a major role as generators of Earth’s fair-weather circuit.

Earth’s Lightning and Electrified Storms – Right now, at this very moment, there are about two-thousand thunderstorms occurring around the world. Even though thunderstorms are common, they are still dramatic events with intense rain, hail, wind, lightning, thunder, and even tornadoes. Many people consider lightning to be the most spectacular element of a thunderstorm. In fact it is how thunderstorms got their name. After all, lightning causes thunder.

Lightning is a discharge of electricity. A single stroke of lightning can heat the air around it to 30,000°C (54,000°F). This extreme heating causes the air to expand explosively fast. The expansion creates a shock wave that turns into a booming sound wave known as thunder.

As ice crystals high within a thunderstorm cloud flow up and down in the turbulent air, they crash into each other. Small negatively charged particles called electrons are knocked off atoms within water molecules as they crash past each other. This separates the positive (+) and negative (-) charges within the cloud. Most often, the top of the cloud becomes positively charged while the base of the cloud becomes negatively charged.

Because opposites attract, the negative charges at the bottom of the storm cloud are attracted to the ground’s positive charge or the positive charges gathered at the cloud’s top. In regard to cloud-to-ground lightning, once the negative charges at the bottom of the cloud build, a flow of negative charge called a stepped leader rushes toward the Earth. The positive charges on the ground are attracted to the stepped leader, so positive charge flows upward from the ground. When the stepped leader and the positive charge meet, a strong electric current carries positive charge up into the cloud. This electric current is known as the return stroke. We see it as the bright flash of a lightning bolt followed by thunder.

Thunderstorms and lightning represent one of the sources within this global electrical system. But there are still questions as to how much lightning contributes. It’s also very interesting to know how much Transient Luminous Events contribute, including sprites, elves, and blue jets. Because they are related to lightning and/or thunderstorms, their influence is of equal importance. Gigantic jets, another type Transient Luminous Event, are especially interesting because they take the negative charge from thunder-clouds and transport it to the ionosphere. They also form a direct pass of electrical contact between a thundercloud and the lower ionosphere.

The Sun, the Earth, Earth’s magnetosphere, and the atmosphere’s layers, ionosphere, clouds, particles, lightning-filled thunderstorms, and Transient Luminous Events are all essential components to Earth’s Global Electric Circuit. We may not know everything we need to at this point in time to fully understand and model the system, but scientists are beginning to unravel its secrets.
Meet the Scientists

Project Scientists Working on the Frontiers of Earth System Dynamics
to Understand Earth’s Global Electric Circuit

Learn more about the team from video interviews about their work:
http://sisko.colorado.edu/FESD/Public.htm

Sarah Al Momar – Sarah is an undergraduate student studying science at Valaparaiso University. She is working on the Global Electric Circuit (GEC) research as an intern with the SOARS program at NCAR. Her scientific mentor is Wiebke Deierling.

Wiebke Deierling – Wiebke is a scientist at NCAR researching the properties within clouds that lead them to be electrified (or not) and produce lightning (or not). Cloud physics is her specialty.

Stan Edwin – Stan is a student at the University of Alaska, Fairbanks who spends his summers contributing to the Global Electric Circuit research at NCAR as an intern within the SOARS program. His scientific mentors are Art Richmond and Astrid Maute.

Jeff Forbes – Jeff is the principal investigator of the research to better understand and model the Global Electric System in all its parts. He is a professor within the University of Colorado’s Aerospace Engineering Sciences.

Christina Kalb – Christina is an associate scientist at NCAR who is working to advance our knowledge of the role clouds play as an essential component of the Global Electric Circuit (GEC).

Victor Pasko – Victor is a co-principal investigator on the GEC research. He is a leading scientist on lightning and Transient Luminous Events – sprites, elves, and blue or gigantic jets – and works at Pennsylvania State University.

Art Richmond – Art’s research interests and expertise include upper atmospheric dynamics and electrodynamics. He is one of the principal investigators on the GEC research and is a scientist with NCAR’s High Altitude Observatory division.

Ray Roble – Ray is a senior scientist emeritus at NCAR and lead the way with some of his early research on the Global Electric Circuit in the 1970s. His specialty is the science of the upper region of the atmosphere.

