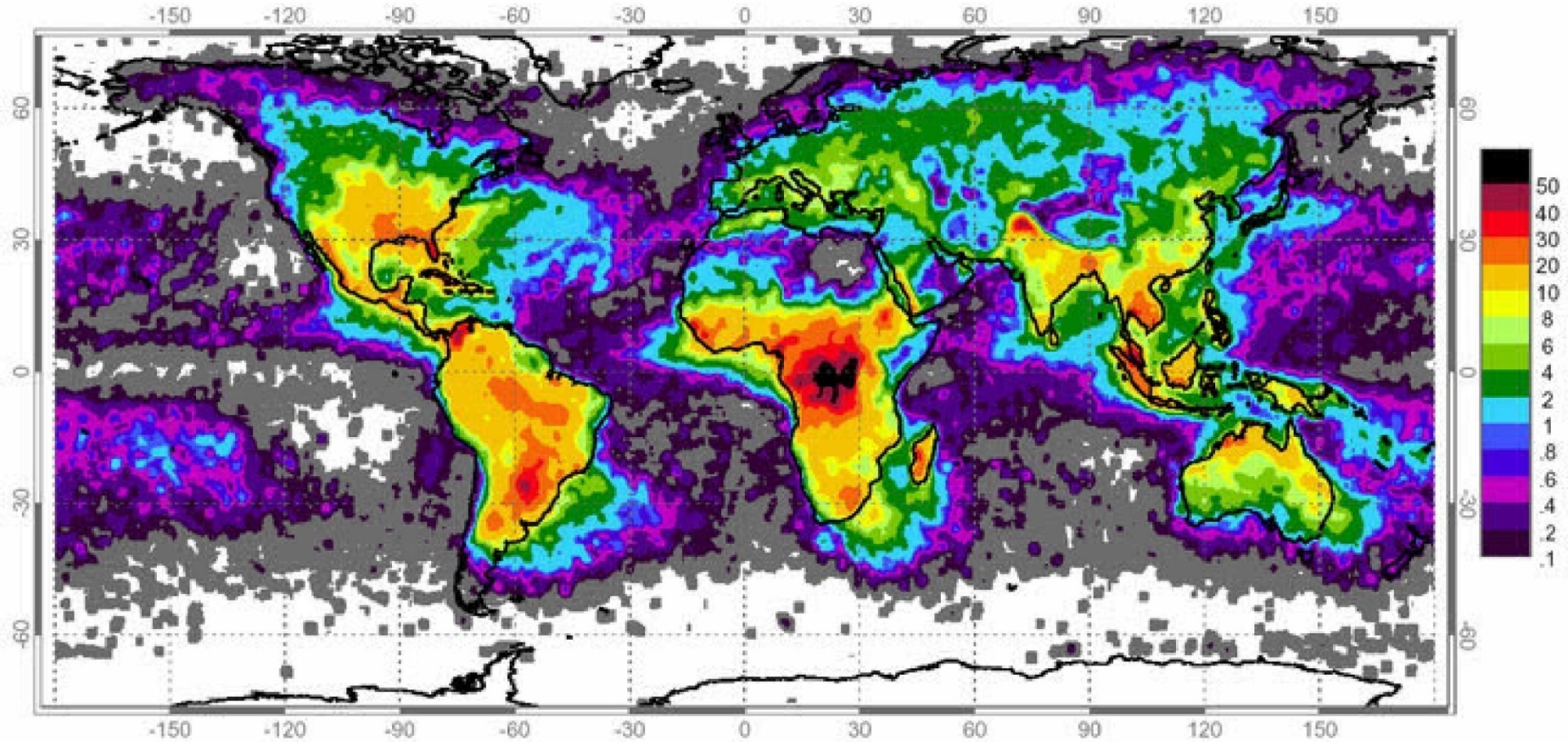
MET4300

Lecture 27: Lightning (CH21)

Lightning Frequency

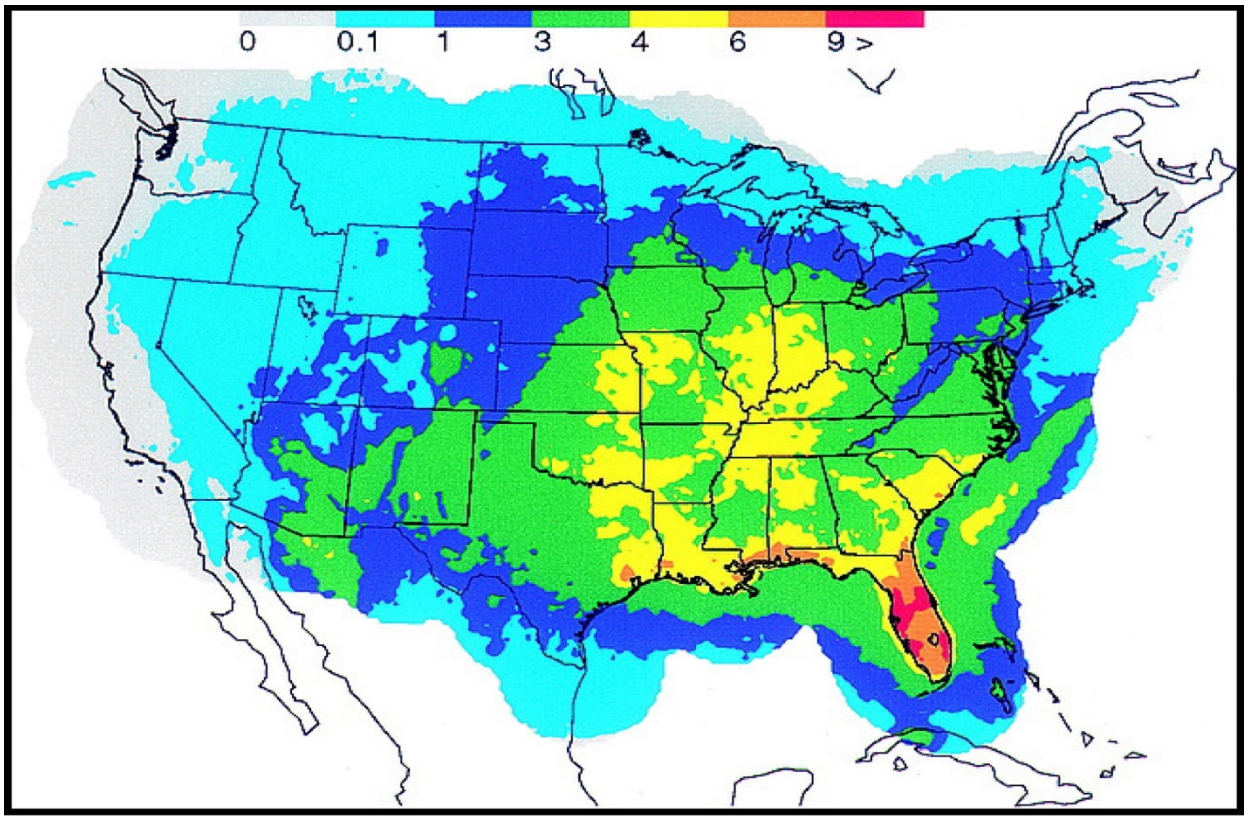
- About 100 lightning strikes every second over the world
- Over continental US, about 20 million cloud-to-ground flashes annually.
- Nearly half of all flashes strike the ground at more than one location simultaneously; so, on average, about 30 million locations are struck each year.

Lightning Distributions: Average annual number of lightning flashes per km^2 worldwide



More flashes over land, especially central Africa, central South America, southeast Asia, northern Australia, and the southeast US

Distribution of lightning strikes per km^2 per year in the US from 1989 to 1998

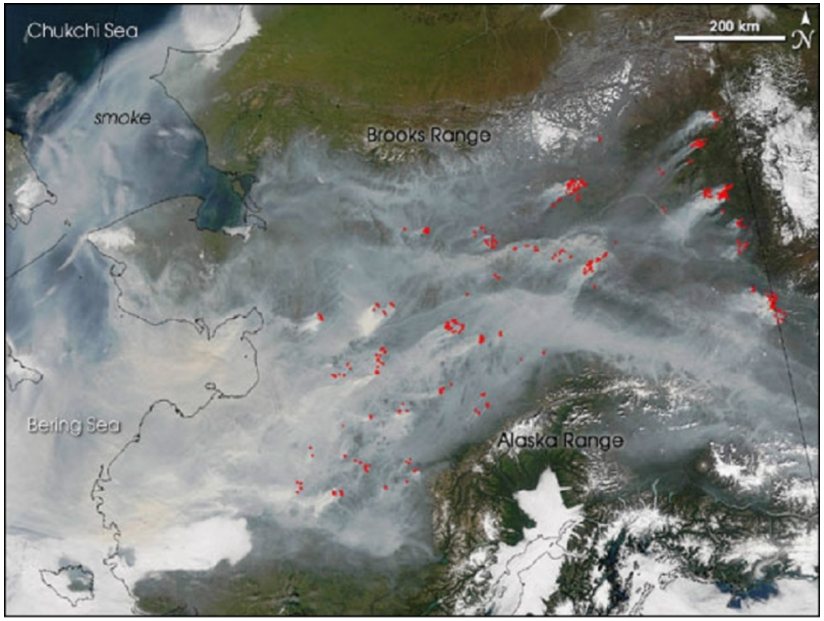


- Highest flash density in FL
- Higher along the Gulf and south Atlantic coasts, and the midwest
- Decreases northward and westward

Lightning Impacts

- Cause many forest fires in remote areas: 12,000 lightning-related forest fires in US.
- Damage buildings and start structure fires
- Kill 26 people a year (US), and injure 151 people on average around 2015 (80% male, 50% deaths occurred in open areas: ballparks, under trees, near or on water, on golf courses, on or near heavy equipment, in campgrounds, talking on corded telephones, etc.)
- Florida has the most fatalities
- Annual damage $50 million mostly due to lightning induced fires.

