Electricity in the Atmosphere (Extra Credit Assignment)

Israel Ben Aron

When we think of electricity in the world, we tend to think of electronics such as phones, televisions, appliances, and lights. Much less considered is the electricity on a literal global scale- electricity in the atmosphere. Before modern electronics and even before we discovered that rubbing amber with silk produces static electricity, the only exposure humans had to electricity was from that of the heavens. Of course, there was electrical phenomena occurring all around our predecessors, but what they saw was what we nowadays neglect, the thunderstorm. Many attributed the enormous lightning strokes to be the might of the gods such as the Greek god Zeus or the Roman equivalent Jupiter. As this paper will show, the mechanism for the Earth's atmospheric electricity is much more complex than the sudden whims of the gods' temperament. Ironically, after all these years of being fascinated by lightning, we still know little about it. This paper will answer some basic questions and will explore what we know and do not know about electricity in the atmosphere. It will also maintain some historical context throughout in the hopes the reader gains some understanding about how the results were obtained.

The first major breakthrough in atmospheric electricity came by the hands of Benjamin Franklin. He was the first one to make a connection between electricity and lightning. He observed that lightning and electrical sparks make the same sound and both travel in zigzags [1]. Franklin eventually devised a complicated experiment using a sentry box with a large external metal rod. However, after he came up with this experiment, Franklin thought of an even simpler way of proving that lightning and electricity were one and the same- by using a kite. Standing next to a barn, he flew a kite with a metal key attached at the end. He held the string of the kite with a silk ribbon, to act as an insulator. When he moved his hand near the key, he observed sparks jumping from the key to his hand proving that lightning was just another form of electricity [1]. This discovery opened the door for scientists to uncover more results in atmospheric electrical phenomena.

Many people know that the Earth has a magnetic field which allowed sailors to navigate through the oceans in late antiquity. Few know that there is an electric field as well as a magnetic field. From many measurements which will be discussed later, the Earth's electric field is about 100 V/m. One may wonder why they do not get shocked by just walking down the street. The reason we do not is because of equipotential surfaces. Equipotential surfaces are surfaces that maintain the same electric potential at all points. Usually, the equipotential surfaces on Earth are parallel to its surface [2]. Good conductors, such as our bodies, when on the ground, become part of the electrical ground that is the Earth. This means that when our bodies or any conductor is jutting out from the Earth's surface, the equipotential surface shifts so that the conductor maintains a zero electric potential at any height along the object. Equipotential surfaces of the Earth are shown in Fig. 1 [2].

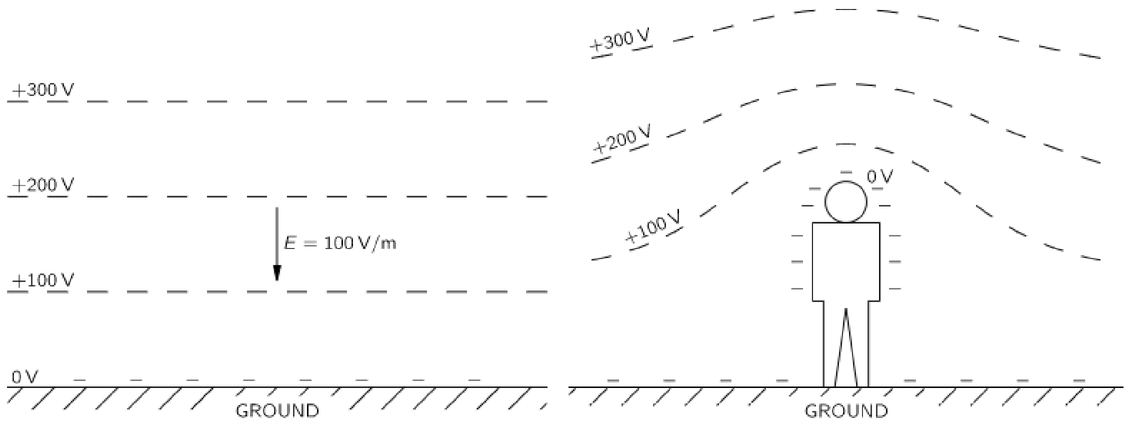

Fig. 1. The equipotential surface of the Earth at normal conditions juxtaposed with the equipotential surface when there is a conductor present [2].