Jeff Thayer – Jeff is a professor in the University of Colorado’s Aerospace Engineering Sciences. His focus is the region of space strongly influenced by Earth’s gravitational field, magnetic field, plasma, and neutral interactions.
The sites below highlight some of the best resources online for various ages to learn about electricity and science relevant to the Global Electric Circuit research. They are classified as follows:  
A = Advanced  MS = Middle School Level  G = General, All

**Educational Sites**

**Global Electric Circuit Video on YouTube** (G) –  Access the video designed as an accompaniment to this Teacher’s Guide on the National Center for Atmospheric Research’s AtmosNews YouTube site. A general overview of the Global Electric Circuit is provided appropriate for upper elementary through high school levels. It also highlights the challenges inherent in modeling Earth’s electrical system across various spatial and time scales. [www.youtube.com/user/ncarucar](http://www.youtube.com/user/ncarucar)

**Caltech Physics Applets** (A) – This site was developed for Caltech physics students but why not learn about electricity and magnetism through their exceptional interactive applets? A circuit tutorial demonstrates how a resistor, a capacitor, and an inductor react with one another. Still another applet illustrates the electric fields surrounding variously distributed charges; Others demonstrate concepts relating to moving charges, magnetic fields, and more. [www.cco.caltech.edu/~phys1/java.html](http://www.cco.caltech.edu/~phys1/java.html)

**Electric Ben Franklin** (G) – Ben Franklin is one of the most well-known people in American history. In addition to his involvement in government and the printing industry, Franklin was a great innovator in science and technology. Learn about his famous kite experiment and his other electrical research by visiting this informative interactive site dedicated to his life and work. While you’re there, don’t forget to watch “The Ben Show.” [www.ushistory.org/franklin/index.htm](http://www.ushistory.org/franklin/index.htm)

**Electricity and Magnetism Experiments** (G) – This site describes more than a dozen exciting electricity and magnetism experiments designed for a fourth-grade level. The experiments introduce important concepts, such as why resistors are resistant to electrical flow. [www.galaxy.net/~k12/electric/index.shtml](http://www.galaxy.net/~k12/electric/index.shtml)

**Electronics for Kids** (G) – This site introduces elementary students to the basics of electronics by showing how magnetism, static electricity, and simple circuits work. [www.users.stargate.net/~eit/kidspage.htm](http://www.users.stargate.net/~eit/kidspage.htm)

**Exploring Electric Fields** (A) – This site offers an interactive electric charge field simulator. Charges are placed in a plane area where field lines can be traced or deleted along with charges. The site offers a bit on theory and additional details to explain the use of the program. [www.gel.ulaval.ca/~mbusque/elec/main_e.html](http://www.gel.ulaval.ca/~mbusque/elec/main_e.html)

**Fizzics Fizzle** (A, MS, G) – This is a site that offers physics interactive applets and content. Click on the appropriate Beginner, Intermediate, or Advanced section to review content on electricity and magnetism at an appropriate level. Intermediate and above assumes basic knowledge of algebra and trigonometry. [www.galaxy.net/~k12/electric/index.shtml](http://www.galaxy.net/~k12/electric/index.shtml)
FOSS Web Magnetism and Electricity Module (G, MS) – This is the official site for the FOSS science curriculum and includes a collection of interactive materials on electricity and magnetism aimed at elementary and middle school students that are both engaging and educational. www.fossweb.com/modules3-6/MagnetismandElectricity/

Interactive Plasma Physics Education Experience (MS) – This site provides interactives aimed at middle-school students and older to learn about energy, matter, electricity, magnetism, the laws of motion and related topics. It is designed to make abstract concepts concrete and easier to understand. www.ippepx.ipp.uk/research/interactive

Magnet Lab at the National High Magnetic Field Laboratory at Florida State University (MS) – Explore this site and its many activities to learn about magnetic fields through hands-on activities, slides shows, and more. www.magnet.fsu.edu/education/tutorials/slideshows/fieldlines/index.html

Magnet Man (G) – This website is devoted to magnetism and the cool experiments you can carry out with permanent magnets and electromagnets. It includes basic activities appropriate for elementary through high school students. www.coolmagnetman.com/magindex.htm

MIT Open Course Ware on Electricity and Magnetism (A) – There’s much to learn via the multitude of course offerings online at MIT on electricity and magnetism. You’ll find many multimedia visualizations, illustrations, and interactives. www.ocw.mit.edu/courses/physics