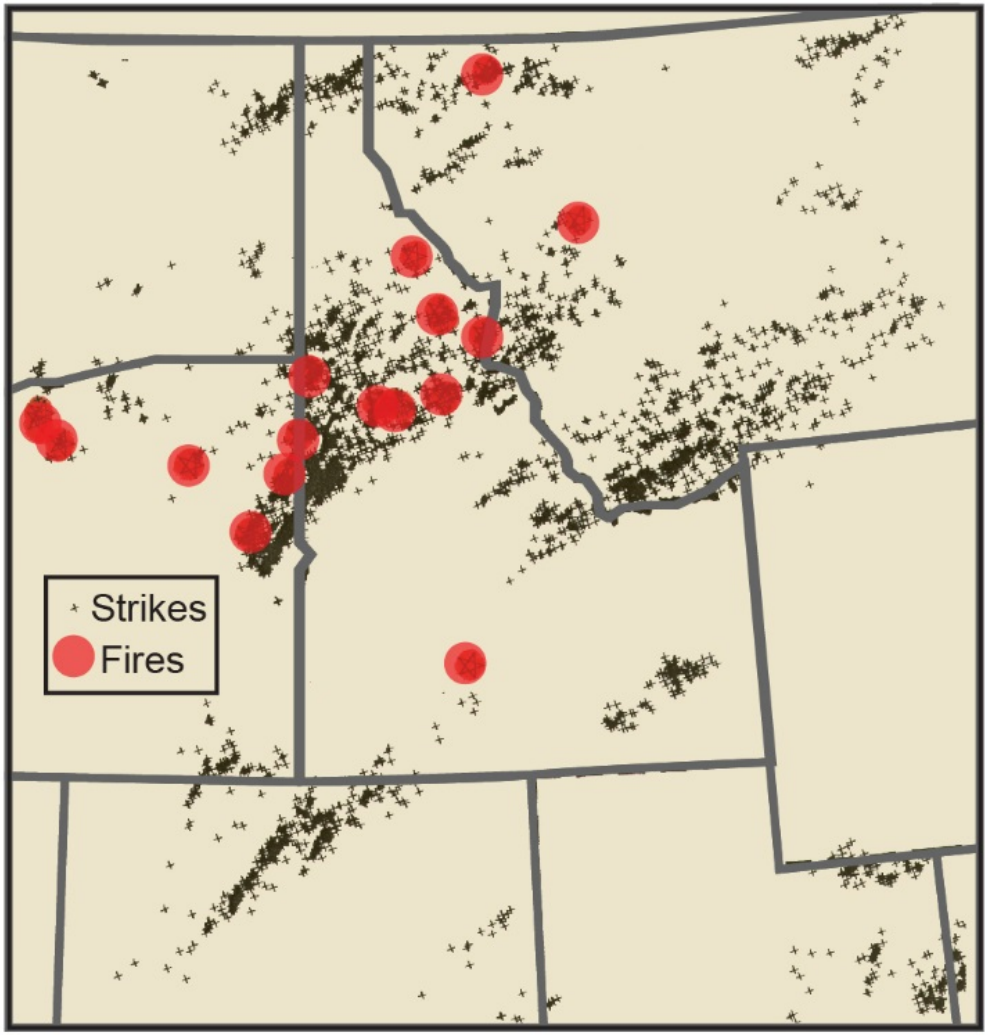
Lightning-started fire in the bitterroot national forest



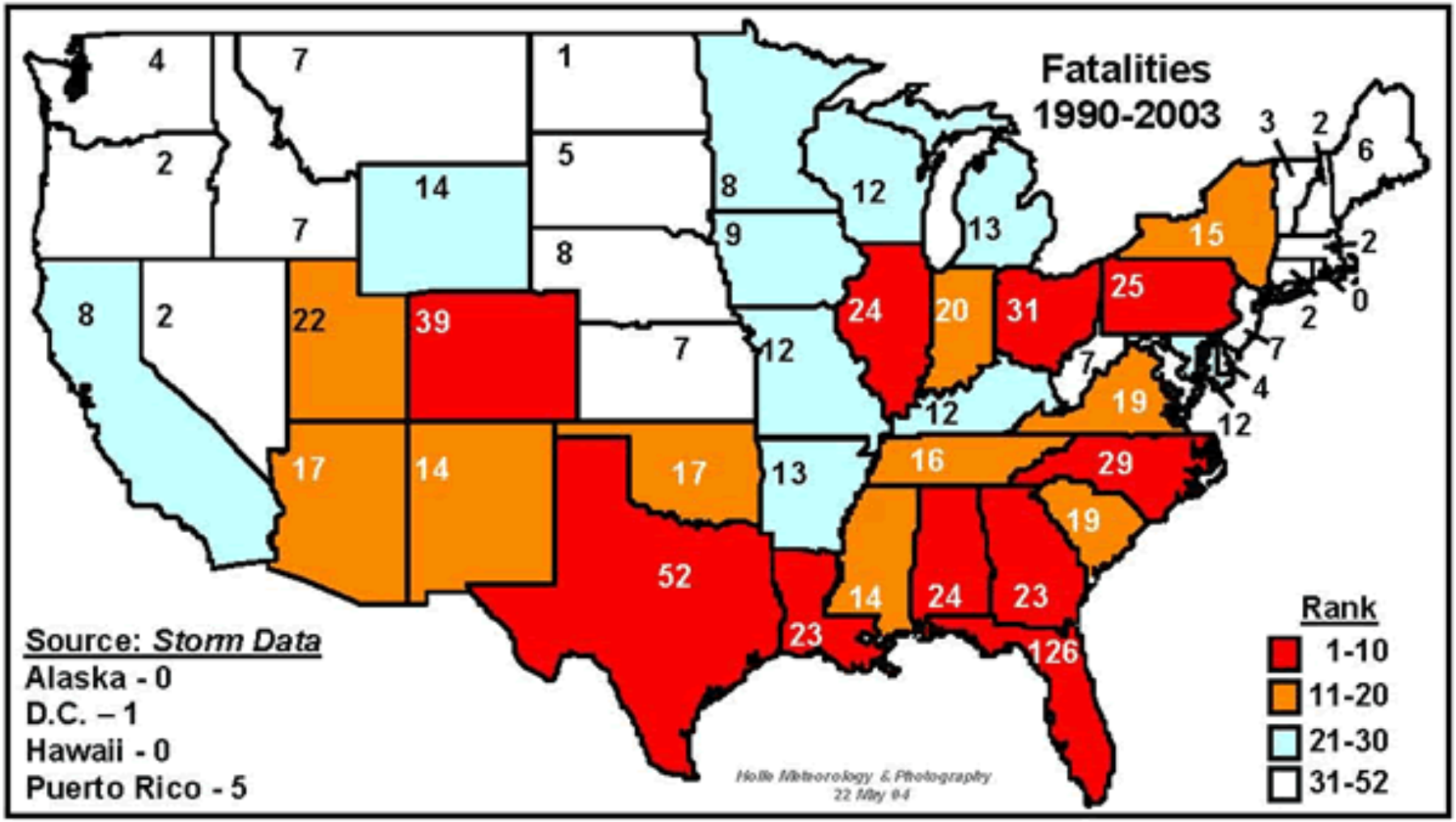
Lightning-started fires in Alaska (July 2004)

Lightning Strokes (+) and Associated Fires (red dots) in the Northwest US on a Single Day in Summer

- Observed by the National Lighting Detection Network (NLDN)
- NLDN provides important information for the US forest service