This electric field can be measured in many ways which will briefly be outlined. One of the earliest measurements employed an insulated wire that was exposed to the atmosphere with an electrometer connected to it [3]. Yet another measurement used a water dropper which consisted of a bucket constantly spewing water droplets. When the water broke into droplets, a little bit of charge was transferred into the air. After a period of time, the water dropper's electric potential became equal with the potential of the air at which point a measurement for the electric field can be obtained. Credit for this experiment goes to Lord Kelvin, who in 1860 came up with this method [3].

It was discovered that the electric field points down towards the Earth's surface. This means that the Earth is negatively charged i.e. the Earth has more electrons and negatively charged ions than it does positively charged ions. This also means that at some point in the upper atmosphere, there is an abundant amount of positively charged ions. This is because the electric field points from positive points to negative ones. The region in the atmosphere that has this abundance of positive charges is known as the ionosphere as shown in Fig. 2. The ionosphere is made up of ionized gases that act as excellent conductors [4]. This separation of charges yields a potential difference of about 400,000 V. This is obtained since the height of the atmosphere is about 50,000 m. If one were to simply multiply this height by 100 V/m, one would assume that the answer would be the potential difference. This is true except that the electric field gets weaker as one goes up to higher elevations. In reality, most of the potential difference is at lower altitudes yielding the 400,000 potential difference. The measurements for the electric field in the upper atmosphere came from sending balloons up with equipment like the water dropper system which began in the late nineteenth century.

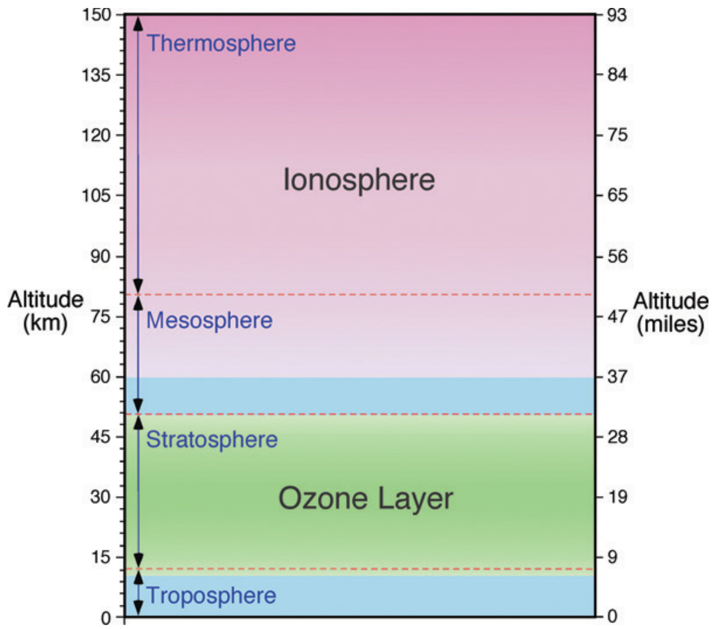

Fig. 2. Layers of the atmosphere. The ionosphere is about 90 km about the surface.

Since there is a charge separation, we can imagine that the Earth acts as one giant spherical capacitor with air as a dielectric. Whenever there is a potential difference there also is a current flow. Since air is not a perfect insulator, there is conduction between the ionosphere and surface of the Earth. This current flows from the ionosphere to the Earth's surface since current by convention is the flow of positive charges. This also means that electrons and negatively charged ions are flowing away from the surface. As a result, the Earth becomes more positively charged as time goes on. The Earth would lose almost all its charge within an hour if it was not replenished in some way [5]. The current can be found by using the basic principle that relates current with current density J and area A given by

$$I = JA. \qquad (1)$$

Using this relation with measured current density and surface area of the Earth yields an approximate current of 1800 A. A good illustration of this is shown in Fig. 3 [4].

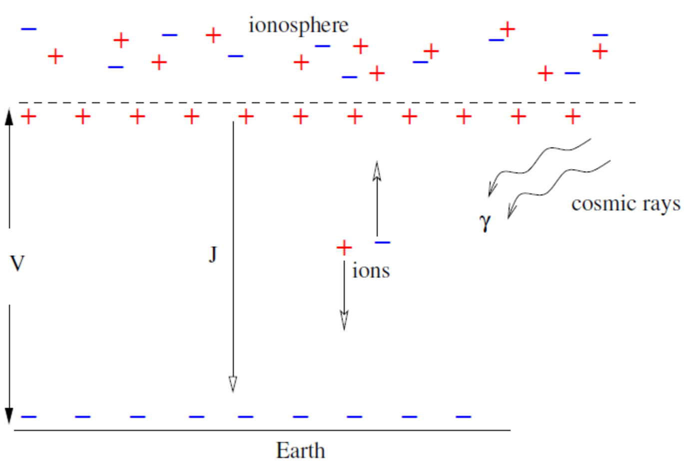

Fig. 3. Separation of charge between the ionosphere and Earth's surface with current density flow [4].