NATIONAL ENERGY EDUCATION DEVELOPMENT (NEED) Project (G, MS) – NEED designs and delivers curriculum and support for virtually any classroom and at any grade level—from Kindergarten to High School and beyond—from Science and pre-engineering labs to Language Arts and Afterschool Clubs. Students use hands-on, inquiry based lessons to explore the physics and chemistry of energy. Their electricity modules are highly recommended. www.need.org

NOAA’s Space Weather Brighten Up the Classroom Resources (G) – Teacher materials on space weather are freely downloadable from this site. Be sure to download the "Out of this World" board game to use in lessons about radiation hazards. www.swpc.noaa.gov/info/kids/index.html

PhET at the University of Colorado (A) – PhET offers fun, interactive, research-based simulations of physical phenomena from the University of Colorado at Boulder. View simulations under Electricity, Magnets & Circuits. www.phet.colorado.edu

Physics 2000 (A) – This University of Colorado at Boulder Website conveys physics concepts and interactive applets, many on electromagnetism in a manner that is conversational and well-conveyed through animations on this award-winning site. www.colorado.edu/physics/2000/index.pl

Scientific Models Video from Annenburg (MS) – A scientific model is a “testable idea... created by the human mind that tells a story about what happens in nature.” Annenburg’s video explaining models helps students understand the value of scientific models. www.learner.org/courses/essential/physicalsci/session2/closer1.html

UCAR Center for Science Education at the National Center for Atmospheric Research (NCAR) (G) – NCAR is one of the partners on the NSF-supported Global Electric Circuit research. Find out about the atmosphere and the Global Electric Circuit itself from their educational site. www.sciEd.ucar.edu/atmosphere

Key Website and Other Resources on Content Relevant to Research on Earth’s Global Electric Circuit

The references listed below provide much more content information on the Global Electric Circuit:

Frontiers of Earth System Dynamics at the University of Colorado (A, MS) – This is the official website for the NSF-sponsored research on the Global Electric Circuit. Hear from the scientists themselves through video interviews made available on the site. www.sisko.colorado.edu/FEOSD/

NCAR’s High Altitude Observatory (HAO) – This scientific site at the National Center for Atmospheric Research will expose individuals to research on the Sun and the many areas of solar physics. Scientists from HAO are active members of the Global Electric Circuit research team sponsored by the National Science Foundation (NSF). www.hao.ucar.edu

AtmosNews – Air, Planet, People – on YouTube – The National Center for Atmospheric Research’s AtmosNews YouTube site introduces a variety of videos pertinent to atmospheric research. www.youtube.com/user/nrcarucar

Heliophysics from NASA – This website highlights NASA flight missions that advance our knowledge in the following areas: the heliophysical system and understanding of the Sun and its effects on the Earth, the solar system, and space environment conditions that are experienced by human and robotic explorers. It also explores technologies that enable and enhance life and society that are related to and/or impacted by the Sun-Earth system. www.heliophysics.nasa.gov

NOAA’s Space Weather Prediction Center – Obtain up-to-the-minute information about space weather and geomagnetic storms from this site. Explore the site map to access other helpful resources. www.swpc.noaa.gov

Sun-Earth System Comics – A variety of expertly written explanations of different features of the Sun-Earth system in comic book form can be found and downloaded from this site: www.bu.edu/cawses/capacity.html

Lightning and Atmospheric Electricity Research – This website highlights the work of NASA’s Global Hydrology and Climate Center (GHCC). They seek to advance our knowledge of the relationship between the electrical characteristics of storms and precipitation, convection, and severe weather. GHCC has designed, constructed, and deployed numerous types of ground-based, airborne, and space-based sensors used to detect lightning and characterize the electrical behavior of thunderstorms. The data collected is routinely shared with scientists around the globe, resulting in numerous advancements in the field of Atmospheric Science. thunder.msc.nasa.gov

Sailing the Magnetic Fields, The story of the Carnegie Vessel – Find out more details about the Carnegie Vessel and the creation of the Carnegie Curve during the early 1900s from this informative site. http://carnegiescience.edu/legacy/exhibits/aultexhibition/bibl_sailing.html