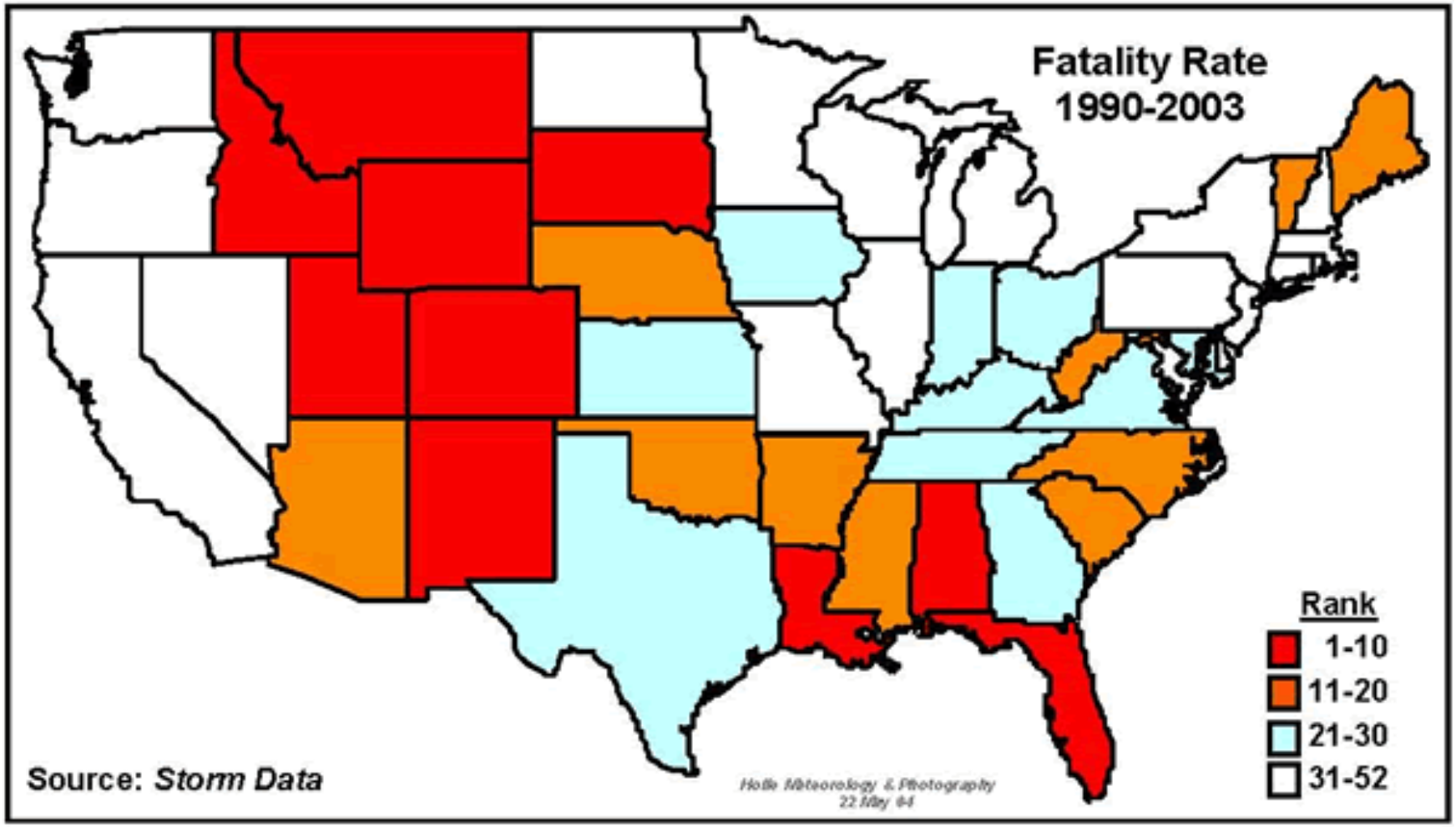


US Lightning Fatalities



Second most fatal after floods

US Lightning Fatality Rate



The rank of fatality rate (# of fatalities divided by # of lightning flashes)

Lightning Facts

- **Lightning** is an **electrical discharge** in the atmosphere, a form **of static electricity** similar to the spark created by rubbing your shoes on a carpet and then touching a metal object.
- **A lightning stroke** is ~5 km long and 2-3 cm in diameter
- **High Voltage**: 1-3 million volts/meter
- **High Current**: 15-30K Amperes
- **High Temperature**: 30,000 ^{o}C (5 times as hot as the surface of the sun)
- Energy radiating from the lightning heats the air and generates the sound waves we hear as **booming thunder**
- **100 flashes per second worldwide**
- A flash may be composed of 1-30 strokes; 3-5 is typical
- **Energy output** (1-10 billion joules):

  Total energy of a bolt of lighting could supply ~ 0.5 – 5.5 month of power in a household

  Electrical energy only: 6-h of power in a household

How does lightning forms?

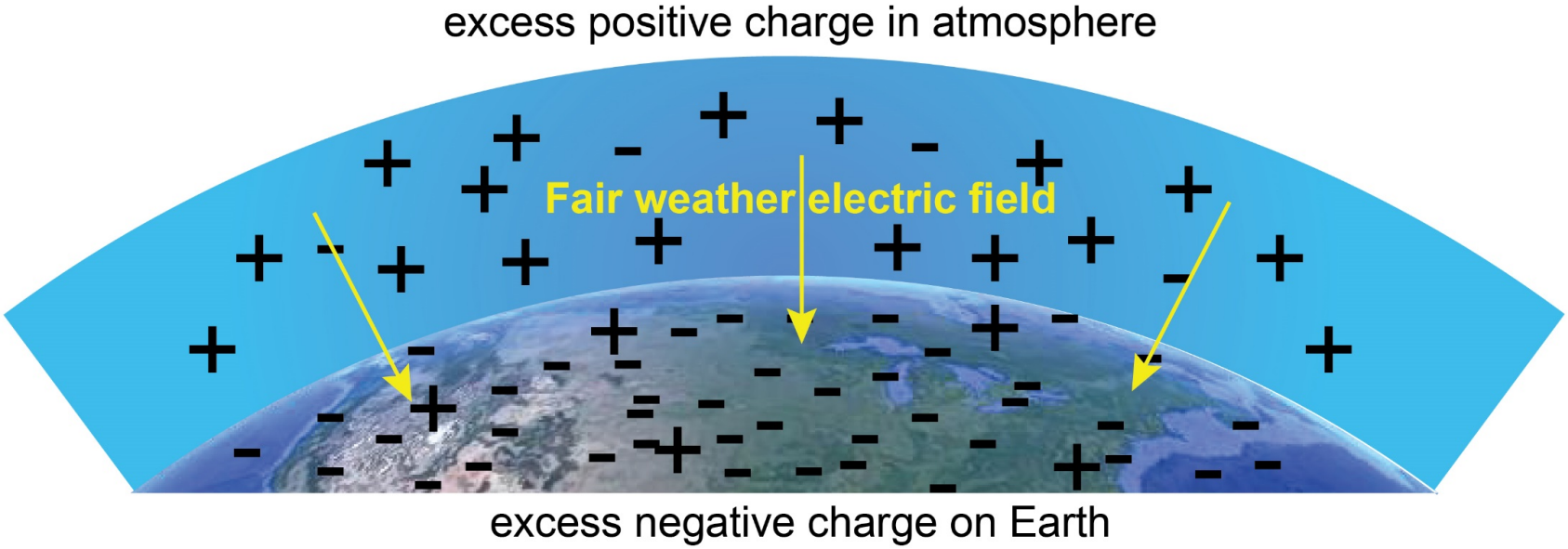
- 3 types of lightning:
  - In-cloud-lightning: within clouds
  - Cloud-to-cloud lightning: between clouds
  - Cloud-to-ground lightning: between a cloud and the ground
  - >80% of all flashes are either in-cloud or cloud-to-cloud
- Here we only consider the formation mechanism of **cloud-to-ground lightning**, which causes the most damage from all lightning.
- To understand lightning and how it forms, we need to examine the cloud at a molecular level.

Review: Electricity and Charge

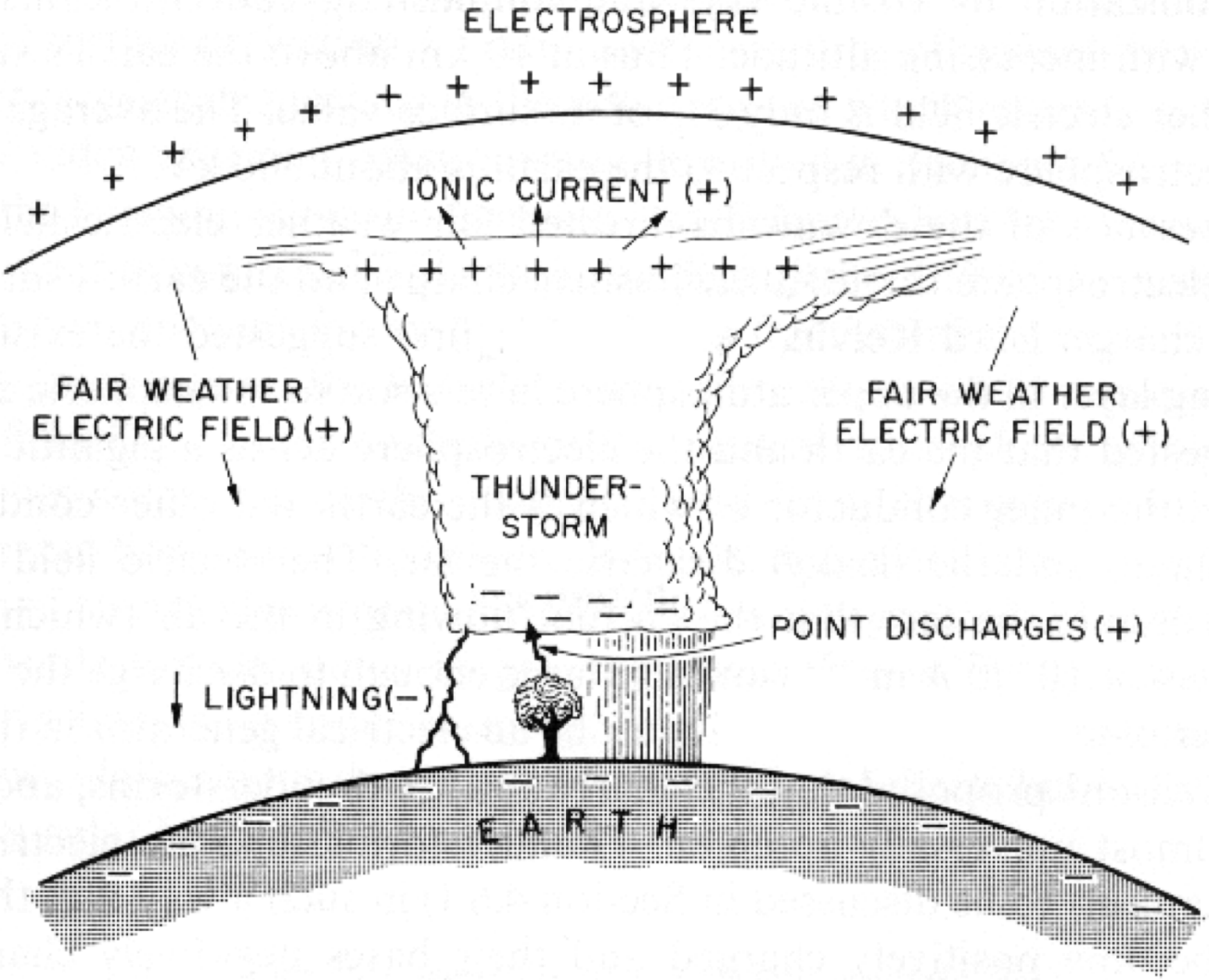
- Consider two types of charged particles in cloud molecules: protons –carry positive charge; electrons – carry negative charge
- An atom is neutral when it contains the same number of protons and electrons
- A non-neutral atom is called ion.
- An electronic field is present in any region exposed to charges
- A charge, such as positive or negative ion, when placed in an electronic field, experiences attractive or repulsive force: same sign charges repel and opposite sign charges attract
- The magnitude of the force of attraction: Volts
- Strength of an electric field: volts/meter
- Current flows easily through conductors (metal and water) and poorly through insulators (plastic and air)
- Because air is an excellent insulator, a very strong electric field must exist before charges can move freely through the atmosphere.