As stated above, the current relies on the ability of the air to conduct electricity. We can measure the conductivity of air using various measurement techniques. The same balloons used for potential gradient measurements were also used to measure air conductivity. A device known as a Gerdien tube was used (named after inventor). This consisted of an insulated electrode inside an outer electrode in a cylindrical shape with a gap between the electrodes. The central electrode was charged up and air was pumped through the gap between the electrodes. Using an electrometer, the rate at which the voltage of the center electrode decreased was able to be measured. This allows the air conductivity to be found [3]. The air conductivity is what allows current to flow so these measurements were important in determining the current in the atmosphere.

One can imagine that the electric field, current or air conductivity are constant all the time over the entire surface of the Earth. This, however, is a false presumption. The truth is that these parameters fluctuate over a 24-hour period in universal time. From 1909-1929, several voyages aboard the *Carnegie* took place. On these voyages, scientists were able to measure the potential gradient of the Earth and the air conductivity (i.e. current) at various positions across the globe. At first, the measurements were approximate at best since the instrumentation was lacking. On later voyages more sophisticated equipment was used with better data collection methods. Scientists were able to collect data of the air conductivity and potential gradient using devices such as a parasol collector as shown in Fig. 4 [3]. They also employed a radioactive collector which was used for continuous collection of the potential gradient [3]. The results of these voyages were quite astounding. They found that the electric field oscillates over a 24-hour period as shown in Fig. 5 [3]. This time is universal meaning that the same fluctuation occurs all over the Earth at the same time (i.e. when the electric field peaks, it peaks everywhere). Further investigation into this oscillation found that thunderstorm activity across the globe correlates strongly with the curve as shown in Fig. 6 [3].

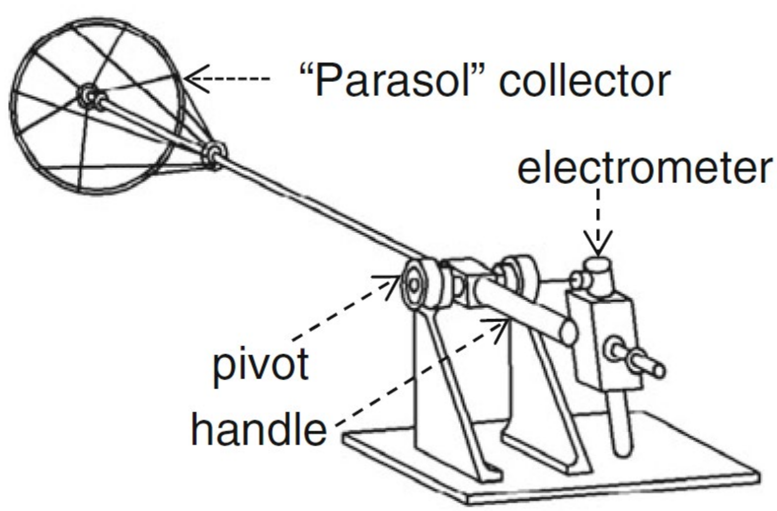

Fig. 4. Parasol collector used to measure the potential gradient of the Earth.

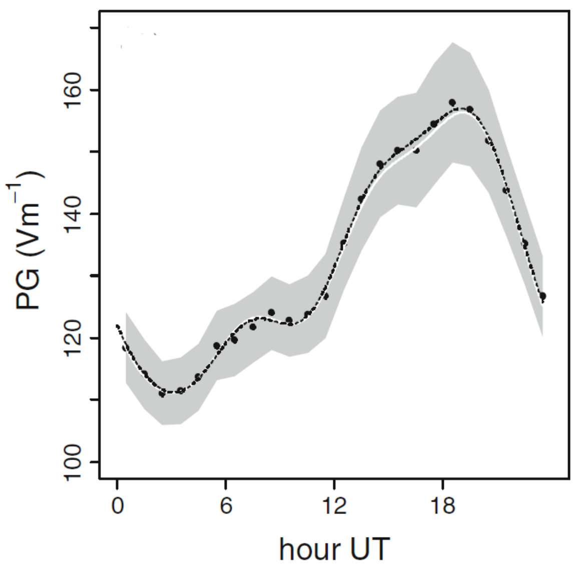

Fig. 5. Potential gradient oscillation of the Earth over a 24-hour period.