The Sun, The Earth, and Near-Earth Space, a book by John A. Eddy ; NASA Living with a Star, 2009, p. 301 – A non-technical introduction to the highly hazardous world just outside Earth's door in near-Earth space that is governed by less familiar laws of physics and ruled by the often moody star we call our Sun. It illustrates the many ways that the Sun-Earth system affects much of what we do in our everyday lives.
Glossary of Terms
Amp or Ampere: a unit of electrical current density (A/m²)

Aerosol: a fine solid or liquid particle suspended in air, such as a dust mote

Atom: the smallest unit of a chemical (such as carbon or oxygen) that exhibits the properties characteristic of that element

Aurora: diffuse, glowing light emitted from atoms and molecules in the Earth's upper atmosphere when incoming high energy particles from the Sun or the Earth's magnetosphere collide with them. Auroras are associated with geomagnetic activity and occur approximately 100 to 250 km above the ground.

Capacitor: a capacitor (formerly called a condenser) is a passive two-terminal electrical component used to store energy in an electric field. They are used commonly as parts of electrical circuits. When there is a potential difference (voltage) across two capacitors (conductors), a static electric field develops.

Carnegie Curve: the characteristic and universal variation of Earth's atmospheric electric field, that was first discovered from 1909 to 1928 via trans-oceanic measurements taken on board the Carnegie vessel sponsored by the Carnegie Institute

Carnegie Vessel: a yacht that was nearly entirely non-magnetic and wood-hulled, sailed around the world – nearly three hundred thousand miles through its oceans – carefully locating and measuring then unknown magnetic influences in the atmosphere from 1909 to 1928.

Charge: a basic property of matter carried by some elementary particles. Electric charge can be positive or negative.

Conductor: an object or type of material which permits the flow of electric charges in one or more directions

Coronal Mass Ejections (CMEs): segments of the Sun's outer corona that have been expelled from the Sun into interplanetary space in the form of expanding clouds of solar plasma, some as large or larger than the Sun itself

Cosmic Rays: highly energetic atomic nuclei stripped of most or all of their electrons, that pass at all times and from all directions through intergalactic, interstellar and interplanetary space. The most energetic of these (called galactic cosmic rays) presumably originate in dynamic cosmic phenomena within or beyond the galaxy, such as supernova explosions

Dynamo: a device through which mechanical energy (e.g., in an electric generator, or the movement of a conductor through a magnetic field) is changed into electric energy. The solar dynamo works in a similar way by harnessing the mechanical energy of differential rotation to twist polar field magnetic lines within the Sun into toroidal fields (perpendicular to the Sun's axis of rotation.) These in turn give rise to sunspots when they are carried upward by convection to the solar surface.

Electric Field: a region of space in which a detectable electric intensity is present at every point

Electromagnetic radiation: radiation consisting of oscillating electric and magnetic fields, including gamma rays, visible light, ultraviolet and infrared radiation, radio waves and microwaves

Electromagnetic Spectrum: the entire range or electromagnetic radiation, from gamma rays to microwaves

Electron: a sub-atomic particle with a single negative charge and a mass of less than 1/1000 that of a proton, the corresponding positively charged particle

Elve: rapidly expanding rings of predominantly red light centered well above causative cloud-to-ground lightning; Believed to be faster than light with diameters up to 300 km across on time scales faster than 1 millisecond.

Exosphere: the region of relatively constant high temperature in the Earth's atmosphere above an altitude of about 600 miles. Here the few neutral atoms and molecules that remain are on their way out of the atmosphere due to their high thermal velocities and the very low density of the region.

Flare; Solar Flare: a sudden eruption of energy on the Sun lasting minutes to hours, from which radiation and particles are emitted

Gamma Rays: high energy radiation (energies in excess of 100 keV) observed during large, extremely energetic solar flares.

Geomagnetic Storm: a worldwide disturbance of the Earth's magnetic field, distinct from regular diurnal variations that is caused by solar storms

Global Electric Circuit: an atmospheric system that links the electric field and current flowing in the lower atmosphere, ionosphere, and magnetosphere forming a giant spherical condenser, which is charged by the thunderstorms to a potential of several hundred thousand volts and drives vertical current through the atmosphere

Ion: an atom or molecule in which the total number of electrons is not equal to the total number of protons, giving the atom a net positive or negative electrical charge

Ionization: electromagnetic radiation or energetic nuclear particles that are capable of producing ions (charged atoms) directly or indirectly as they pass through matter.

