ESCI 340 - Cloud Physics and Precipitation Processes
Lesson 12 - Lightning
Dr. DeCaria

References:

The Lightning Discharge, Uman
The Electrical Nature of Storms, MacGorman and Rust
Fundamentals of Lightning, Rakov
'Runaway Breakdown and the Mysteries of Lightning', Gurevich and Zybin, *Physics Today*, 2005

Mechanisms of Charge Separation

- The top of a thunderstorm (cumulonimbus) cloud becomes positively charged, while the middle-to-lower portions of the cloud becomes negatively charged.
- Often there is also a smaller pocket of positive charge near the bottom of the cloud.
- The reason for this charge separation is not completely understood, but some of the more prominent theories are described below.
- Those mechanisms requiring a preexisting electric field are called ***inductive*** charging mechanisms, while those not requiring a preexisting electric field are called ***noninductive*** charging mechanisms.

  Inductive ion capture: In a preexisting electrical field, there will be a separation of charge across a hydrometeor. As the hydrometeor falls, gaseous ions will either be attracted or repelled from the underside of the hydrometeor, depending on their sign. Thus, the hydrometeor will gain an increasing charge of whatever sign it has on its topside. In Fig. 1 the positive ions are repelled as the hydrometeor falls, but the negative ions are attracted. Thus, the hydrometeor gains a net negative charge as it falls.

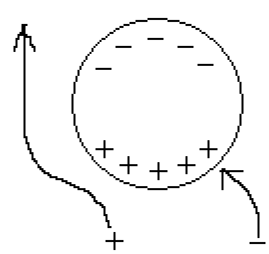

Figure 1: Inductive ion capture.

Ion capture may play a role in weakly electrified storms, but cannot be used to explain the amount of charge separation seen in a thunderstorm without the presence of other mechanisms.

Inductive particle rebound: Two hydrometeors in a preexisting electric field, falling at different speeds, will exchange charge during collision as shown in Fig. 2. The larger particle becomes negatively charged, and the smaller one becoming positively charged.

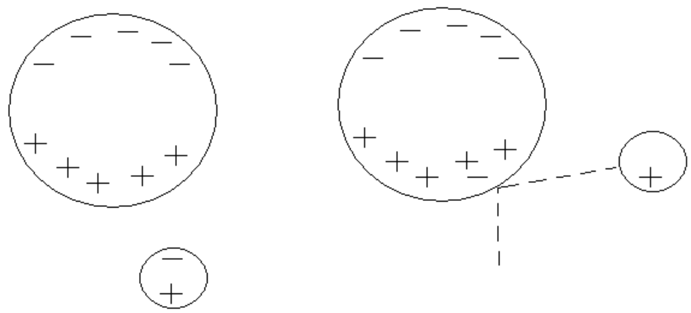

Figure 2: Inductive rebound.

According to MacGorman and Rust, this mechanism is only plausible for collisions between frozen precipitation and supercooled water droplets. The role of inductive particle rebounding in thunderstorm electrification is still controversial.

Noninductive convection: In this mechanism the charges for the thunderstorm come from external sources such as fair-weather positive space charges, corona discharges (positive charges), and cosmic rays (negative charges). The convection in the thunderstorm then redistributes these charges, with the updrafts moving the positive charges upward in the interior of the cloud, while along the negative charges are attached to cloud droplets at the edges of the cloud, and move downward with the entrainment-cooled downdrafts.

Noninductive graupel-ice mechanism: Laboratory experiments have shown that precipitation-sized graupel colliding with smaller ice crystals in the presence of supercooled liquid droplets results in the graupel and ice crystals obtaining charges opposite from one another. The sign of the charge on the graupel (+ or −) depends nonlinearly on the cloud liquid water content and temperature, shown qualitatively in Fig. (3).