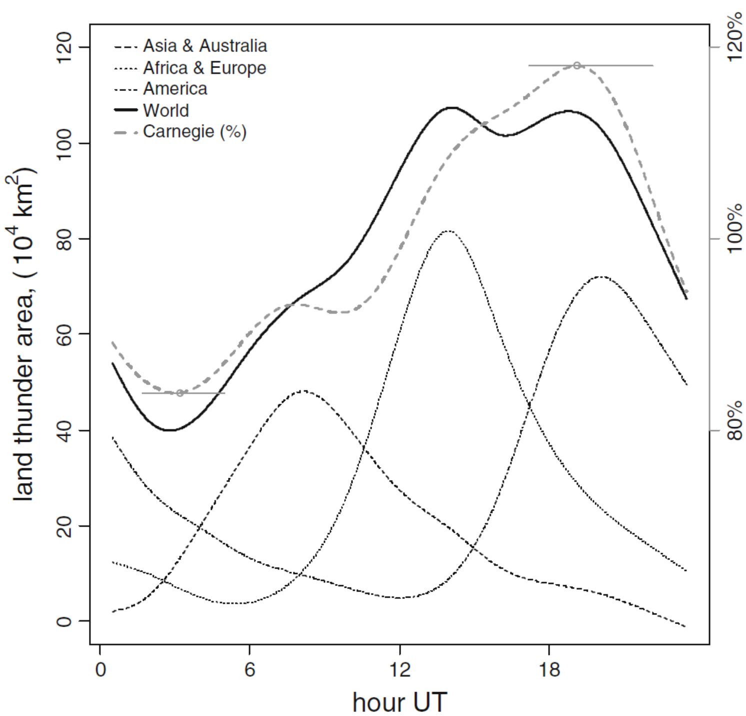

Fig. 6. Correlation between Carnegie curve (dashed line) and total area of thunderstorms occurring (thick solid line). The other lines are the contributions of thunderstorm land area from regions around the globe.

Since the Earth acts as a capacitor and there is conduction in the air, an active discharging of charge occurs. The Earth can be portrayed as one giant circuit as shown in Fig. 7 [1]. This shows that between the ionosphere and the surface of the Earth, there is a capacitance, a resistance and current. The capacitance can be easily found using the simple relation given by

$$C = \epsilon_0 \frac{A}{d}, \tag{2}$$

where A is the surface area of the Earth and d is the distance between the surface and the ionosphere. This gives us about a 0.7 F capacitance between the ionosphere and surface. The resistance can be found using Ohm's law which gives

$$R = \frac{V}{I}, \tag{3}$$

where V is the potential difference between the lower regions of the ionosphere and Earth's surface (about 250 kV) and I is the current which was found using (1). This yields a resistance of about 200 Ω. Then the discharging of the voltage in the capacitor as time t increases is given by

$$V(t) = V_0 e^{\frac{-t}{RC}}, \tag{4}$$

where V_0 is the initial voltage and R and C are the found resistance and capacitance, respectively. Equation (4) shows that the voltage decreases exponentially as a function of time.

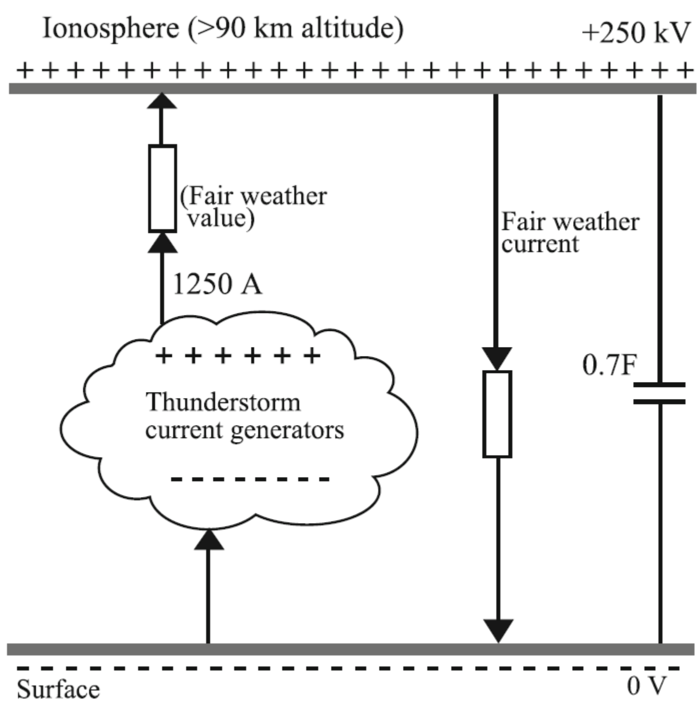

Fig. 7. Circuit representation of the Earth.