Earth's Fair Weather Field (without clouds): ~100 volts/meter

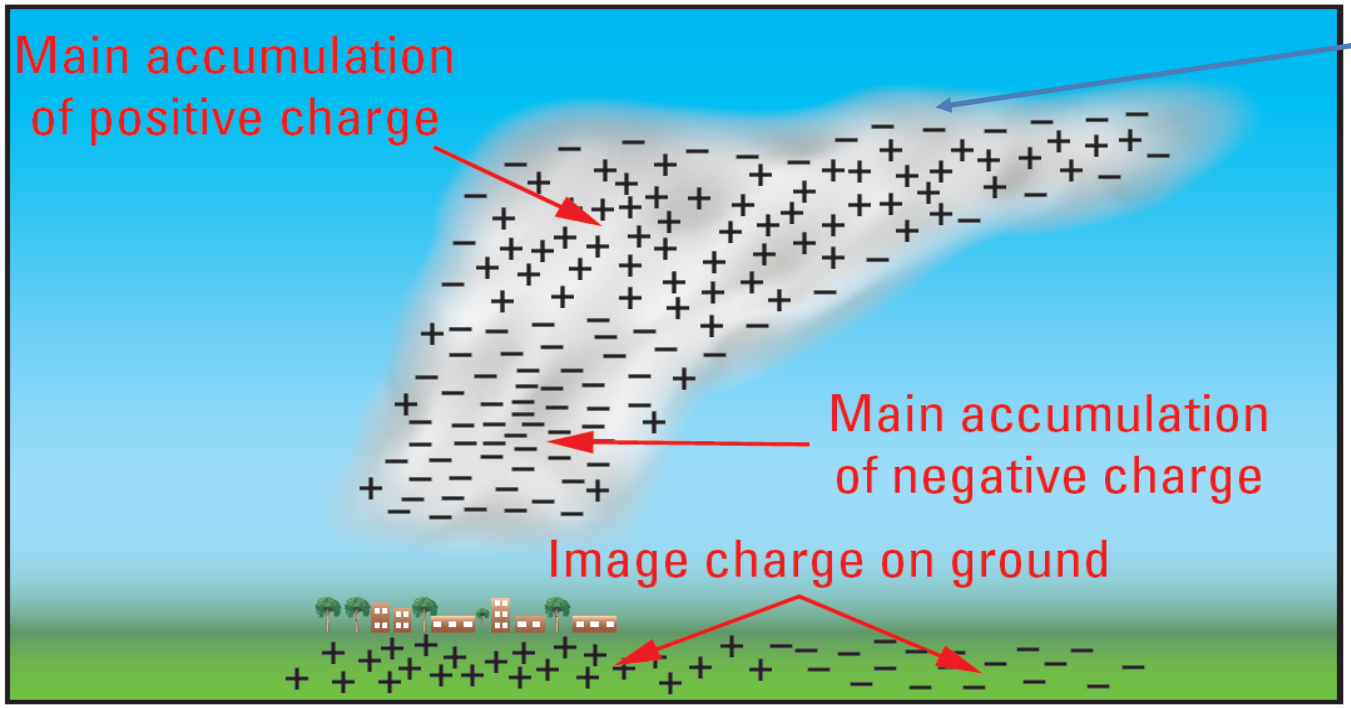
- An excess # of positively charged ion in the atmosphere
- An excess # of negatively charged ions on the earth's surface
- This is a consequence of the action of thunderstorms, which deposit electrons on the Earth's surface and remove them from the atmosphere.



Maintained by Thunderstorms



Distribution of charge in a thunderstorm and on the ground prior to a lightning stroke



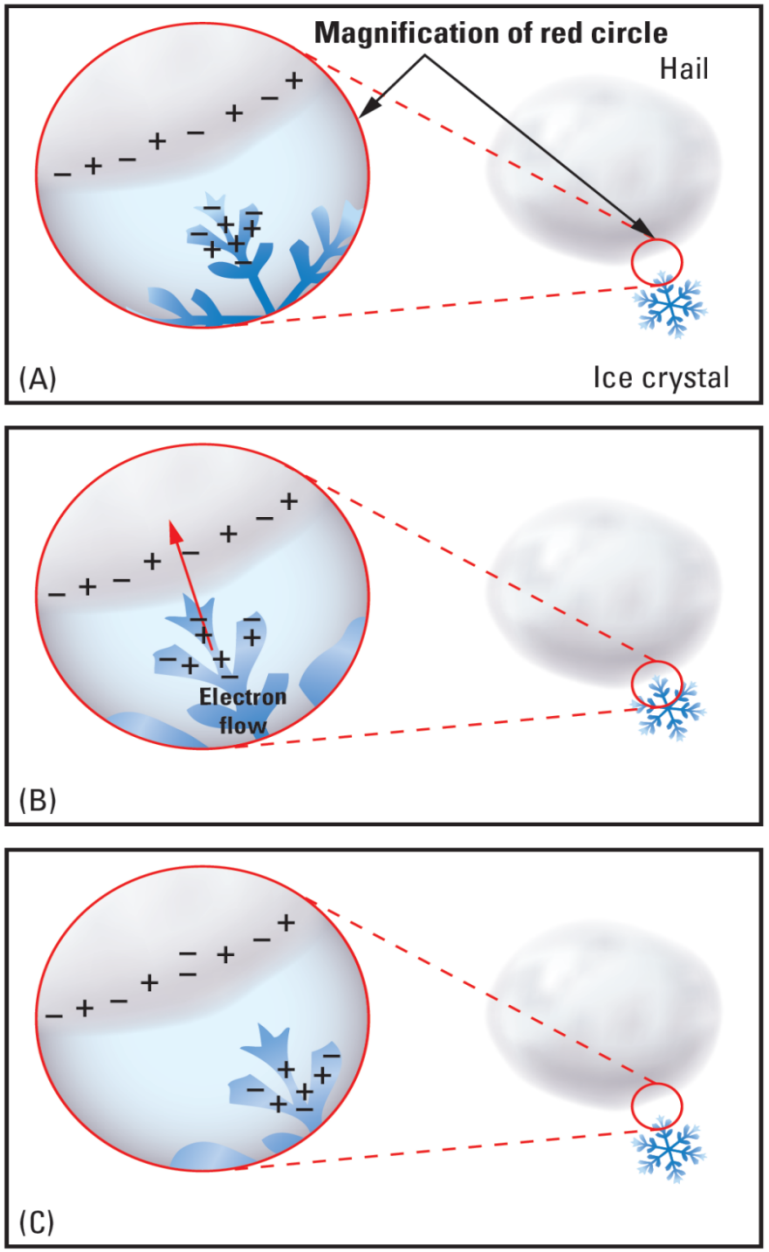
Screening Layer: the very thin layer of positive charge that appears along the sides of the clouds

- Upper part is positively charged.
- Lower part of the storm is negatively charged.
- The ground beneath has “Image charge”: as the strong negative charge develops at the base of the storm, the negative charges on the Earth’s surface under fair weather condition are repelled away from the storm’s base, leaving a positively charged region called image charge.

How this charge distribution in T-storms come out?