- The transition temperature at which the graupel goes from obtaining positive to obtaining negative charges is in the range of −10°C to −20°C. This may explain why the negatively-charged region of a thunderstorms usually has temperatures in this range.
- The positively charged ice crystals are advected upward in the updraft, resulting in positive charge at the top of the storm. Any graupel which does gain a positive charge will fall toward the base of the thunderstorm, and may

help explain the existence of the positive charge pocket often found at the base of cumulonimbus clouds.

 – The physical mechanism by which the graupel-ice mechanism works is not understood.

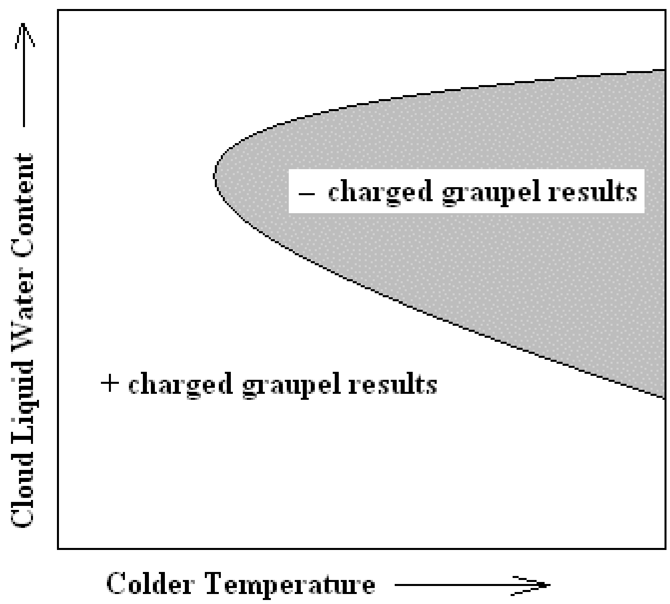

Figure 3: Qualitative relationship between cloud liquid-water content, temperature, and production of positive vs negative graupel via the noninductive graupel-ice mechanism.

- According to Rakov, "there is growing consensus that the graupel-ice mechanism is the dominant electification mechanism."
- However, lightning is also observed in volcanoes or severe dust storms, indicating that charge separation can occur even without the presence of graupel, ice, or other hydrometeors.

Corona

- The ***electric field*** is a vector whose positive direction is defined as the direction a positively charged particle will accelerate.
- Electrons, being negatively charged, will accelerate opposite to the electric field vector.[1]
- Corona, also known as ***point discharge***, occurs when the electric field is strong enough to accelerate free electrons to energies strong enough to ionize molecules.
- The ionization process produces additional free electrons which can then cause further ionization. This process is known as an ***electron avalanche***.

[1] In some applications the polarity of the electric field may be defined in the opposite manner.

- Narrow, pointed objects enhance the electrical field strength, and are the focal points for corona discharges (see Fig. 4).
  - Positive corona emanates from positively charged objects, and the electrons move toward the object.
  - Negative corona emanates from negatively charged objects, with the electrons moving away from the charged object.

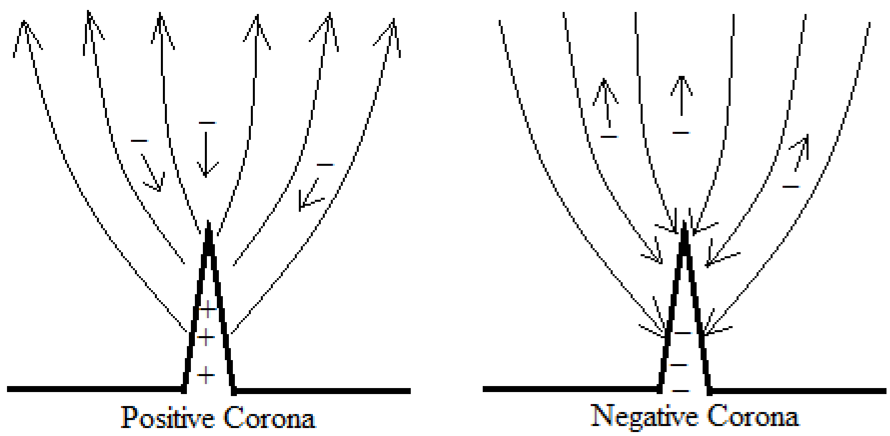

Figure 4: Positive and negative corona form a pointed object. The long, thin curved arrows represent the electric field lines. Electrons are represented by the '−' charges. Adapted from MacGorman and Rust.