As mentioned earlier, the discharging would deplete the Earth's charge within an hour if the charge was not returned somehow. This replenishing of charge comes from the thunderstorms that occur all over the Earth's surface. From the thunderstorms, lightning strokes return charge to the Earth. This is very profound. How does the Earth know to replenish charges? In this sense, the Earth acts like a giant autonomous organism. Charge in the ionosphere is replenished from cosmic rays penetrating the upper atmosphere and delivering positive charges to the ionosphere. This results in the overall positive charge in this region. Then the positive charges are brought down to the surface of the Earth through the current that exists from the charge separation and conduction in the air. This means that the Earth becomes more positively charged. So why is there still an electric field from the ionosphere to the surface? If the surface became more positive and we know that the ionosphere is always positive from cosmic rays, there should not be an electric field pointing towards the surface, it should be pointing away from it. However, there is charge separation. This is maintained from the lightning striking the Earth.

One can make the comparison between the Earth and a biological cell- particularly a neuron. In neurons, there is a charge separation maintained between the intracellular and extracellular regions. In the extracellular region, there is a concentration of Sodium (Na^+) ions and in the intracellular region there is a concentration of Potassium (K^+) ions. These ions can pass in between the cell membrane when their corresponding ion channels are open. Ion channels are openings in the cell membrane that are selective to which molecules they let through. The sustained potential difference is due to ion pumps imbedded in the cell membrane. These pumps pump out Potassium ions which make the overall concentration of positive charges on the outside of cell greater than the charges inside the cell. This maintains the overall negative charge inside of the cell and on the membrane. A healthy neuron has about a -70 mV potential inside the cell membrane which is known as the membrane potential [6]. There is also a current that is flowing from outside the cell to inside it. This current delivers positive ions making the membrane potential less negative. This process is known as depolarization. If the neuron depolarizes enough to increase the membrane potential above a threshold value, an action potential is created. An action potential is essentially a fluctuation in the potential of the cell membrane. This is shown in Fig. 8 [6]. These action potentials send electrical signals to other neurons and are responsible for our ability to think, react, release endorphins and process information. Modelling these action potentials can be done quite accurately using the Hodgkin-Huxley model which describes the membrane current i_m as time goes on. This is given by

$$i_m = g_L(V - E_L) + g_K n^4(V - E_K) + g_{Na} m^3 h(V - E_{Na}), \quad (5)$$

where g_L, g_K, g_{Na} are constant conductances of the ion channels, E_L, E_K, E_{Na} are constant reversal potentials of the ion channels, V is the voltage across the cell membrane, and n, m and h are gating variables which are solved using given equations.

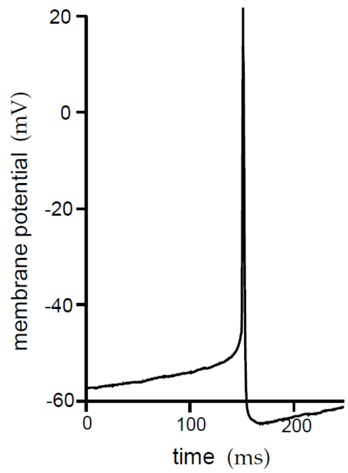

Fig. 8. Action potential plotted as membrane potential versus time.

This biological process is easily comparable to atmospheric electricity. There is a maintained charge separation between the intracellular and extracellular regions just like there is a charge separation between the ionosphere and surface of the Earth. The extracellular region holds positive charge and is supplied from the extracellular medium which is made up of nutrients we ingest that are allowed to pass through the blood-brain barrier. This is just like the positive charge-supplying ionosphere which is made up of positive ions from cosmic rays and solar wind. The pumps that separate the charges on each side of the cell membrane is easily comparable to the thunderstorms that return negative charges back to the Earth. One can even compare the spiking action potentials to the rapid strikes of lightning.

Thunderstorms, just like the ion pumps, maintain the charge separation between the ionosphere and the surface. Thunderstorms are made up of thunderclouds which form just like any other cloud. Given the right conditions, a cumulus cloud can turn into a cumulonimbus cloud which we call thunderclouds. These thunderclouds have a distribution of charge within them which develops as the thundercloud develops. Inside the thundercloud, updrafts push the warm, damp air to heights where it condensates. This promotes the condensing of water vapor inside the cloud. At the same time, the temperature of the cloud decreases. There is also air coming from the sides of the thundercloud which contributes to the height of the cloud. This rising air column is known as the cumulus stage [1]. This is shown in Fig. 9 [2].