A mechanism called Interface Charging:

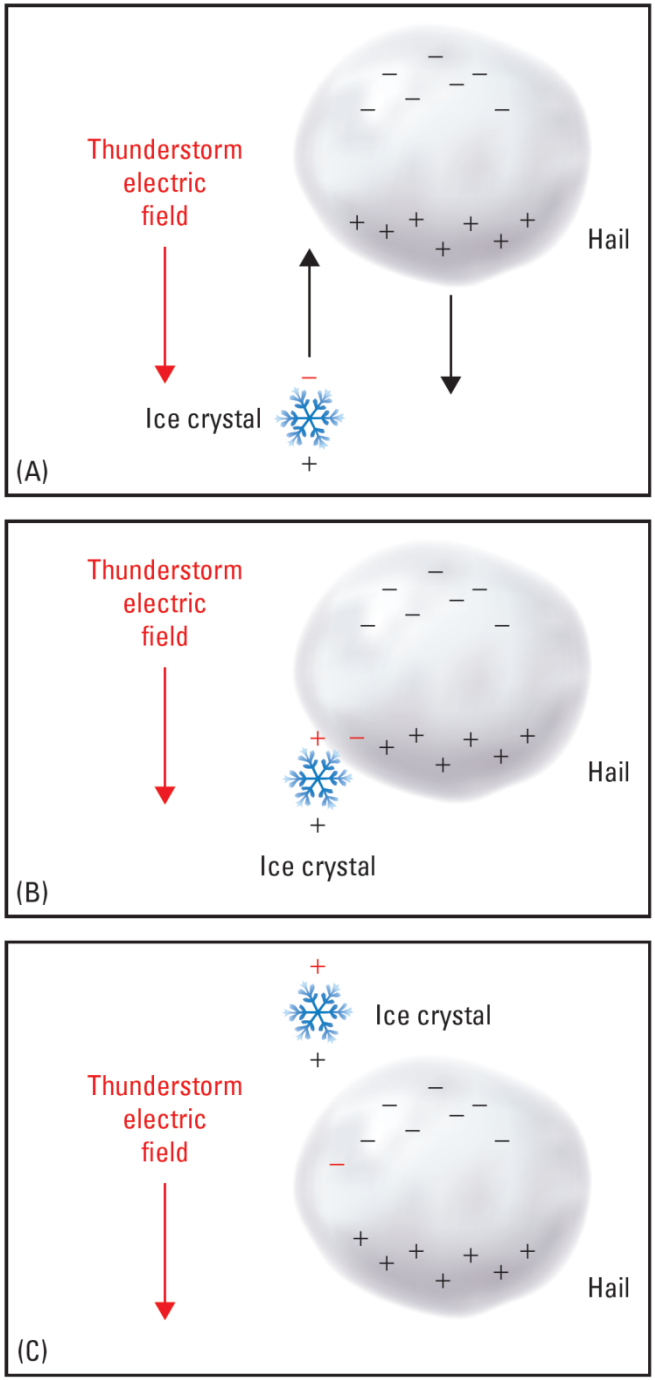
- A possible mechanism for initial charging in T-storms
- An electric field exist between two conductors with different materials
- **Panel A**: In a cloud, graupel and hail (grown by collection of supercooled water) are very different with tiny ice crystals (formed by vapor deposition). A charge potential (voltage) exist between the two types of ice particles
- **Panel B**: When ice crystals collide with hail or graupel, interface charging occur: electrons will jump from the small crystal to the larger particle.
- **Panel C**: Ice crystals become positively charged, the larger particles become negatively charged.
- The positively charged ice crystals are brought upward into anvil by updrafts, while the negatively charged heavier hail/graupel remain around the freezing level or below toward the Earth surface.



A second mechanism

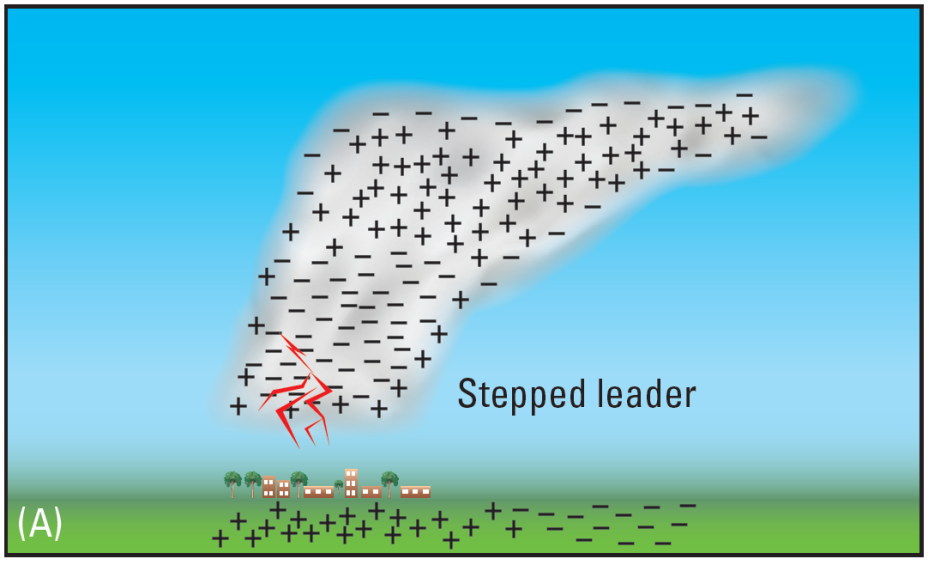
Induction Charging:

- A feedback mechanism which can accelerate the charging process
- **Panel A:** In a charged thunderstorm cloud with positive charge above and negative charge beneath, strong electric fields develop. The electrons within each particle will migrate toward upper part of the cloud.
- **Panel B:** Now when a hailstone collide with ice crystals when the hailstone is falling, the electrons on top of the ice crystals will jump to the big particle, leaving the hailstone being negatively charged and ice crystals being positively charged.
- **Panel C:** Ice crystals moving up and hailstone moving down, the electric field is reinforced.
- Eventually, the storm changes to a point where lightning can occur.



Stages of a lightning stroke: A. Stepped Leader

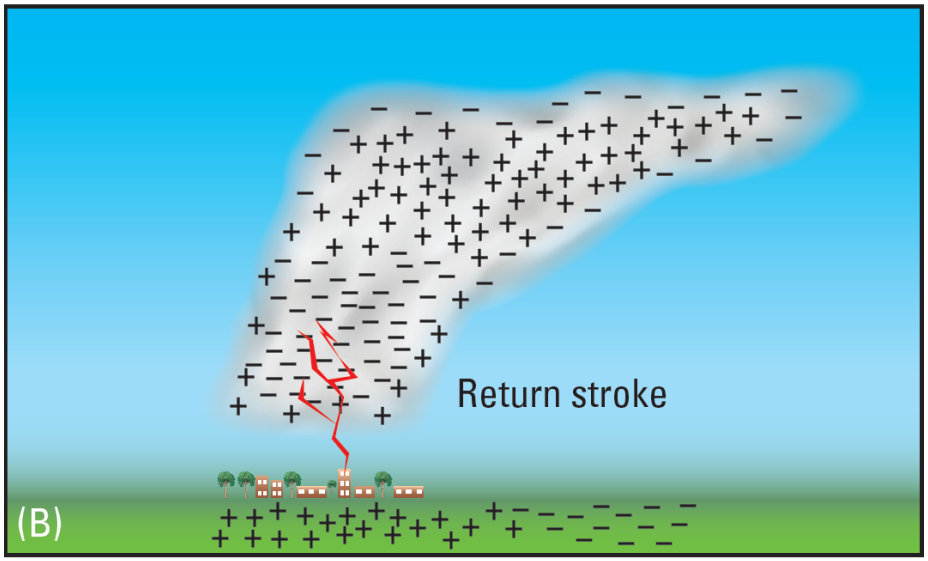
- A cloud-to-ground stroke begins when the electric field in a local area of the cloud reaches about 3 million volts/meter.
- At this field strength, air no longer acts as an insulator, and electrons begin to move freely.
- The electrons surge toward the cloud base and to the ground in a series of steps called stepped leader.
- Each step is about 50-100 m long, with a pause of a few millionths of a second between steps.



- Negative charges search for the path of least resistance to the ground, jumping downward through raindrops.
- The charges can take several paths simultaneously: forked looking of lightning strokes.

Stages of a lightning stroke: B. Return Stroke

- As one of the branches of the stepped leader approaches the ground, the electric field becomes so great that positive charges jump upward off the object (or ground) to meet the descending stepped leader. This is called **traveling spark**.
- A powerful ***return stroke*** develops when the ***traveling spark*** of positive charge surges upward to meet the stepped leader.
- At this time, the full current is reached and **the flash occurs**.

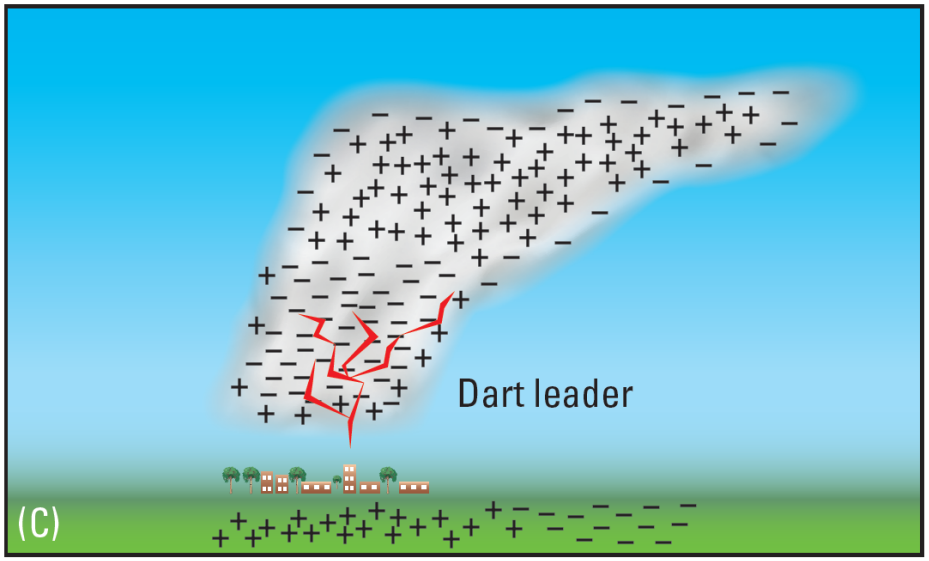


- The lightning flash is associated with the **ionization** of the molecules in the path of the lightning stroke.
- All the stepped leader & return stroke happen in about 10 microseconds.
- All we see are the branches of the lightning with **forked path & bright return stroke** near ground.