- In positive corona the electrons are moving into a region of stronger electrical field, and their acceleration increases. In negative corona the electrons are moving into weaker electric field.
  - Because of this, positive corona can occur in weaker ambient electric fields. Negative corona requires a stronger ambient electric field.
- Corona may also be initiated by precipitation droplets or graupel in a cloud, particularly if they are irregularly shaped.
- The ionization and recombination process produces optical phenomena such as a luminous glow, halos, branches, and streamers.
- Corona may be intermittent or steady.
- Corona often occurs on the masts of ships, or wings of airplanes, and is known as ***St. Elmo's fire***.

Streamers

- A streamer begins at the tip of a pointed or narrow object, due to the enhanced electric field at the tip.
- Streamers are easier to produce from a positively charged object, and we will use positive streamers for our illustration of how streamers begin and propagate.
  - A free electron in the region of large electric field accelerates and collides with a molecule, ionizing the molecule and creating another free electron, which then accelerates an strikes another molecule, creating yet another free electron, resulting in electron avalanche.
  - The free electrons move toward the pointed object, while the positive ions move away. Thus, the head of the streamer is positively charged, and therefore behaves in a similar manner to the pointed object in term of altering the electric field lines (see Fig. 5).
  - Under the right conditions the streamer can become self-propagating.

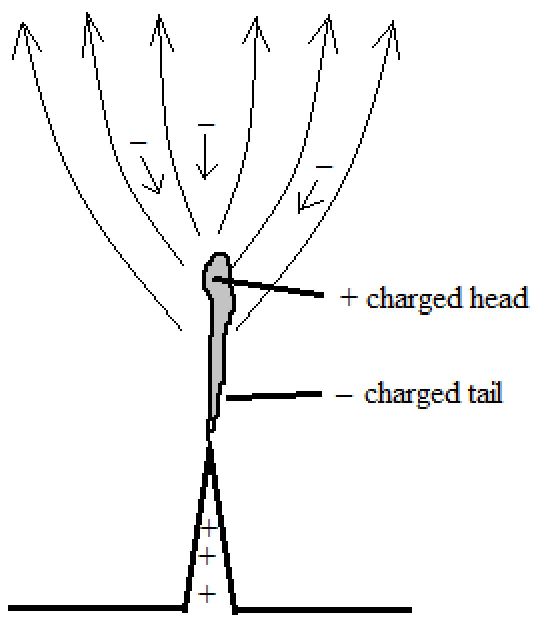

Figure 5: Streamer resulting from positive corona. The head of the streamer is positively charged, altering the electric field lines and promoting further corona.

Initiation of Electrical Breakdown

- In order for lightning to be initiated the electric field must reach the ***breakdown*** potential for the given atmospheric conditions.

- Even the strongest electrical field observation in a thunderstorm, 4×10^5 V m^{-1}, is smaller than the expected breakdown electrical field, which is around 10^6 V m^{-1}.
- Breakdown and initiation of lightning must be a more localized phenomena, and there are two main theories for how lightning is actually initiated.

Conventional Breakdown: Conventional breakdown theory postulates that the lighting discharge is initiated by corona and streamers forming on irregularly-shaped precipitation particles.

  - The precipitation particles can either be frozen particles such as graupel, or liquid droplets that have been deformed in the presence of an electric field.
  - The positive charge on the head of the streamer builds up, possibly due to sequential streamers developing and utilizing the debris field created by the previous streamer.
  - If the streamer head gains enough positive charge then the electric breakdown field value can be achieved.