Ionosphere: the region of Earth's upper atmosphere containing a small percentage of free electrons and ions produced by photo ionization of the constituents of the atmosphere by solar ultraviolet radiation at very short wavelengths.
Ionospheric D, E, and F Regions: horizontal strata in the middle and upper atmosphere of the Earth where free electrons are sufficiently abundant to affect the passage of radio and other electromagnetic radiation through these regions: D region at 40-60 miles; E region at 60-80, and F region at about 100 to 1000 miles or more above Earth's surface.

Jet: electrical phenomena associated with upward-directed lightning shooting out of cloud tops with various sizes. Jets are most commonly blue in color.

Magnetic Field: a mathematical description of the magnetic influence of electric currents and magnetic materials. At any given point, it is specified by both a direction and a magnitude (or strength) and is produced by moving electric charges and the intrinsic magnetic moments of elementary particles.

Magnetosphere: the magnetic cavity surrounding the earth, carved out of the passing SOLAR WIND by virtue of the Earth's geomagnetic field which prevents, or at least impedes, the direct entry of the solar wind plasma into the cavity.

Mesosphere: a layer of Earth's atmosphere above the stratosphere approximately 50 km (31 miles) to 85 km (53 miles) high.

Model (scientific/mathematical): a mathematical description of nature and its processes that can be tested and can predict things about many similar situations.

Neutron: a subatomic particle forming part of the nucleus of an atom and having no charge.

Ohm's Law: Ohm's law states that the current through a conductor between two points is directly proportional to the potential difference across the two points.

Plasma: any ionized gas, that is, any gas containing ions and electrons.

Potential Gradient (V/m): also called electric potential that refers to the electric potential charge measured between two points.

Proton: a subatomic particle forming part of the nucleus of an atom and having a positive charge.

Radiation: a process in which energetic particles or energetic waves travel through a media or vacuum that are not required for their propagation.

Radiation Belts: "belts" formed by clouds and currents of particles that are trapped in Earth's magnetic field high in the atmosphere.

Resistance: a measure of the degree to which an object opposes an electric current through it.

Schumann Resonance: global electromagnetic resonances, excited by lightning discharges in the cavity formed by the Earth's surface and the ionosphere.

Solar Cycle: the approximately 11-year quasi-periodic variation in frequency or number of solar active events.

Solar Maximum: the month(s) during the solar cycle when the 12-month mean of monthly average sunspots reach a maximum.

Solar Minimum: the month(s) during the solar cycle when the 12-month mean of monthly average sunspot numbers reaches a minimum.

Solar Wind: the outward flux of solar particles and magnetic fields from the Sun. Typically, solar wind velocities are near 350 km/s.

Sprite: large, brief, and often highly-structured bursts of light occurring high above thunderstorms in response to cloud-to-ground lightning flashes that remove large amounts of charge from the upper portions of a cloud. A single sprite can span altitudes from 40 km up to 80 km (25 miles to 50 miles).

Stratosphere: the second major layer of Earth's atmosphere, just above the troposphere, and below the mesosphere. It is stratified in temperature, with warmer layers higher up and cooler layers farther down and occurs from approximately 10–13 km (30,000–40,000 ft; 6–8 mi) and 50 km (160,000 ft; 31 mi) altitude above the surface.

Thermosphere: the layer of Earth's atmosphere directly above the mesosphere where the Sun's ultraviolet radiation (UV) causes ionization or charged particles in a region called the ionosphere. Meaning heat in Greek, the thermosphere begins about 85 kilometers (53 mi) above the Earth and temperatures increase with altitude due to absorption of highly energetic solar radiation. Temperatures are highly dependent on solar activity, and can rise to 2,000 °C (3,630 °F).

Transient Luminous Events (TLEs): a term that collectively includes fleeting optical and electrical phenomena associated with lightning and electrified clouds in Earth's atmosphere that include elves, sprites, and jets.


Troposphere: the lowest layer of Earth's atmosphere extending to approximately 20 km (or 12 miles) at most at the equator where it is thickest. Weather occurs in this layer and temperatures commonly decrease in altitude.

Voltage: electric potential energy per unit charge, measured in joules per coulomb (V = volts).

Wilson Current: semi-continuous current flow above electrified clouds considered a critical component of the Global Electric Circuit; however, only a few studies have directly investigated this current, yielding a few dozen measurements.