Branching occurs in the stepped leader and initial return stroke

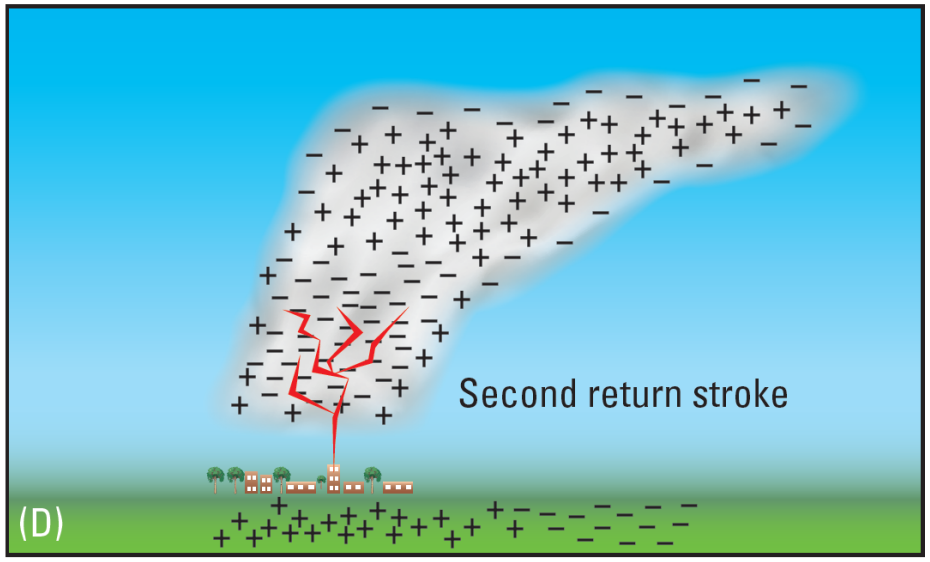
Stages of a lightning stroke: C. Dart Leader

- The same process, **leader & return stroke**, will occur in the same channel one or more times.
- A second surge of negative charge descends along the ionized path of the previous stroke creating the **Dart Leader**.



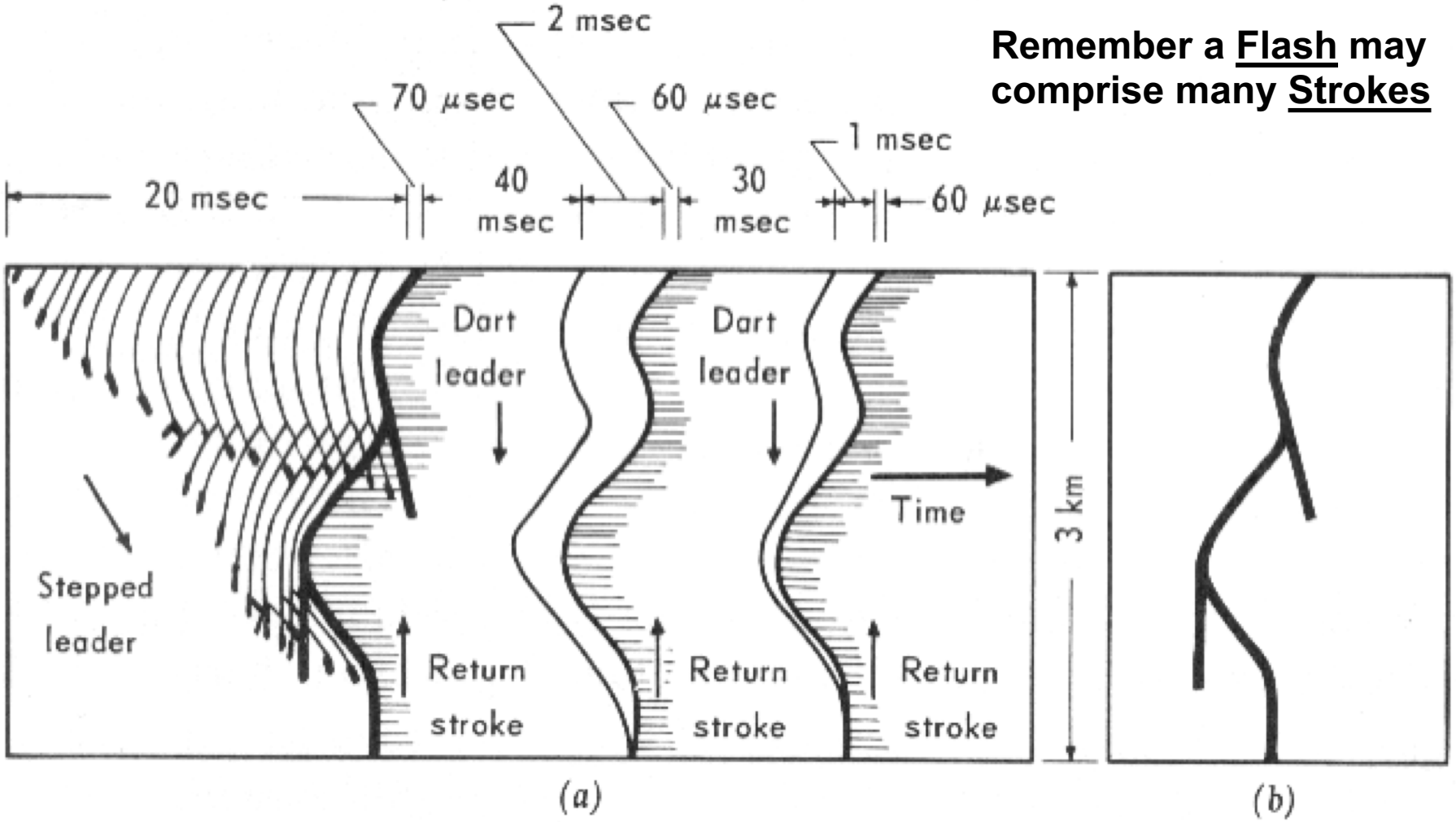
Stages of a lightning stroke: D. Second return stroke

- As before, when the dart leader approaches the earth, a **traveling spark** will jump up to meet it, initiating the **second return stroke**.
- These repeat strokes can occur rapidly.
- In rare cases, over 20 strokes occurred within a single discharge event.
- The whole process repeats until the cloud is discharged. This all happen in 10 microseconds. Your eyes can't see any of this details.