Runaway Breakdown: In this theory, a ***runaway electron*** ionizes molecules, creating other runaway electrons, in a cascade-like sequence.

  - A runaway electron is an electron that is moving fast enough that it is gaining more kinetic energy from the electric field between collisions than it is losing during the collisions.
  - In order for runaway electrons to occur the electric field must exceed the ***break-even*** electric field, which is an order of magnitude less than the breakdown electric field.
  - It is believed that the initial high-energy electrons needed to start the cascade are provided by the numerous cosmic rays that constantly bombard the Earth's atmosphere.
  - In addition to creating high energy electrons, many slower free electrons will also be produced in the electron cascade.
  - Enough of these slow electrons may be produced that a small, highly conductive region will be created. The electric field created at the margins of this highly conductive region can exceed the conventional breakdown electric field.

- Which of these mechanisms is the dominant mechanism for lightning initiation is still an open question. It is also possible that neither mechanism is dominant, and an as-yet undiscovered mechanism may be the true mechanism.

Cloud-to-ground (CG) Lightning

- Cloud-to-ground lightning is any lighting discharge connecting the cloud to the ground.
- Negative CG lightning is defined to be that lightning that lowers negative charge to the ground (or moves positive charge upward).

- Positive CG lightning is defined to be that lightning that lowers positive charge to the ground (or moves negative charge upward).
- Negative CG lightning is more common than positive CG lightning.
- The negative charge region in the lower part of the cloud induces a positive charge at the ground underneath the cloud.
- Negative CG lightning proceeds in a distinct sequence:

Stepped leader: The stepped leader is an ionized path that forms from the cloud to the ground.

- It has many short segments, and is highly branched.
- Usually it is not even visible.
- The mechanism by which the leader advances is not completely known. Figure 6 illustrates the process observed in laboratory sparks, and described below.
  1. A detached, positively charged **space stem**, which is a zone of plasma, forms a few meters or so ahead of the leader tip.
  2. Positive streamers extend upward from the space stem toward the leader tip, while negative streamers extend downward.
  3. When the positive streamers connect with the leader tip the leader advances to the space stem, and enhanced negative streamers extend downward.
  4. A new space stem forms, and the process repeats.

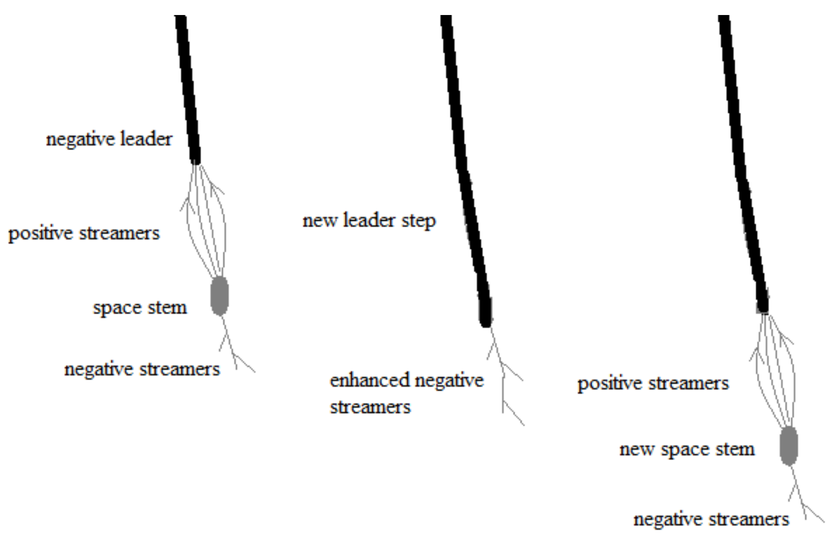

Figure 6: Theorized steps of an advancing negative stepped-leader.

Attachment: When the negative leader is within a few tens or hundreds of meters from the ground, a positive leader moves upward from the ground, usually from a tall or protruding object such as a tree, flagpole, golfer, etc. When the two leaders meet, a complete, ionized and conductive path is created between the cloud and the ground.