As the temperature continues to decrease within the thundercloud, some of the water droplets form ice crystals and some form supercooled water droplets which are droplets that stay in liquid form below $0\ °C$. These supercooled droplets can collide with the ice crystals to form graupel particles (essentially soft hail) [1]. When the collision occurs, the supercooled droplets can freeze onto the ice crystals which allow them to grow into graupel particles. Once the graupel particles reach a big enough size, the upward air drafts cannot counteract their weight and they begin to fall. When the graupel falls, they drag air with them which generate downdrafts. As they fall, they collide with ice crystals and supercooled water droplets which are moving up in the updrafts. This is what is thought to generate electric charge within a cloud. The cloud at this stage is known as a mature thundercloud [1]. This is shown in Fig. 10 [2]. This is the stage where the thundercloud can generate lightning strikes.

As the graupel particles continue to fall, they reach a height where the temperature is high enough to melt them. This produces the water droplets which we know as rain. As the precipitation intensifies, the downdrafts intensify. This means that the updrafts cease, and the cloud mainly has downdrafts. This is the final stage of the thundercloud as shown in Fig. 11 [2]. Without the updrafts, the cloud does not receive the warm humid air necessary for growth. Thus, after some time, the cloud vaporizes ending the cycle of the thundercloud. However, this does not stop the thunderstorm since it is made up of many thunderclouds which continue to grow and evolve.

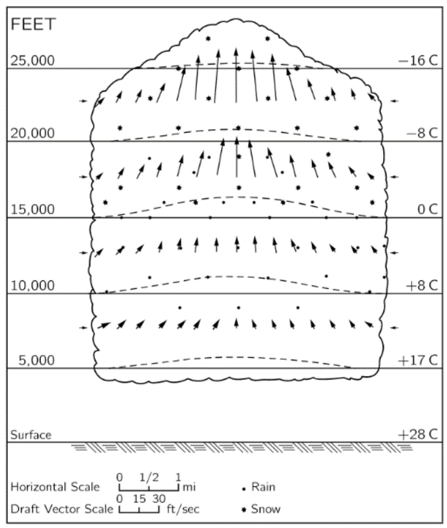

Fig. 9. First stage of a thundercloud. The updrafts drive moist air upwards until it condensates.

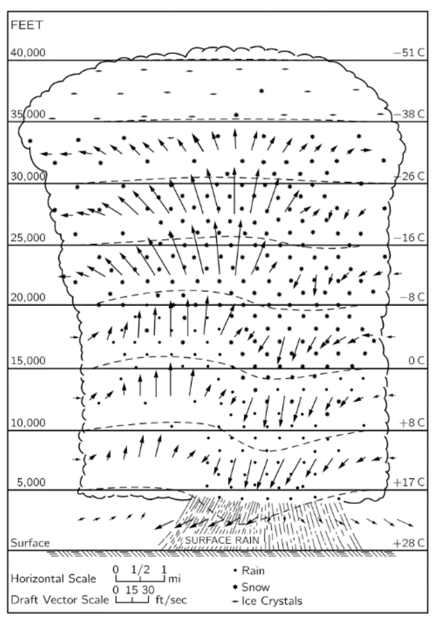

Fig. 10. Second stage of a thundercloud. The cloud has updrafts and downdrafts from the falling graupel.

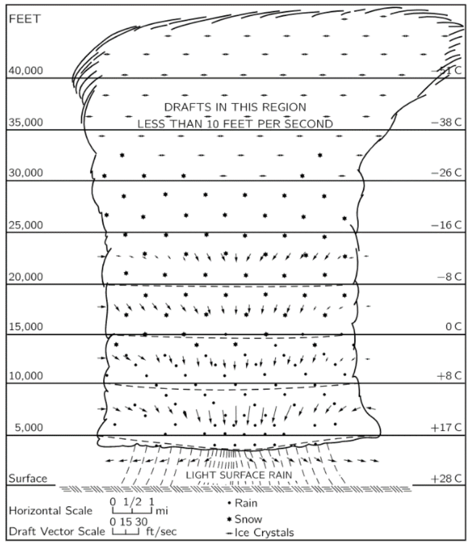

Fig. 11. Final stage of a thundercloud. This is where downdrafts are mainly present over updrafts.