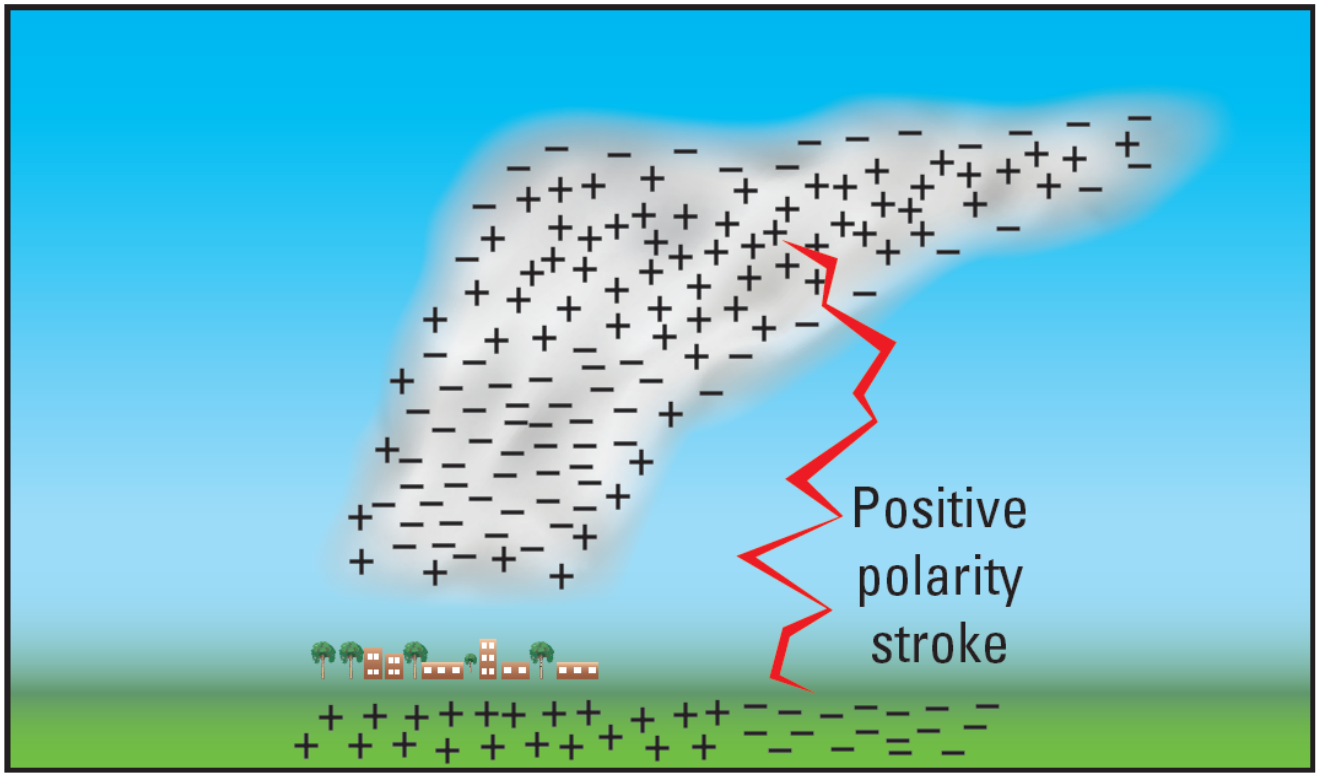


Another View

Remember a <u>Flash</u> may comprise many <u>Strokes</u>

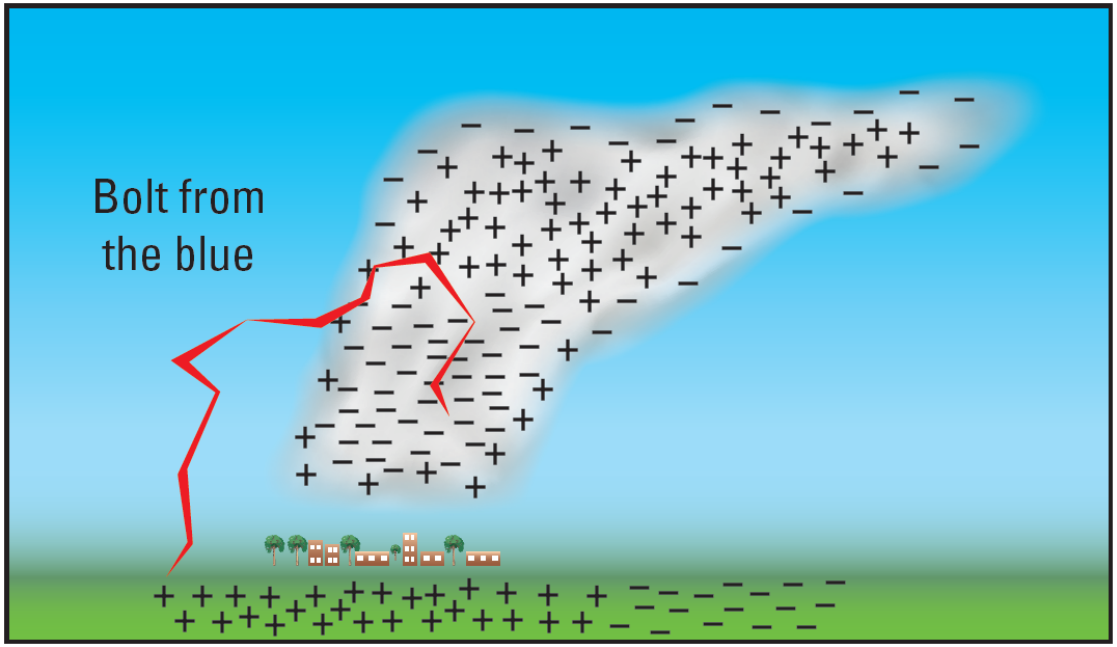


Other types of cloud-to-ground lightning strokes: positive polarity strokes



- Between anvil and ground
- Positive charges travel downward to the ground
- Less common, 8% of all cloud-to-ground lightning stroke are this type
- More dangerous because they require stronger electric fields and discharge more current.

Other types of cloud-to-ground lightning strokes: bolt from the blue



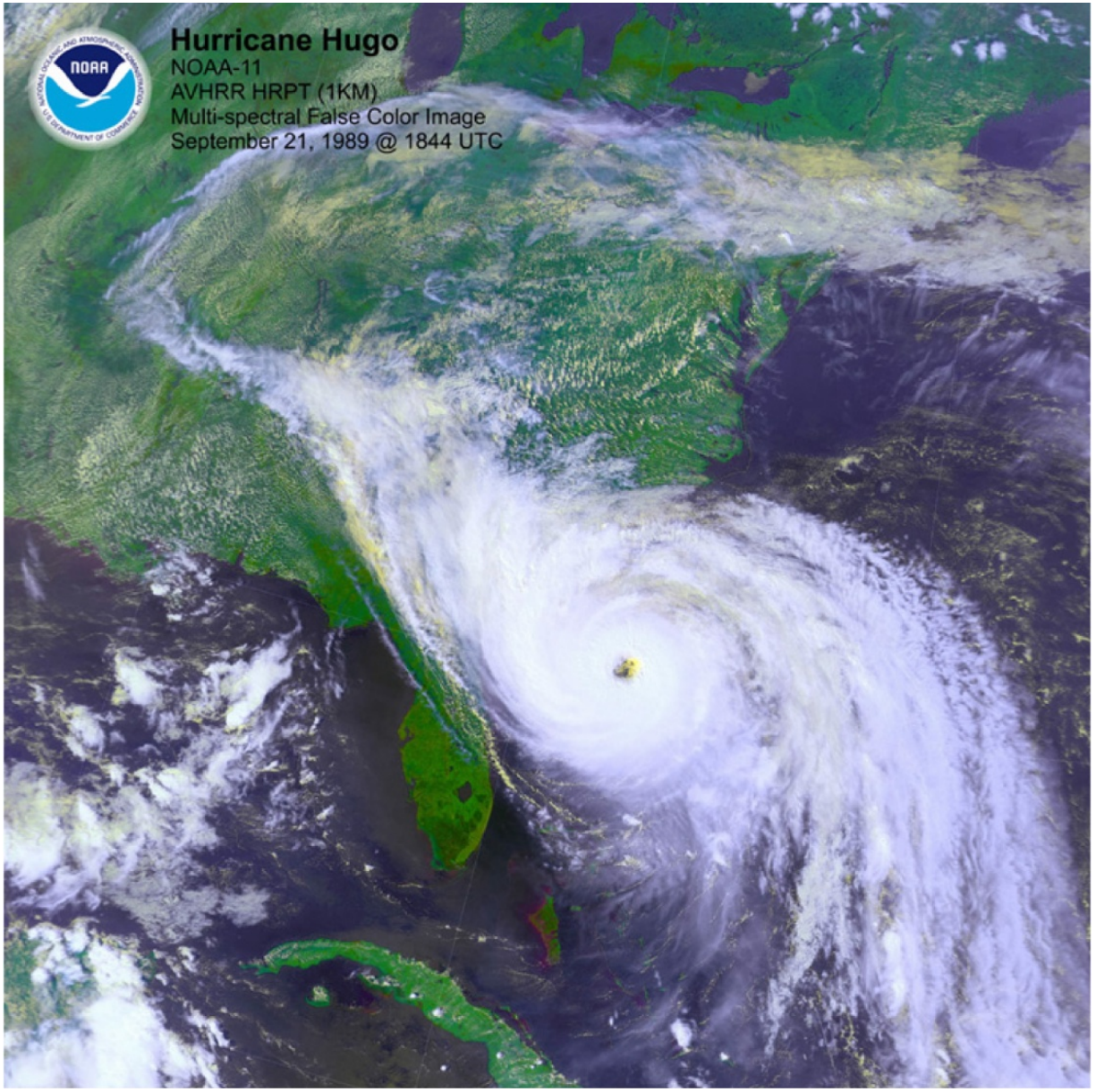
- The bolt from the blue is a type of cloud-to-ground lightning that exits from the side of a thundercloud and comes to the ground away from the thundercloud
- The ground strike can be over 10 km from the cloud boundary, arriving at the ground in an area where the sky is blue
- Normal (negative) polarity, begins as in-cloud discharges, initiated between the main negative charge and the upper positive charge within the cloud.
- After neutralizing much of the upper positive change, the discharge continues toward the positive charge at ground.

Ball lightning

- Ball lightning is a luminous, small, glowing ball of gas, typically 10–40 cm (4–16 in) in diameter. Ball lightning appears very rarely and always follows a lightning stroke.
- Has been seen by about 5% of the people on Earth
- Typically becomes bright and then disappears with an explosion.
- Behaves strangely. It floats in the air, ranges in color from red, orange, and yellow to blue, and has an “electrical” odor, indicating that ozone may be present. It sometimes floats from cloud to cloud, or cloud to ground, ground to cloud, or just horizontally. It appears to be attracted to open windows and tends to be attracted to grounded objects.
- Its lifetime varies from a few seconds to several minutes