Return stroke: Once attachment has occurred, negative charge is quickly transferred to the ground.

- The charge transfer begins at the point of attachment, and proceeds as a wave both upward and downward from this point.
- The downward propagating wave reflects of the ground, and moves upward, quickly catching up with the upward propagating wave.
- The area of charge drainage moves quickly and continuously up the leader channel, with the area behind it becoming brightly illuminated due to the intense currents in the channel.
- The branches of the leader become illuminated as the return stroke reaches their junctions with the main channel.

Dart leader: After the return stroke subsides, another leader progresses back down the lightning channel.

- This leader is similar to the stepped leader, but is not branched and proceeds much more rapidly.
- As the dart leader approaches the ground another return stroke is initiated from the ground back to the cloud.

- The dart leader-return stroke sequence continues until enough charge is neutralized that the atmosphere is able to once again act as an insulator.
- On average there are 3 or 4 return strokes per CG flash, though there may be more than a dozen.
- The entire sequence of a CG flash lasts for only a few-tenths of a second.
- In rare instances lightning may be initiated by a positive leader extending upward from the ground, with the return stroke traveling downward from the cloud.
  - These upward flashes still lower negative charge to the ground.
  - Upward flashes will have branches extending upward rather than downward.
  - Upward flashes are most commonly initiated from very tall towers.
- The peak electrical current in a CG flash is typically 30 to 40 KAmps.
- The lightning channel is only a few centimeters in diameter.
- The air in the lightning channel is heated to temperatures as high as 60,000F.
- Most CG lightning normally lowers negative charge to the ground.
- A very small percent of CG lightning lowers positive charge to the ground.

  - Positive CG lightning connects the positive charge centers at the top of the cloud with the negative charge area on ground well away from the storm.
  - Positive CG discharges are usually much more energetic than negative CG lightning, and can have peak currents in the neighborhood of 60 kAmps.
  - Positive CG lightning is more likely to cause damage and start fires than is negative CG lightning.
  - Positive CG lighting is more likely to occur in winter and in colder climates. This is likely because winter convection is not as deep, so the positive charge center is closer to the ground.

Intracloud (IC) Lightning

- Intra-cloud lightning is a lightning discharge between charge centers within the cloud, or between clouds, and doesnt reach the ground.
- The vast majority (60 to 80 percent) of lightning is IC lightning.
- Less is known about IC lightning than CG lightning, because it is much harder to observe and measure.

Variants of CG and IC Lightning

- In this section we discuss some variants of CG and IC lightning. They are not really different from regular CG and IC lightning. It is just the perspective of the observer with respect to the location of the lighting channel that makes them appear different.

  Heat lightning: Heat lightning is distant lighting that occurs on a hot, clear night. People associated it with the hot temperatures, but it is really just lightning from very distant thunderstorm. It is so far away that the thunder is not heard.

  Sheet lightning: Sheet lightning is just IC lightning that illuminates a large section of the sky seemingly all at once. The lightning is embedded with a cloud, so the channel itself is not seen. The entire cloud appears to illuminate.

  Ribbon Lightning: Ribbon Lightning appears as multiple, parallel lighting channels that illuminate sequentially. It is caused by the wind blowing perpendicular to the observer, so that the lightning channel appears in a different location for each return stroke.

Ball Lightning

- Ball lightning is a rarely reported phenomenon of a ball of light or electricity that occurs during a thunderstorm. It may move through buildings or even airplanes.

- The balls are reported to be about the size of a grapefruit, and last for only a few second.
- Not much is known about ball lightning other than anecdotal accounts from persons encountering it.
- Many occurrences have been associated with CG lightning strikes, with the balls emanating from the ground contact point.
- It is a real phenomenon, and it is estimated that about 1 in 100 persons have seen it.