As mention earlier, the graupel inside a thundercloud is thought to be responsible for the charge separation within the cloud. There has been much debate about the polarity of the thunderclouds within the last few hundred years [7]. For many years, it was thought that thunderclouds were essentially giant dipoles with positive charges at the top and negative charges at the bottom of the cloud. From data collected by pilots who flew through the thunderclouds, it is now known that the structure of charge in a thundercloud is tripolar as shown in Fig. 12 [1].

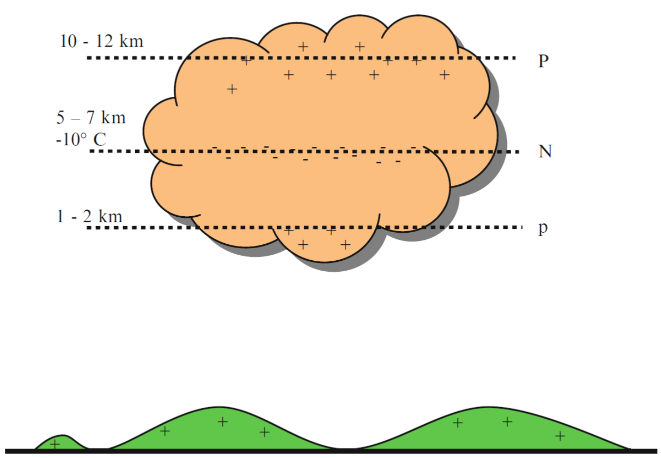

Fig. 12. Tripolar charge composition within a thundercloud.

The tripolarity of the thundercloud is mainly due to ice-graupel collisions within the cloud. When graupel falls from high altitudes, it collides with ice particles moving upwards in the updrafts. When the temperature is below -15 to -10 $°C$, the graupel charges negatively and the ice crystals charge positively [1]. The updraft takes these newly positively charged ice crystals to high altitudes in the thundercloud. This results in the overall positively charged region in the cloud. It also results in the negatively charged center which is composed of the falling graupel particles. As the temperature increases above -15 to -10 $°C$, the graupel charges positively and the ice crystals charge negatively. These negatively charged crystals also contribute to the central negative region in the cloud. The positive graupel falls towards the lower regions of the cloud forming the pocket of positive charges which accounts for the tripolar structure of the thundercloud. This process expresses that the particles being charged within a thundercloud depend on temperature. This is shown in Fig. 13. In the upper regions of the clouds the temperature is low as compared with the higher temperature at the bottom of the cloud.

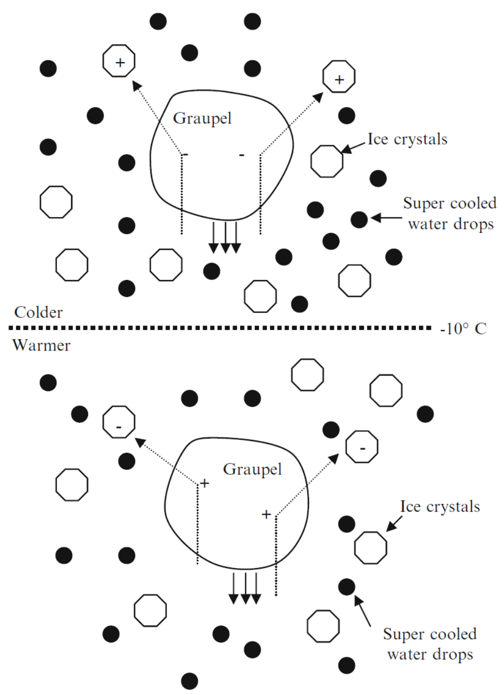

Fig. 13. Graupel charging as the temperature changes in the cloud.

When the thundercloud matures with a present charge separation, lightning can begin to form. Lightning is a rapid release of charge from a thundercloud [5]. The thunderstorm forms over a region where the Earth has more positive charge on the ground. This is what promotes lightning to strike at these locations. The lightning comes from within the negative region of the thundercloud striking the Earth in an attempt to return negative charges there. Thus, lightning is responsible for maintaining the charge separation between the ground and the ionosphere by delivering negative charges to the ground. Lightning strikes when the difference in charge between the negative region of the cloud and the ground become great enough that there is a current flow between them. Essentially, the lightning overcomes the breakdown voltage of the air which allows conduction.