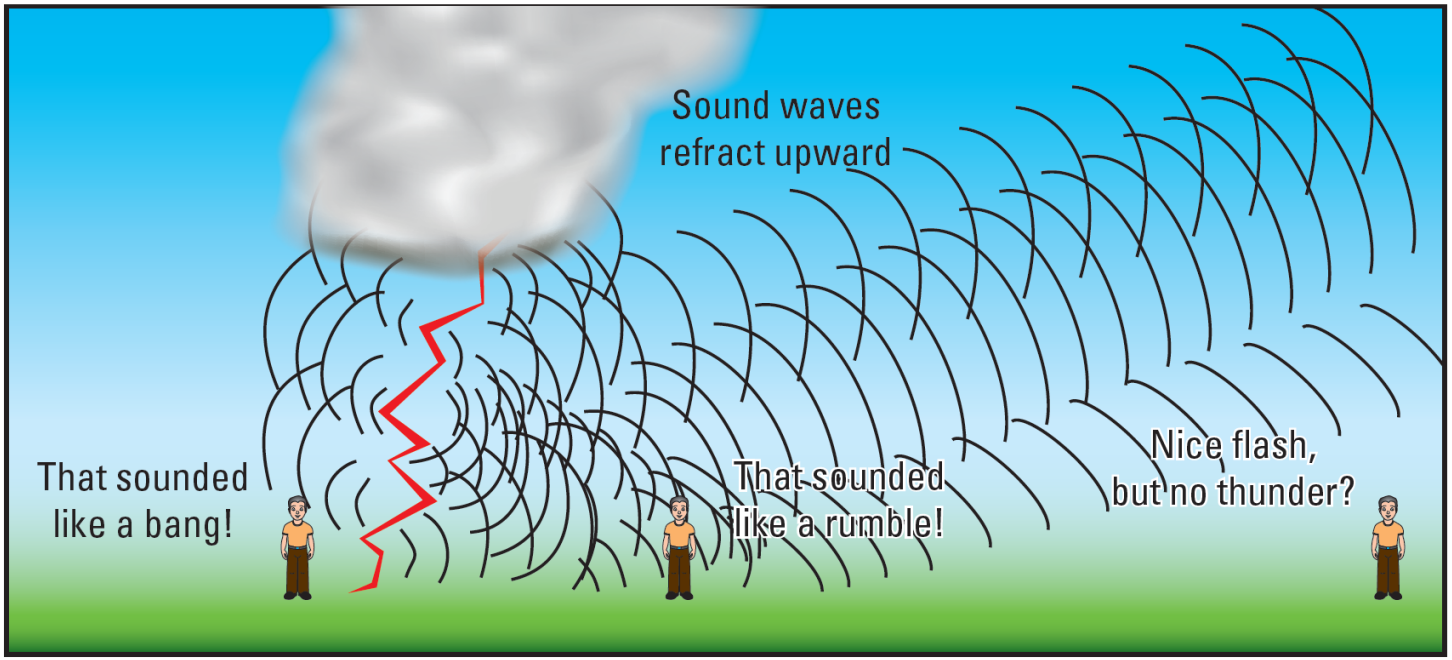
Lightning in Hurricanes

- Hurricane Hugo at landfall on the South Carolina coast. Hugo produced only 16 lightning strikes in an 8-hour period as the storm devastated South Carolina's coast.
- Updrafts in hurricanes are not as strong as those in T-storms
- Not enough supercooled water to produce hail & graupel, therefore lightning charges



Thunder

- During lightning, the air channel is heated to 54K°F (30K°C).
- The air expands explosively, creating a shock wave that evolves rapidly into crashing sound waves.
- Sound speed is 330m/s (5 seconds to travel a mile), while light speed is very fast (300million m/s). So you see lightning first, then hear thunder.
- You'll hear different sounds depending on your location from the stroke.
  - The lower the temperature, the slower the sound travels
  - The sound waves are bended upward in the atmosphere due to T decreases with height.
  - Higher frequencies bend more rapidly, so you'll hear the lower, deeper sounds near the stroke at ground.

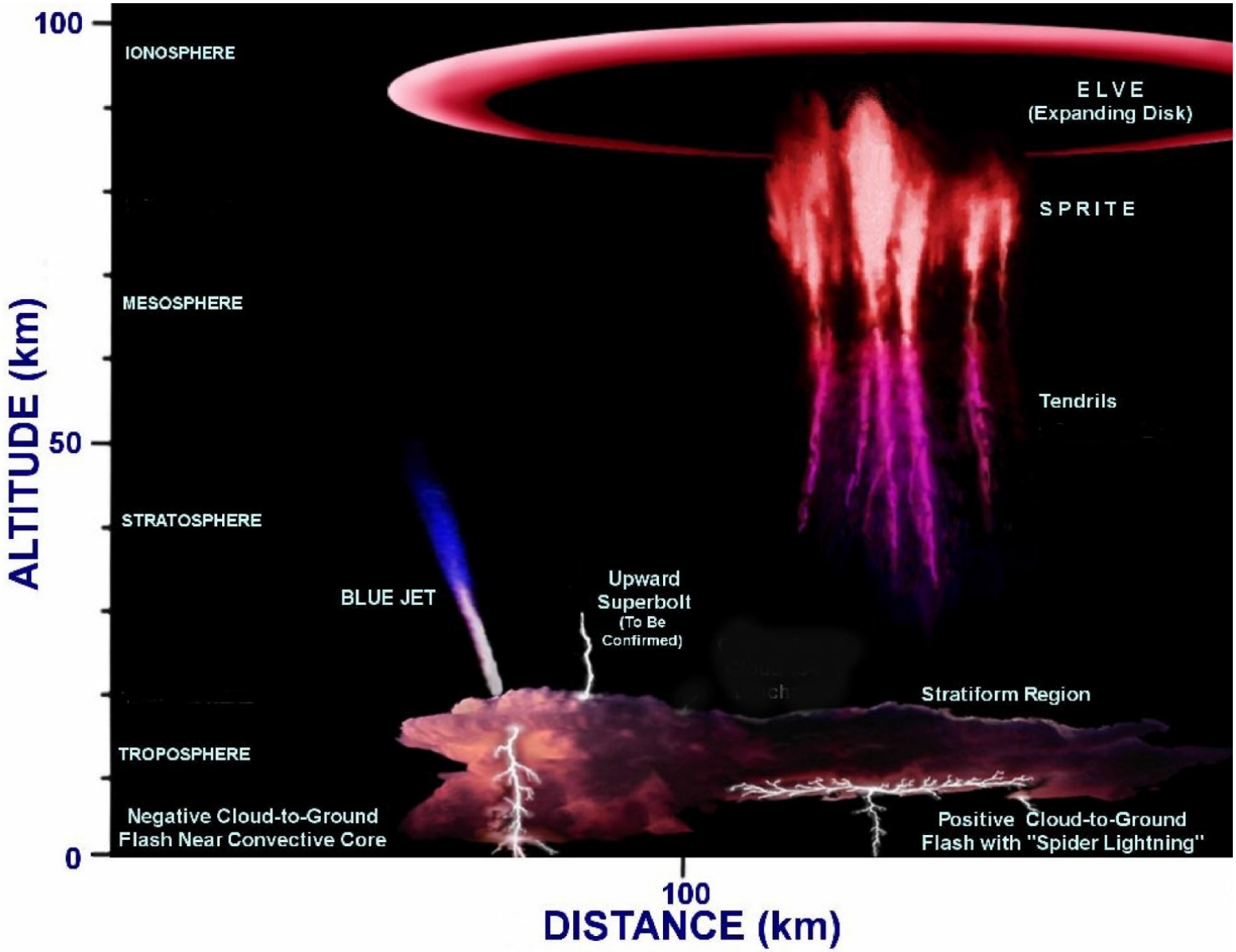


Other Phenomena Associated with Electrical Discharges in the Atmosphere

- **Heat Lightning**: Produced by a thunderstorm far off in the distance. The light will be scattered by air molecules or dust particles or reflected from clouds and appear as a light flash in the sky overhead.
- **Bead lightning**: following a lightning stroke, lightning channels sometimes break up very briefly into a series of luminous "beads". Can't be seen by the eye, but have been observed with high-speed cameras.
- **Sheet lightning**: lightning within or behind a cloud, illuminating the clouds' exterior uniformly, giving an appearance of a sheet of lightning.
- **St. Elmo's fire**: Underneath a thunderstorm, tall objects from the ground develop positive changes on their tips. If too much charge accumulates, a discharge of some spark will occur.

Red Sprites, Blue Jets, and Elvs

- **They are optical phenomena that occur between the tops of thunderstorms and the mesosphere**
- **Sprites**: are red, large weak luminous flashes that occur simultaneously with lightning strokes.
  - The brightest regions are 65-75 km above surface. A faint red glow extends to above 90 km.
  - Blue tendrils are below the brightest regions and extend downward to 30 km.
  - Most commonly found above anvil; always occur with positive polarity strokes.
  - Sprites develop as charged particles in the mesosphere & stratosphere move in response to rapid charges in the electric field triggered by a lightning discharge in the troposphere.
- **Elves**: are disk-shaped regions of light that last less than a thousandth of a second. They occur high above positive polarity lightning in the ionosphere and are centered on the lightning strke below.
- **Jets**: are blue and cannot be detected by the eye. They extend upward from the cloud top in narrow cones and can have upward speed of 100 km/sec. Usually develop over the region of active convection within thuderstorms.



Sprites and elves are triggered by cloud-to-ground positive polarity strokes that occur in the anvil region of thunderstorms. Blue jets develop over the region of active convection where most lightning strikes occur.

Lightning Safety

- Signs of lightning stroke: Sizzling sound or hair standing up indicates a strong field
- 5 s gap between flash and thunder implies a 1 mi range
- 30-30 rule (conservative)
  - 30s lag → 6 mi range
  - Wait 30 min
- Take refuge in a car or a building with plumbing and wiring
- Not under trees
- Assume a low crouch with only feet in contact with the ground
- Avoid holding elongated metal objects, like rifles or golf clubs; avoid open water outdoors, avoid taking shower indoors.
- Details on lightning hazards available from www.lightningsafety.com

Hair standing on end is a sign that Lightning is about to strike