Discharges Above Thunderstorms

- Sprites, Jets, and ELVEs (a tortured acronym of Emissions of Light and Very low frequency perturbations from Electromagnetically pulsed source) are discharges in the upper atmosphere due to the rearrangement of charge from a positive CG flash.
- The rearrangement leads to a breakdown in the upper atmosphere above the thunderstorm.
- These were theorized to exist as early as 1925 when C.T.R. Wilson predicted their existence, but were not documented until 1989.

Thunder

- Thunder is the sound caused by the rapid expansion of the heated air in the lightning channel.
- The speed of sound in air is given as

  $$c_s = \sqrt{\gamma R_d T} \tag{1}$$

  where $\gamma = c_p/c_v$, the ratio of the specific heat at constant pressure to that of constant volume. R_d is the specific gas constant for dry air.
- Under standard atmospheric conditions sound travels at around 750 mph, or about 1/5 of a mile per second.
- Light travels at about 186,000 miles per second.
- An observer at a distance d from a lightning channel will see the light nearly instantaneously, but will not hear the thunder until later.
- Since sound travels at about 1/5 of a mile per second, each second of delay between observation of the light and hearing the thunder equates to a distance of 1/5 of a mile.

- Because sound travels more slowly in colder air, sound rays usually bend upward in the atmosphere. Therefore, if lightning is more than about 15 miles away the sound passes over your head and you do not hear it.

- Thunder rumbles because the sound generated by different parts of the lightning channel reaches you at different times. The closer you are to the lightning, the sharper and shorter the thunder will sound.

Lightning Protection and Safety

- A lightning rod is a long, metal rod designed to attract the lightning bolt and direct its current harmlessly through a wire to the ground.

- Lightning rods DO NOT prevent lightning strikes! They merely guide the strike to a hopefully safer contact location.

- A rod of height H will nominally protect a cone around it having a base of $2H$.

- The lightning rod must be well grounded. Otherwise the lightning may jump from the rod and pass through the structure that it was designed to protect.

- Some rules for general lightning safety are:
  - Lightning can travel great distances from the thunderstorm. If you can hear thunder, you are in range to be struck by lightning.
  - You are safer indoors than out of doors.
  - Stay away from doors and windows.
  - Do not use corded telephones during lightning storms.
  - Do not take baths or showers, as the current from a lightning strike can travel through the water pipes into your house.
  - Cars are relatively safe, but it IS NOT because of the rubber tires. It is because electricity stays on the outside of a metal cage such as a car body.
  - If caught outdoors, do not stand under trees, particularly isolated trees.
  - If caught in the open, crouch down on the balls of your feet, to minimize your height and to cut down on your surface contact with the ground.

Lightning and Atmospheric Chemistry

- Electrical discharges can alter the chemistry of the atmosphere in both the short-term and long-term.

- The smell of ozone(O_3) is often present near and in thunderstorms.

- Lightning does not produce significant amounts of ozone (at least not immediately and directly).
- However, corona discharge can directly produce significant amounts of ozone, and explains the odor of ozone near thunderstorms (and near electrical motors or equipment).

- Lighting does produce significant quantities of nitric oxide (NO) via the Zel'dovich mechanism

$$\begin{aligned} \mathrm{O_2} &\leftrightharpoons \mathrm{O} + \mathrm{O} \\ \mathrm{O} + N_2 &\leftrightharpoons \mathrm{NO} + \mathrm{N} \\ \mathrm{N} + \mathrm{O_2} &\leftrightharpoons \mathrm{NO} + \mathrm{O} \end{aligned}$$

  which requires very high temperatures. The net result is

$$\mathrm{N_2} + \mathrm{O_2} \leftrightharpoons 2\mathrm{NO}.$$

- NO is an important trace gas in the atmosphere, and can subsequently react with hydrocarbons to eventually produce ozone.
- Although lightning is not the most dominant source of NO in the atmosphere, the fact that most of the NO production occurs at high altitudes and cold temperatures means the lightning-produced NO has a longer lifetime than surface-produced NO, and can have a more significant impact on ozone chemistry.