Lightning can also strike from cloud to cloud, but we will focus on cloud to ground discharges. The lightning strokes begin with a pilot leader. This leader is emitted from the cloud which is faintly visible and travels at a sixth the speed of light [2]. Then surge currents trail the leader along its path. These currents are known as step leaders. These leaders progress through the air towards the ground in a step like fashion as shown in Fig. 14 [2]. As a leader moves towards the ground, it ionizes the air creating a path that can conduct electricity. Once they get near the ground, the electric field at the surface increases. Eventually, the leader will get close enough (a few hundred meters) so that the electric field at the tips of ground structures intensifies enough to where positive leader discharges are instigated from them [1]. These discharges are called connecting leaders and are positive since they emanate from the positively charged ground region as shown in Fig. 15. Taller structures give off taller connecting leaders which accounts for why tall buildings get struck by lightning.

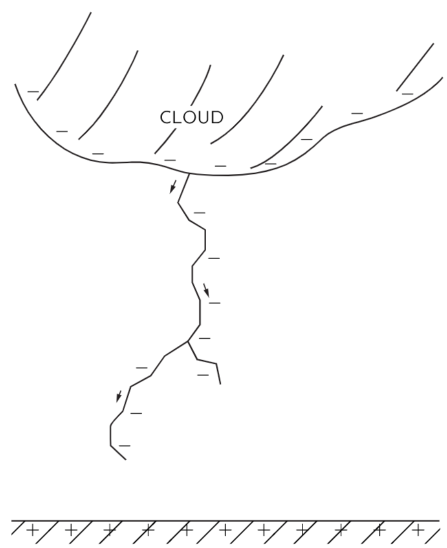

Fig. 14. Step leader progressing towards the ground.

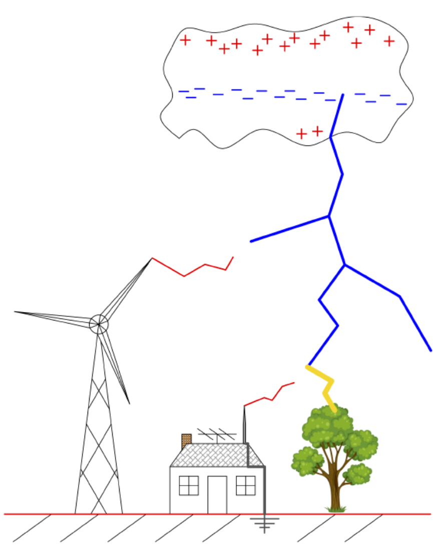

Fig. 15. Connecting leaders emanating from ground structures.

Eventually, the step leader will get close enough to the connecting leader and they will jump towards each other until they connect. This connection establishes a conductive path for the negative charges inside the thundercloud to escape from it. Before the negative charges from the cloud leave, however, the electrons in the step leader discharge to the ground. When they discharge, they leave a positive charge in the channel connecting the ground and the higher region of the step leader. This positive charge attracts the negative charge from the channel above which gets discharged too. This process continues until there is a positive current column (since negative electrons move in the opposite direction) travelling up the step leader to the cloud. This is known as the return stroke. This stroke is the main stroke which creates the sound we hear as thunder. This sound comes from the rapid expansion of the surrounding air and we hear it because sound propagates with the movement of air molecules.

After the return stroke occurs, another leader from the cloud emerges. This time it travels along the path of the previous leader that made the connection with the ground. Because of this, the new leader travels to the ground almost immediately unlike the step leader which was trying to “find” the ground. This leader is known as a dart leader. Dart leaders carry negative charges just like the step leader. Then once it connects to the ground, a return stroke is generated again along the same path up to the cloud. These dart leaders can continue to come down until the charge within the cloud is dissipated. Each stroke can reach a current of about 10,000 A and delivers about 20 C of charge.

There are still many things we do not know about lightning. For instance, we do not exactly how lightning works. The best we can do is describe it using the tools we have. Furthermore, we do not *why* lightning strikes the way it does. These mysteries may or may not be answered as we discover more about the electrical phenomena in the atmosphere. Research in this field has been ongoing since the time of Franklin. As we have explored, results in atmospheric electricity have steadily come out. At the beginning of the twentieth century we did not know how to measure the electric field of the Earth and by the end of it, we have come up with theories about how charge separation occurs within a thundercloud. When compared to results from other fields, atmospheric electricity does not have much to show for itself. It is surprising that more emphasis has not been placed here since humans have always wondered about lightning. But perhaps people think we understand enough to explain what we see. This is unfortunate since many wonderful, surprising results have emerged such as the tripolar structure and the ice-graupel collision theory. There is still a lot to explore and many more questions to answer.

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